Response to "Comments on 'TDR Laboratory Calibration in Travel Time, Bulk Electrical Conductivity, and Effective Frequency'"

We thank Huisman and Vereecken (2006) for their close reading of our paper and their suggestions for improving measurements of the soil bulk electrical conductivity, σ_a, using time domain reflectometry (TDR) waveforms. In our original paper (Evett et al., 2005), we suggested that the TDR calibration model for water content (θ_v, m^3 m^{-3}) could be improved by including σ_a and the effective frequency, f_{vi}, of the TDR pulse:

$$\theta_v = a + b[c_o t_t/(2L)] + c[\sigma_a/(2\pi f_{vi}\varepsilon_o)]^{0.5} \qquad [1]$$

where ε_o is the permittivity of free space (8.854×10^{-12} F m^{-1}), c_o is the speed of light in a vacuum (299 792 458 m s^{-1}), L is the TDR probe length (m), t_t is the pulse travel time (s), and a, b, and c are linear regression fitting parameters. We defined an effective frequency, f_{vi}, primarily by the slope of the second rising limb of the waveform (Evett et al., 2005). Rather than contradict these suggestions, Huisman and Vereecken (2006) endorse them, but they question the accuracy of the method that we used to determine σ_a.

We calculated σ_a using methods given by Wraith (2002).

$$\sigma_a = \frac{\varepsilon_o c_o}{L}\frac{Z_0}{Z_u}\left[\frac{2(V_0 - V_I)}{V_F - V_I} - 1\right] \qquad [2]$$

where V_0, V_F, and V_I are relative voltages measured from the wave form (Fig. 1), Z_0 is the characteristic impedance of the probe (Ω), Z_u is the characteristic impedance of the cable (50 Ω in our case), and the other terms are as defined previously. In particular, Huisman and Vereecken (2006) question the method used to determine Z_0. We determined the mean value of Z_0 for three probes from repeated ($n = 8$) measurements of V_0 and V_{min} in deionized water using

$$Z_0 = Z_u \varepsilon_w^{0.5} \frac{V_{min}}{2V_o - V_{min}} \qquad [3]$$

where ε_w is the permittivity of water, and V_0 and V_{min} are as in Fig. 1. Water temperature was measured using a thermometer traceable to NIST, and water permittivity was calculated according to Weast (1971, p. E-61). Probe characteristic impedance measurements were repeated for each total cable length (6.4–10 m) and with the multiplexers included in the circuit. We found that Z_0 ranged from 260 to 267 Ω for cable lengths ranging from 6.4 to 10.0 m, respectively. In so doing, we thought to correct the cell constant ($\varepsilon_o c_o Z_0/L$ in Eq. [2]) for the well-known increase in impedance caused by including longer cables and multiplexers in the circuit between TDR instrument and probe. However, we did not complete this thought by using V_R in place of V_0 in Eq. [2].

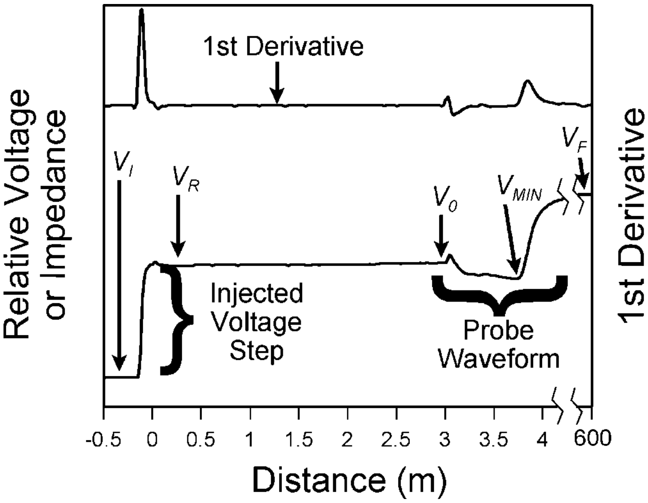

Fig. 1. Plot of a waveform and its first derivative from a Tektronix 1502C TDR cable tester set to begin at −0.5 m (inside the cable tester). The voltage step is shown to be injected just before the zero point (BNC connector on instrument front panel). At 3 m from the instrument, a TDR probe is connected to the cable. The relative voltage levels, V_I, V_{min}, V_0, and V_F are used in calculations of the bulk electrical conductivity of the medium in which the probe is inserted, and for determining the probe characteristic impedance. Waveform positions for determining values of these parameters are described numerically in Evett (2000a, 2000b, 2000c) where V_{02} was used for V_0.

