Impact of cable lengths on the accuracy of dielectric constant measurements by time domain reflectometry

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Kahimba, F.C., Sri Ranjan, R. and Krishnapillai, M. 2007. **Impact of cable lengths on the accuracy of dielectric constant measurements by time domain reflectometry.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **49**: 1.11 - 1.18. Time domain reflectometry (TDR) probes are usually connected with a 2-m long coaxial cable to the TDR instrument necessitating the instrument to be close to the point of measurement. However, during the winter time, the TDR instrument has to be operated in a warm enclosure and connected with an extension cable to the probes embedded in the field. The varying length of the extension cable has an influence on the accuracy of measurement. This paper presents the influence of extension cable length on the accuracy of dielectric constant measurement. Measurements were made in pure water using eleven coaxial cables with lengths from 2.5 to 70.0 m. The TDR probes were made of stainless steel rods 1.6-mm diameter and 35 mm long (3-rod configuration). The dielectric constant of water calculated from the waveforms obtained with varying lengths was compared to the actual value of the dielectric constant at 20±0.3°C. The sensitivity of measurements decreased with increasing cable lengths. Cables from 2.5 to 40.0 m measured the dielectric constant accurately, with a variation in dielectric constant of ±0.05. The maximum cable length for the RG-58 cable was found to be 40.0 m. A regression equation was derived relating physical and apparent cable lengths. This equation could be used to correct for the change in dielectric constant measurement arising from varying cable lengths. Results from this study can be used to develop calibration equations for different extension cable lengths. **Keywords**: TDR, dielectric constant, waveform, physical cable length, apparent length.

Les sondes des réflectomètres temporels (TDR) sont habituellement connectées au TDR lui-même par un câble coaxial de deux mètres de longueur; par conséquent, l'instrument doit être placé très près des points de mesure. Durant la période hivernale, le TDR doit cependant être maintenu dans un endroit fermé et chaud et un câble d'extension est nécessaire pour assurer la connexion avec les sondes enfouîtes au champ. La longueur variable de ce câble d'extension a une influence sur la précision des mesures. Cet article présente l'influence de la longueur du câble d'extension sur la précision des mesures de constante diélectrique. Des mesures ont été prises dans de l'eau pure en utilisant onze câbles coaxiaux ayant une longueur comprise entre 2,5 et 70,0 m. Les sondes TDR étaient faites de tiges d'acier inoxydable d'un diamètre de 1,6 mm et de 35 mm de longueur (configuration à trois tiges). Les valeurs de la constante diélectrique de l'eau, telle que calculée à partir des spectres obtenus à l'aide des différents câbles d'extension, ont été comparées aux valeurs connues de la constante diélectrique à une température de 20 ± 0,3°C. La sensitivité des mesures décroissait avec une augmentation des longueurs de câble. Les câbles de 2,5 à 40,0 m mesuraient la constante diélectrique précisément avec une variation de ±0,05 de celle-ci. Il a été démontré que la longueur maximale pour un câble RG-58 est de 40,0 m. Une équation de régression a été dérivée en considérant les longueurs physique et apparente des câbles. Cette équation pourrait être utilisée pour faire la correction du changement de la mesure de la constante diélectrique provenant de différentes longueurs de câble. Les résultats de cette étude peuvent être utilisés pour développer des équations de calibration pour différentes longueurs de câbles d'extension. **Mots clés**: TDR, constante diélectrique, spectre, longueur physique de câble, longueur apparente.

INTRODUCTION

Time domain reflectometry (TDR) is a widely used method for measuring soil water content and electrical conductivity. The ability to non-destructively measure both water content and electrical conductivity simultaneously makes it a very important method for measuring water content and nutrient movement in porous media (Robinson et al. 2003a; Vanclooster et al. 1994). The accuracy of measurement with TDR instruments depends on factors such as cable length, probe length, calibration method, waveform analysis, and temperature (Zegelin et al. 1992; Logsdon 2000; Evett 2000b; Robinson et al. 2003b). In this study, we present the influence of cable length on the accuracy of the TDR method for dielectric constant measurements. Calibrations of the extension cables were performed to determine the optimum length of RG-58 50Ω coaxial cable used in the experiment.

The TDR probes are usually connected with a 2-m long coaxial cable to the TDR instrument necessitating the instrument to be close to the point of measurement in the field. However, because of the narrow operating temperature range of -10 to 55°C for the 1502B cable tester as recommended by the manufacturer (Tektronix, Inc. 1998), field measurements during the winter under temperatures below the operating temperature range are not possible. Other researchers who have used this instrument in the field have recommended a narrower range of 5 to 55°C (Jones et al. 2002; Jones and Or 2002; Blonquist et al. 2005). During wintertime soil moisture measurements, the TDR instrument has to be operated in a warm enclosure located away from the field where the probes are embedded. Therefore, another extension cable of varying length is used to connect the TDR probe to the TDR instrument located in the warm enclosure i.e. a truck cab. Normally the user has to set the relative dielectric constant for a given cable type and assume that the same length is used for all the different probe measurements. Thus any change in dielectric constant is attributed to the material in which the TDR probe is embedded. However, it is impractical and expensive to have the same extension cable length for all the probes irrespective of the distance to the warm enclosure. The variable distances from the cable tester necessitates the use of extension cables of various sizes depending on the proximity between the probes in the field and the location of the cable tester in the warm enclosure.

Various studies have been conducted on the effects of cable lengths on the accuracy of TDR measurements. Logsdon (2000) observed that long cables affect the dielectric constant measurement in all ranges of soils. Pierce et al. (1994) used a 22.2-mm diameter coaxial cable to investigate the effect of length, shear, and crimps on long cables to the reflection signatures measured by TDR. They used the coaxial cable with lengths from 90 to 530 m. Their results indicated that resolution of the reflection signatures decreased with increase in cable length. Shorter cables were more accurate in detecting the cable deformations compared to longer cables. When the cable length was increased from 94 to 268 m, the reflection amplitude was reduced by 80%. For cables longer than 268 m, they commented that TDR measurement resolutions decrease non-linearly causing difficulty in getting accurate measurements. The optimum cable length they obtained for the 22.2 mm coaxial cable was 268 m. The experiment however involved large diameter cables (22.2 mm) that are not typical of the RG-58 cables used for soil moisture measurements.

Brendan (2003) investigated the RG-58 and RG-8 extension cables for multiple measurements. The extension cables were connected to shorter cables holding the TDR probes. A longer cable filtered high frequency electromagnetic waves causing a loss of resolution in the reflected wave. The decrease in the returning EM wave-energy caused a decline in the slope used for the automatic end-point determination. The author recommended the use of similar types of cables when extension cables are to be used. While the author did not perform optimization to determine the maximum cable lengths, he recommended a maximum length of 35 m for the RG-58 cable depending on manufacturer's recommendations. Brendan (2003) also noted that the cables with heavier shield such as the RG-8 have lower signal loss; hence they can be used for extensions up to 60 m. The RG-58 cable is 5 mm in diameter, has a single and thinner shielding, and is more flexible. On the other hand, the RG-8 cable is 10 mm in diameter, has a double insulation, and is less flexible. Both cables have the same 50-Ω impedance values (Fuller and Blankenship 2002; Logsdon 2000).

Other researchers have also used extension cables for automation and multiplexing the TDR measurement with multiple probes (Logsdon 2000; Herkelrath and Delin 1999). Despite these advances, studies also have shown that a combination of accessories such as extension cables and multiplexers greatly affect the accuracy of dielectric constant measurements (Logsdon 2000). The use of extension cables affects the accuracy of TDR measurements depending on the type and size of the cable used, length extended, temperature, and type and size of the probes used (Deutsch et al. 1994; Robinson et al. 2003a).

Many experiments with longer cables have been reported in the literature (Fuller and Blankenship 2002; Logsdon 2000). However, not much has been done to determine the optimum extension cable length that can still give accurate measurements of dielectric constant. The influence of a combination of materials used in the construction of the probe, i.e., probe head and probe rods, has not been explored. The relationship between physical cable length and its equivalent length is important for determining the dielectric constant.

The aim of this experiment was to investigate the maximum cable lengths of RG-58 50-Ω coaxial cable that can still give accurate measurement of the dielectric constant. The results were used to develop a calibration equation that can be used to correct the data for the effect of extension cable lengths on the TDR water content measurements. Similar procedures could also be adopted to develop calibration equations for different probe-cable combinations and for different non-lossy and lossy dielectric media.

Theory of TDR method

The principle of operation of the TDR for measuring the dielectric constant has been presented by a number of researchers (Topp et al. 1980, 1982; Baker and Allmaras 1990; Jones et al. 2002; Evett 2000a; Or et al. 2004). It involves the measurement of the propagation velocity of an electromagnetic (EM) wave generated by the TDR cable tester into a dielectric material such as water or soil solution. The length of the waveguide embedded in the dielectric material and the propagation velocity of the EM wave determine the two-way travel time as:

$$t = \frac{2L}{v} \tag{1}$$

where:

L = length of waveguide,
v = propagation velocity of EM wave, and
t = time of travel.

The propagation velocity is related to the apparent dielectric constant of the medium as:

$$v = \frac{c}{\sqrt{\mu K_a}} \tag{2}$$

where:

μ = magnetic permeability of the medium (assumed to be 1.0 for non-magnetic dielectric material),
c = speed of light in free space or velocity of the EM wave in vacuum (3×10^8 m/s), and
K_a = apparent dielectric constant of the material.

Combining Eqs. 1 and 2 and setting μ=1gives the apparent dielectric constant as:

$$K_a = \left(\frac{c}{v}\right)^2 = \left(\frac{ct}{2L}\right)^2 \tag{3}$$

During waveform analysis, the horizontal axis on the 1502B Tektronix cable tester is set in the equivalent length (L_a) units. The apparent length of the probe, L_a, is therefore defined as:

$$L_a = \frac{ct}{2} \tag{4}$$

Hence K_a can be expressed in terms of the ratio of apparent length of the waveguide to the physical length by Eq. 5.

$$K_a = \left(\frac{L_a}{L}\right)^2 \tag{5}$$

During soil moisture measurement, the TDR probe embedded in the soil measures the composite dielectric constant of the media. However, most materials in the soil have much smaller dielectric constants compared to water ($K_{soil} = 3 - 5$; $K_{ice} = 4$; $K_{air} = 1$; $K_{water} \approx 81$). This large contrast in dielectric constant can be used to determine the water content of the mixture.

The calculated apparent dielectric constant is related to the water content θ_b using either empirical models such as the model proposed by Topp et al. (1980) or physical (dielectric mixing) models. The empirical models are less accurate for water contents above 0.5 m^3/m^3 and on soils with high organic matter and clay contents (Jones et al 2002). The physical (dielectric mixing) models are more accurate for wider ranges of water contents and soil salinity since they consider the geometry of the medium in relation to the axial direction of the wave guide and the dielectric constant of various materials in the soil (Baker and Allmaras 1990; Jones et al. 2002; Warrick 2002). However for most practical soil moisture measurement purposes, the Topp model has been accepted and used in various studies involving TDR measurements (Topp et al. 1982; Sri Ranjan and Domytrak 1997; Wraith and Or 1999; Blonquist et al. 2005). The model relates the apparent dielectric constant K_a with the water content as:

$$\theta_v = -0.053 + 2.92\times 10^{-2} K_a - 5.5\times 10^{-4} K_a^2 + 4.3\times 10^{-6} K_a^3 \tag{6}$$

The TDR waveform analysis

Analysis of the waveform is another key factor in getting an accurate measurement of the dielectric constant. The analysis involves determination of the first peak of the wave at the base of the probe when the wave enters the dielectric medium and the end reflection when the wave encounters the discontinuity at the end of the probe. The waveform interpretations can be done by manual graphical methods or by waveform analysis using software.

Using the graphical method (Baker and Allmaras 1990; Evett 2000b), the initial travel time t_1 at the first peak is taken as the intersection between the tangent on the first descending limb and the horizontal line at the first peak (Fig. 1). This same point is also defined by Logsdon (2000) as 90% of the height of the first peak or rise time. The second reflection point at time t_2 is defined as the intersection between the tangent on the second rising limb and the tangent on the horizontal or sloping portion of the waveform at the 'global minimum' (Evett 2000b). The difference between the two times gives the travel time of the EM wave. These two key points can also be obtained using the first derivative of the waveform whereby the points corresponding to t_1 and t_2 are taken as the minimum of the first derivative and the second peak of the first derivative (Baker and Allmaras 1990; Evett 2000b; Jones et al 2002; Or et al. 2004).

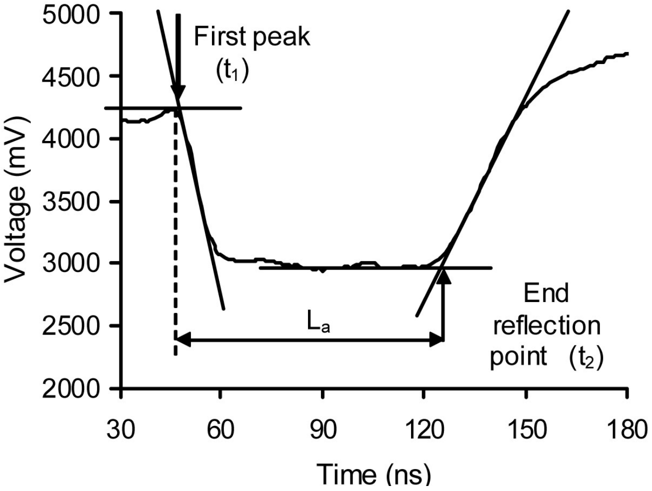

Fig. 1. Typical waveform for a 35-mm TDR miniprobe immersed in pure water and attached to a 2.5-m coaxial cable. The difference between the first peak and the end reflection defines the apparent length L_a of the waveguide.

Owing to the inaccuracies associated with graphical interpretation of the waveforms, computer programs have been developed for the TDR waveform analysis. Some examples are the TACQ program developed by Evett (2000a) and the WinTDR developed by Hubscher et al. (1996) and revised by Or et al. (2004). Procedures for the automatic waveform analysis using the TACQ software are explained in detail in Evett (2000a, 2000b). The WinTDR program currently analyzes waveforms from Tektronix 150X (B/C) cable testers only (Or et al. 2004). Most computer programs for wave form analysis supplied by manufacturers are suitable for commercial TDR probes longer than 0.15 m. However, when probes that are 0.04 m long are used with the Tektronix 150X (B/C), the waveforms have a lot of noise that needs to be filtered. This program was extensively modified to filter the noise associated with shorter probes for use in a study to determine the effective volume measured by miniprobes (Sri Ranjan and Domytrak 1997). It is this modified program that has been used with our miniprobes in this research.

MATERIALS and METHODS

Instrumentation

The TDR miniprobes were made in our laboratory and individually calibrated. The 35-mm miniprobe used in this experiment was made using three 1.6 mm-diameter stainless steel rods (three-rod configuration). The three rods were connected using a Bayonet Nelson (BNC) Connector type KC-79-35 (King's Electronics Co. Inc., Rock Hill, SC). The probe was then connected to a 2.5-m coaxial cable type RG-58 50 Ω (Belden Electronics Division, Richmond, IN), which had BNC coaxial connector cable terminations on both ends. Since the impedance is inversely proportional to the diameter of the probes, smaller diameter probes have the advantage of producing high impedance and peak (Mojid et al. 2003). The three-rod TDR miniprobe construction is described in Sri Ranjan and Domytrak (1997). In the three-rod configuration, it is recommended that the critical rod spacing should be greater than three times the diameter of the central rod to avoid the "skin effect" (Zengelin et al. 1992). The rod spacing was 6 mm, which is 3.75 times the diameter of the rods; hence the conditions for avoiding the skin effect were satisfied. It is also suggested that when performing laboratory calibration, no part of the probe should be within 40 mm of the edge of the container used for calibration (Campbell Scientific, Inc. 2001). This also helps to prevent the energy field from extending outside the container. The TDR probe was inserted in a water column 250 mm deep and 280 mm in diameter leaving a minimum clearance of 130 mm from the sides of the container.

The TDR miniprobes have been successfully used by various researchers for water content measurements. Mojid et al. (2003) used a 45-mm miniprobe and commented that longer probes cause continuous energy loss along the probe rod causing wave attenuation even at lower ranges. The miniprobes are also more accurate for point measurements of soil moisture on depth intervals of 0.10 m or less (Sri Ranjan and Domytrak 1997). Topp et al. (1980, 1982), Sri Ranjan and Domytrak (1997), and Evett (2000a) successfully used 50-mm TDR miniprobes for soil moisture measurements.

The calibration of the miniprobe was done in pure water as a dielectric medium. The probe length, distance per division, and peak were set in the Quick Basic program code. Alterations were made for the probe's apparent length until the probe was able to repeatedly measure the dielectric constant (K_a) value of 80.36 at a specified water temperature of 20°C. Calibration of TDR probes using dielectric fluids such as water, acetone, oil, and air have also been reported by Robinson et al. (2003a), Logsdon (2000), and Blonquist et al. (2005).

Measurement using different lengths of extension cables

Having calibrated the 35-mm TDR miniprobe with a 2.5-m cable, the length of the coaxial cable was then altered. Eleven coaxial cables of type RG-58 50-Ω (Belden Electronics Division, Richmond, IN) and varying lengths (2.5, 4.5, 7.1, 9.6, 12.9, 17.4, 19.9, 30.0, 40.0, 50.4, and 70.0 m) were used to measure the dielectric constant of water in a constant temperature enclosure maintained at an average temperature of 20.0±0.3°C. The cables were uncoiled prior to taking the measurements. Since the TDR assumes a uniform velocity of propagation along the cable length as well as the miniprobe, any large variation in cable length in relation to the probe length will affect the dielectric constant reported by the TDR. Therefore, for longer extension cables, the physical cable length has to be modified to attain the prescribed dielectric constant for the media in which the probe is embedded. This was accomplished by modifying the cable length within the computer program until the cable was able to measure the prescribed dielectric constant of water at the specified temperature. After attaining a stable value, four measurements were taken for each cable, and were used for statistical analysis to determine the measurement accuracy of each extended length. The waveforms captured by the Tektronix 1502B metallic cable tester (Tektronix Inc., Beaverton, OR) for each cable were recorded and analyzed. The waveforms obtained with varying cable lengths were then plotted on the same scale and compared.

Waveform analysis

Waveform analysis can be done both manually and by using the auto-analysis option. Using the manual method, the data file created by the cable tester as a text file was downloaded and plotted using a spreadsheet program. The tangents corresponding to the first peak and end reflection were fitted manually (Fig. 1).

Figure 1 shows a waveform created by a 35-mm TDR probe immersed in pure water and attached to 2.5-m coaxial cable. The distance between the first peak and the end reflection point define the apparent length L_a of the waveguide.

During the initial calibration, the 35-mm TDR miniprobe was attached to a 2.5-m coaxial cable and immersed in pure water at 20°C. The probe's information was entered into the Quick Basic program. The executable program was created and used to run the cable tester. A trace of the waveform was created and tangent lines were drawn that gave the best fit while monitoring the K_a measured by the probe. The procedure was repeated to obtain an apparent length that gave a K_a value of 80.36 at the recorded temperature of 20°C.

The autoanalysis was used to analyze the waveforms generated when the cable lengths were altered from 2.5 to 70.0 m. During this process the probe specifications were unaltered. For each physical cable length, an apparent cable length was input into the computer program until the miniprobe with the extension cable was able to measure the K_a value at the specified temperature.

Comparison of measured and actual dielectric constants

Four readings of dielectric constant of water (K_a values) were taken for each cable length. The aim was to determine the extent to which the measured K_a values deviated from the known K_a value of water at a particular temperature as the cable length increased. A statistical analysis system (SAS) software version 9.1.2 (SAS Institute Inc. 2004) was used for the statistical analysis. Comparison of means was performed between the average of four measurements for each cable length and the actual K_a value. The difference between the average of the measured K_a values and the actual K_a value were compared, and the optimum length with a dielectric constant difference of less than 0.05 was determined. The cable length experiment was also performed by Logsdon (2000) with cable lengths ranging from 6.4 to 49.5 m. He concluded that cable lengths significantly affected the dielectric constant measurements. However, no optimization was performed to determine the maximum length that the RG-58 and RG-8 cables could be extended and still obtain acceptable accuracy for water content measurement.

Comparison between the physical and apparent cable lengths

Comparison was made between the physical cable length and the equivalent length as interpreted by the cable tester (apparent cable length). The apparent cable length is a combination of the effects of the coaxial cable, BNC connectors, and the wave guide. The determination of the apparent length of the cable was performed after the apparent length of the probe had already been determined and fixed in the initial probe calibration with a fixed cable length of 2.5 m. This second stage of calibration involved the alteration of the equivalent length of each specific cable on the computer program. Ideally the physical length of probe-cable combination differs from the length interpreted by the cable tester due to the combination of more than one type of materials (coaxial cable, probe head, and probe rods). This

Table 1. Summary of statistical analysis for the apparent dielectric constant (K_a)* of water measured using variable extension cable lengths at 20±0.3°C.

Physical cable length (m)	Apparent cable length (m)	Statistical parameters for measured K_a values						
		N	Mean	SD	CV (%)	SEM	Variance	Range
2.50	3.00	4	80.48	0.21	0.26	0.01	0.04	0.49
4.50	5.61	4	80.29	0.19	0.24	0/09	0.04	0.40
7.05	8.74	4	80.20	0.25	0.31	0.13	0.06	0.60
9.55	11.95	4	80.37	0.76	0.95	0.38	0.58	1.50
12.85	16.16	4	80.53	0.60	0.74	0.30	0.36	1.37
17.40	21.52	4	80.57	0.61	0.76	0.31	0.38	1.38
19.90	24.91	4	80.73	0.33	0.41	0.17	0.11	0.77
30.00	37.79	4	80.39	0.77	0.96	0.39	0.60	1.72
40.00	49.95	4	80.37	0.62	0.77	0.31	0.38	1.36
50.35	62.86	4	79.61	2.01	2.52	1.01	4.04	4.64
70.00	87.91	4	77.91	3.84	4.47	1.74	12.11	7.50

* The actual dielectric constant of water (K_a value) at 20°C is 80.37.

experiment was aimed at determining what the equivalent length should be whenever the physical cable length is to be changed to satisfy the cable extension requirements.

For a given physical cable length, the equivalent apparent length was iterated in the computer program until it gave the known dielectric constant (80.36) at a temperature of 20°C. The correlation between the two parameters was performed using a correlation procedure in the SAS analysis to ascertain how the physical cable length corresponded to its apparent length as the cable length was increased. A linear regression analysis was performed to establish an equation that could be used to calculate the apparent length for a given physical cable length.

RESULTS and DISCUSSION

Measurement of dielectric constant of water using variable extension cable lengths

The summary of the univariate procedure of SAS statistical analysis for the dielectric constant of water measured at 20±0.3℃ using extension cable lengths are presented in Table 1. Four measurements were taken for each cable length from 2.5 to 70.0 m. The average K_a values ranged from 80.2 to 80.73 for cable lengths from 2.5 to 40.0 m and from 79.51 to 77.91 for 50.4 to 70.0 m lengths, respectively. The standard deviation SD for the K_a values ranged from 0.21 to 0.77 for the cables from 2.5 to 40.0 m and 2.01 to 3.84 for the 50.4 to 70.0 m cables. The standard error of the mean was less than 0.40 for the lengths up to 40.0 m, and it increased by 3.3 times when the length was changed from 40.0 to 50.4 m. This indicated that the cables from 2.5 to 40.0 m were more accurate (CV = 0.26 – 0.77) compared to the cables beyond 40.0 m (CV = 2.52 – 4.47).

Waveform analysis for cable lengths from 2.5 to 70.0 m

Waveforms for different extension cable lengths were plotted on the same graph (Fig. 2) showing changes in shapes of the waveform for the different cable lengths.

The variation in TDR waveforms as a result of an increase in cable length from 2.5 to 70.0 m is shown (Fig. 2). The apex corresponding to the first reflection at the base of the probe rods was approximately the same for the cable lengths from 2.5 to 17.4 m. As the cable length increased, the height of the first peak decreased and the curve became more flat causing difficulty in identifying the inflection points for fitting the tangents associated with the determination of the first reflection point at the probe base.

Similarly, the shape of the waveform corresponding to the end of the waveguide became continuously wider and the minimum point corresponding to the end reflection could not be easily identified. There was no clear demarcation between the horizontal limb and the second rising limb for the longer cables beyond 40.0 m. The reflection depth of the waveforms also decreased with increase in cable length. This was an indication that the accuracy of fitting of the tangent lines to demarcate the first peak and end reflection points decreased with increase in cable length. The accuracy of measurements was verified further

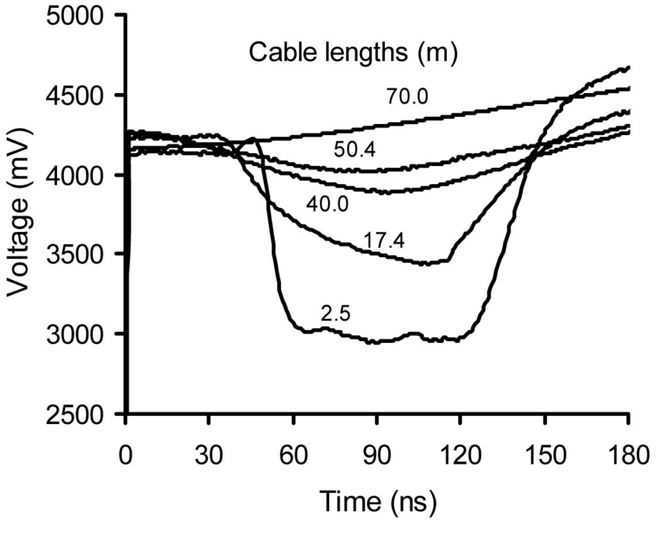

Fig. 2. TDR waveforms for different cable lengths produced using a 35-mm TDR miniprobe immersed in pure water at an average temperature of 20°C.

Table 2. Paired comparison between the measured and the actual dielectric constant (K_a) of water for different cable lengths.

Cable length (m)	Difference K_a measured - K_a actual				Difference $\theta_{measured}$ - θ_{actual} (m^3/m^3)
	N	Mean difference	SD	SEM	
2.50 - 40.0	9	0.05	0.17	0.06	0.001 - 0.007
50.4 - 70.0	2	-1.36	1.01	0.72	0.015 - 0.047
2.50 - 70.0	11	-0.20	0.67	0.20	

by comparing the measured and the actual dielectric constant of water (Table 2) at a specific temperature for the different cable lengths.

Ideally, for a given type and length of probe, the travel time of the EM wave through the probe should be the same regardless of the cable length (Evett 2000b). However, beyond a certain limit of cable length, a deviation occurs due to the inaccuracy of obtaining the peak points from the resulting shape of the waveform. Results on the effect of cable lengths on dielectric constant measurements were also obtained by Logsdon (2000), Brendan (2003), and Robinson et al. (2003a) as explained earlier.

Comparison of measured and actual dielectric constants

The measured dielectric constant of water (K_a measured) and the actual value (K_a actual) were compared using paired comparison procedure of SAS statistical analysis for the various extension cable lengths (Table 2).

From Table 2, cables from 2.5 to 40.0 m had a mean difference of 0.05 and standard deviation of 0.17. The cables from 50.4 to 70.0 m had a mean difference of -1.36 and standard deviation of 1.01. The range of accuracy for the water content determination was between 0.001 and 0.007 m^3/m^3 for cables from 2.5 to 40.0 m, and from 0.015 to 0.047 m^3/m^3 for the cables from 50.4 to 70.0. The range produced by the cables from 2.5 to 40.0 is within the range of accuracy of TDR measurements reported in the literature (Topp et al. 1980; Baker and Allmaras 1990). The deviations are shown between the measured and the actual K_a values (Fig. 3).

The difference between the measured and actual dielectric constant increased with an increase in cable length (Fig. 3). Longer cables underestimated the K_a values. The increase in the deviation with cable length was also an indication of the decrease in accuracy of the TDR measurements with increased cable length. The deviations of the measurement within each individual length of cable are shown in Fig. 4.

The variation of K_a values with increase in cable length are presented for four replicates in each length (Fig. 4). Shorter cables were found to have a lower variability compared to the longer cables. This suggested that there was loss in signal response when longer cables were used causing the data generated by the longer cables to be more dispersed as indicated by an increase in length of the error bars. Hence for the RG-58 cable used in this study, the cables gave an accurate measure of K_a values up to a length of 40.0 m. Similar responses on the effect of cable length on TDR measurement accuracy were also observed by Brendan (2003) and Pierce et al. (1994) on other types of cables. The optimum extension length for the RG-58 50-Ω cable to be used with 35-mm TDR probes was found to be 40 m. Extension cables calibrated using water as a dielectric medium can also be used in soil moisture measurements. However shapes of waveform will be different due to the differences in the amount of water content in the soil.

Comparison of physical and apparent cable lengths

Results from the SAS correlation procedure between the physical and its corresponding apparent length indicated that there was a good correlation between the physical and the apparent cable length ($R^2 = 1.0$). The percent increase of the apparent length from the physical length ranged from 20.0 to

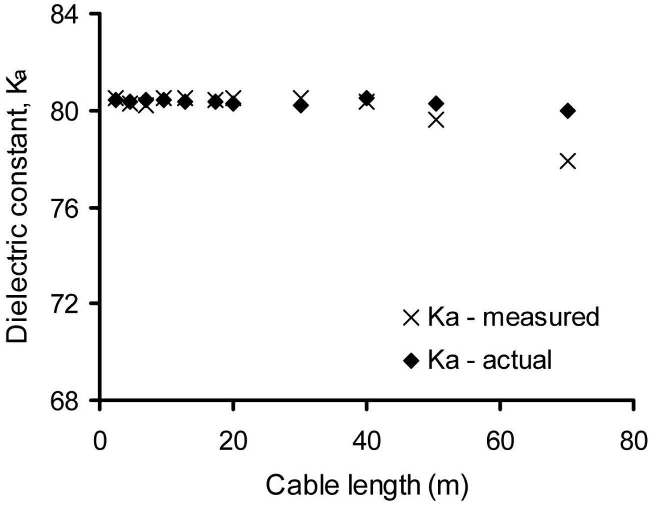

Fig. 3. Comparison of the measured and the actual dielectric constants (K_a values) for water content measurement.

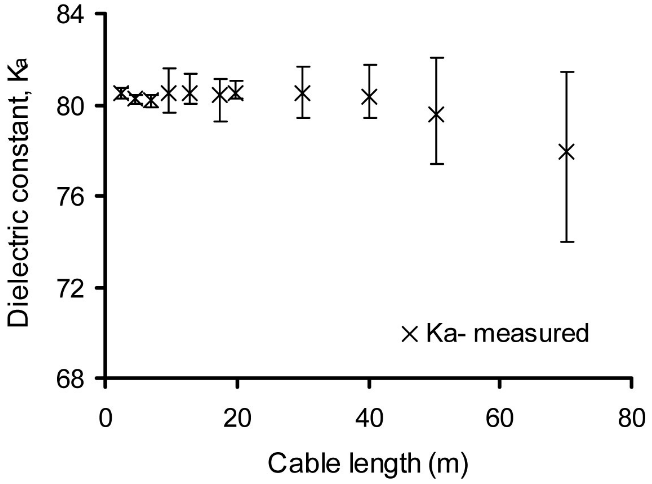

Fig. 4. Variability of the measured dielectric constant of water with increase in cable length. Error bars represent standard errors of measurement.

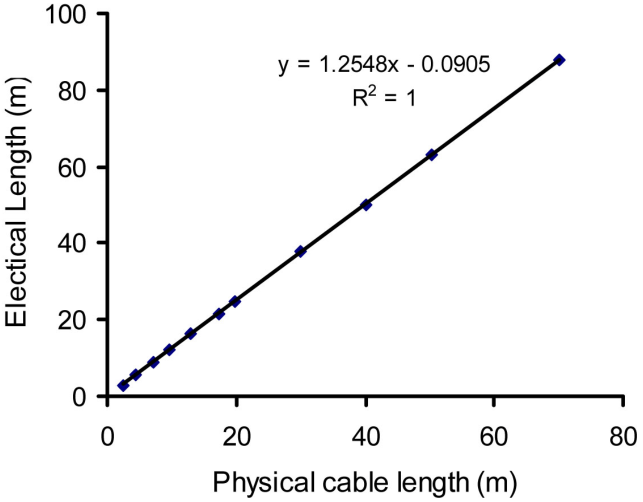

Fig. 5. Comparison of physical and apparent cable lengths for water content measurement.

25.6% with an average of 24.5% (Table 1). The regression equation for determining the apparent length from a given physical cable length was derived (Fig. 5).

The apparent length could therefore be obtained for any given physical length for the RG-58 50 Ω coaxial cable using:

$$y = 1.2548x - 0.0905 \tag{7}$$

where:

y = apparent cable length for water content measurement (m) and

x = physical cable length (m).

The established equation (Eq. 7) is useful especially during TDR calibrations with multiple extensions since the apparent lengths are needed in the TDR software programs to correctly measure the apparent dielectric constant of the medium. Therefore it eliminates the need for multiple iterations on the cable calibration once the waveguide has already been calibrated with a shorter length of cable. The derived equation could also be used in other porous media containing water such as moist soils. However, the equation is specific to the type of TDR probe and type of coaxial cable. For different kinds of probes and/or different types of the coaxial cable, similar procedures could be followed to establish the corresponding regression equation that will eliminate the need for further calibrations with other similar probes and cables.

Procedures that can be followed to calibrate extension cables along with the TDR probes to be used are:

1. Determine the physical length of extension cable depending on field requirements.
2. Decide on the type and size of TDR probes to be used.
3. Calibrate the chosen probe size using a short coaxial cable, example 2.5 m. The probe should be able to read a known dielectric constant of the dielectric fluid used at a particular temperature.
4. Connect the extension cable to the cable with the calibrated probe on one side and to the cable tester on the other side.
5. Perform iterations by changing the apparent length on the waveform analysis program code until the actual value of dielectric constant is obtained.
6. Repeat the procedure for different extension cable lengths and develop a calibration equation relating the physical and apparent cable length.
7. The developed equation can then be used to determine equivalent length for any length to be extended (to the proposed limit of 40 m if the RG-58 50-Ω coaxial cable is to be used) without the need for performing the iterations.
8. For the RG-58 coaxial cable and 35-mm TDR miniprobes, Eq. 7 can be used to determine the apparent lengths for any cable length without the need for performing the iterative procedures.

It should be noted that the diameter of the cable has great influence on the maximum length to which the cable can be extended. The optimum length is expected to increase with cable size as observed by other researchers (Pierce et al. 1994) who worked with large diameter cables and obtained TDR reflection up to 168 m using 22.2-mm coaxial cables.

CONCLUSIONS

A laboratory experiment was conducted to determine the influence of cable lengths on the accuracy of the dielectric constant for TDR water content measurement. The RG-58 50-Ω coaxial cable used in this experiment ranged in length from 2.5 to 70.0 m. The TDR miniprobe was made with three 1.6-mm diameter and 35-mm long stainless steel rods (3-rod configuration). Use of longer extension cables affected the accuracy of TDR measurement. Cables from 2.5 to 40.0 m measured the dielectric constant accurately within a range of 0.05. Beyond 40.0 m, the measurement error increased to a range of ±1.36. The difference between the measured and the actual K_a values increased with an increase in cable length. Longer cables underestimated the K_a values. Therefore shorter cables were more accurate than longer cables. The maximum cable length for the RG-58 50-Ω coaxial cable and 35-mm TDR miniprobe combination was found to be 40.0 m.

The physical cable lengths were compared with their corresponding apparent lengths and they showed a very good correlation ($R^2 = 1.0$). An equation was derived that could be used to determine the corresponding apparent length for each given physical cable length for water content measurement. The derived equation eliminates the need for multiple iterations during the calibration of extension cables once the waveguide has been calibrated with a shorter cable length. If extension cables are to be used, the probes should also be calibrated along with the selected extension cables.

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REFERENCES

Baker, J.M. and R.R. Allmaras. 1990. System for automating and multiplexing soil moisture measurement by time-domain reflectometry. *Soil Science Society of America Journal* 54: 1-6.

Blonquist, J.M. Jr., S.B. Jones and D.A. Robinson. 2005. Standardizing characterization of electromagnetic water content sensors: Part 2. Evaluation of seven sensing systems. *Vadose Zone Journal* 4: 1059-1069.

Brendan, H.G. 2003. Comparison of techniques for measuring the water content of soil and other porous media. Unpublished PhD thesis. New South Wales, Australia: Department of Agricultural Chemistry and Soil Science, University of Sydney.

Campbell Scientific, Inc. 2001. Reducing TDR probe rod length to improve water content measurements in soils with high electrical conductivity. Logan, UT: Campbell Scientific Inc, Application note (435) 753-2342.

Deutsch, A., G. Arjavalingam, C.W. Surovic and A.P. Lanzetta. 1994. Performance limits of electrical cables for intrasystem communication. *International Business Machines Journal of Research Development* 38 (6): 659-673.

Evett, S.R. 2000a. The TACQ computer program for automatic time domain reflectometry measurements: I. Design and operating characteristics. *Transactions of the ASAE* 43(6): 1939 – 1946.

Evett, S.R. 2000b. The TACQ computer program for automatic time domain reflectometry measurements: II. Waveform interpretation methods. *Transactions of the ASAE* 43(6): 1947 – 1956.

Fuller, R. and T. Blankenship. 2002. *Building a Cisco Wireless LAN*, 1st edition. Rockland, MA: Syngress Publishing, Inc.

Herkelrath, W.N. and G.N. Delin. 1999. Long term monitoring of soil-moisture in a harsh climate using reflectometer and TDR probes. In *Proceedings of the Second International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications,* 262-272. Evanston, Illinois: Infrastructure Technology Institute, Northwestern University.

Hubscher, R.A., D. Or, J.M. Wraith and B. Smith. 1996. Win_TDR users guide. Version 1.0. Logan, Utah: Plants, Soils and Biometeorology Department, Utah State University.

Jones, S.B. and D. Or. 2002. Thermal and geometrical effects on bulk permittivity of porous mixtures containing bound water. *Journal of Non-Crystalline Solids* 305(1-3):247-254.

Jones, S.B., J.M. Wraith and D. Or. 2002. Time domain reflectometry measurement principles and applications. *Hydrological Processes* 16: 141–153.

Logsdon, S.D. 2000. Effect of cable length on time domain reflectometry calibration for high surface area soils. *Soil Science Society of America Journal* 64(1): 54-61.

Mojid, M.A., G.C.L. Wyseure and D.A. Rose. 2003. Electrical conductivity problems associated with time-domain reflectometry (TDR) measurement in geotechnical engineering. *Geotechnical and Geological Engineering* 21: 243–258.

Or, D., S.B. Jones, J.R. VanShaar, S. Humphries and L. Koberstein. 2004. WinTDR soil analysis software version 6.1- users guide. Soil physics group research report. Department of Plants, Soils, and Biometeorology, Utah State University, Logan, Utah.

Pierce, C.E., C. Blaine, F. Huang and C.H. Dowding. 1994. Effects of multiple crimps and cable length on reflection signatures from long cables. In *Proceedings of the International Symposium on Time Domain Reflectometry in Environmental Infrastructure, and Mining Applications,* 540–554. Evanston, Illinois: Infrastructure Technology Institute, Northwestern University.

Robinson, D.A, S.B. Jones, J.M. Wraith, D. Or and S.P. Friedman. 2003a. A review of advances in dielectric and electrical conductivity measurements in soils using time domain reflectometry. *Vadose Zone Journal* 2: 444-475.

Robinson, D.A., M. Schaap, S.B. Jones, S.P. Friedman and C.M.K. Gardner. 2003b. Considerations for improving the accuracy of permittivity measurement using TDR: Air-water calibration, effects of cable length. *Soil Science Society of America Journal* 67: 62-70.

SAS Institute Inc. 2004. Statistical analysis system (SAS) software version 9.1.2, Cary, NC: SAS Institute Inc.

Sri Ranjan, R. and C.J. Domytrak. 1997. Effective volume measured by TDR miniprobes. *Transactions of the ASAE* 40(4): 1059 – 1066.

Tektronix, Inc. 1998. Service manual, 1502B metallic time-domain reflectometer, 070-6267-04. Beaverton, OR: Tektronix, Inc.

Topp, G.C., J.L. Davis and A.P. Annan. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. *Water Resources Research* 16(3): 574-582.

Topp, G.C., J.L. Davis and A.P. Annan.1982. Electromagnetic determination of soil water content using TDR: II. Evaluation of installation and configuration of parallel transmission lines. *Soil Science Society of America Journal* 3: 107-127.

Vanclooster, M., C. Gonzalez, J. Vanderborght, D. Mallants and J. Diels. 1994. An indirect calibration procedure for using TDR in solute transport studies. In *Proceedings of the International Symposium on Time Domain Reflectometry in Environmental Infrastructure, and Mining Applications,* p215–226. Evanston, Illinois: Infrastructure Technology Institute, Northwestern University.

Warrick, A. W. 2002. *Soil Physics Companion*. Washington, DC: CRC Press LLC.

Wraith, J.M. and D. Or. 1999. Temperature effects on soil bulk dielectric permittivity measured by time domain reflectometry: Experimental evidence and hypothesis development. *Water Resources Research* 35(2): 361-369.

Zegelin, S.J., I. White and G.F. Russell. 1992. A critique of the time domain reflectometry technique for determining field soil-water content. In *Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice*, eds. R.Green and G.C. Topp, 187-208. Special publication No. 30. Madison, WI: Soil Science Society of America.