To show that cable length and probe length affect the apparent probe impedance estimated using Eq. [3], thus causing inaccurate estimates of σ_a, Huisman and Vereecken (2006) simulated several TDR waveforms. In partial agreement with our results, their Fig. 2 shows increasing values of Z_0 with increasing cable length. However, their Fig. 2 indicates a value of approximately 249 for Z_0 at 5 m and 265 at 10 m, which suggests an effect of 3.2 Ω m^{-1}. Our measurements indicate a lesser effect of 2.3 Ω m^{-1} (Fig. 2). Because of this, the bulk

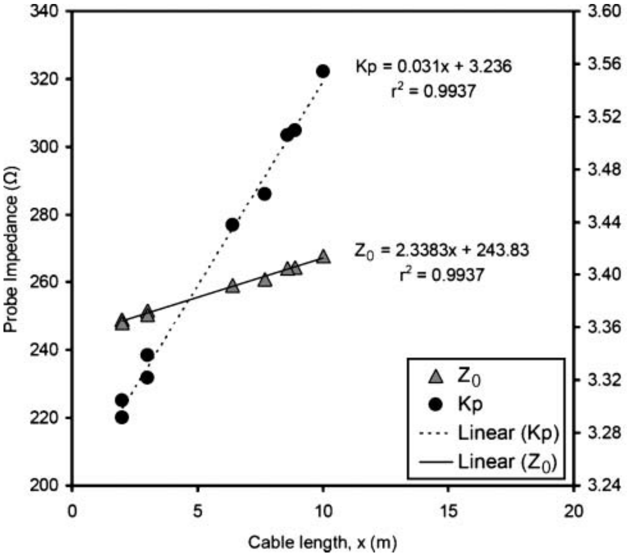

Fig. 2. Probe impedance calculated using Eq. [3] as a function of cable length and the resulting cell constant values. Data from Evett et al. (2005) for 6.4 to 10 m, and new data for 2 and 3 m of cable.

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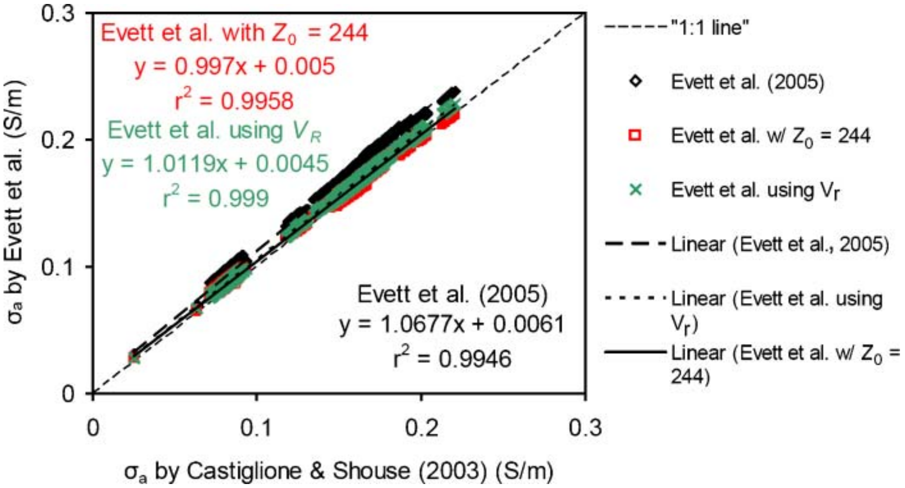

Fig. 3. Bulk electrical conductivities calculated: (i) using the methods of Evett et al. (2005), (ii) using the method of Evett et al. (2005) but with a constant characteristic probe impedance of 244 Ω, and (iii) using the methods of Evett et al. (2005) but with V_R rather than V_0 in the calculation of the reflection coefficient.

electrical conductivities estimated using our measured probe impedances will not be as different from the "true bulk electrical conductivity" as is indicated in Fig. 3 of Huisman and Vereecken (2006).

To investigate this further, we made additional measurements with cable lengths of 1, 2, and 3 m. For cable lengths of 1 m, the apparent probe impedance was smaller than the linear trend of data for longer cable lengths. This result was similar to that shown by Huisman and Vereecken (2006) using modeled waveforms, which caused us to discard data for cable lengths of 1 m from further analysis. Applying linear regression to our data, we estimated a probe impedance of 243.83 Ω at zero cable length (Fig. 2). Using this value in the equation for the cell constant, K_p,

$$K_p = \varepsilon_o c_o Z_0 / L \qquad [4]$$

we obtained $K_p = 3.236$, which is somewhat larger than the value of 2.99 obtained when using the value of $Z_0 = 225$ employed by Huisman and Vereecken (2006) in their model. Somehow, the measurements and modeling results apparently do not agree.

Recently, Castiglione (personal communication, 2006) derived a theoretical equation for the impedance of a trifilar probe with center-to-center rod spacing, s, and rod radius, b:

$$K_p = \frac{1}{4\pi L} \ln\left(\frac{1 - d^4}{2d^3}\right) \qquad [5]$$

where $d = b/s$. For our 0.2-m probes, the value of K_p from Eq. [5] is 3.232, remarkably close to our zero-cable-length limiting value of 3.236 (Fig. 2). We think that this confirms the thought that the apparent probe impedance determined using Eq. [3] in a lossless medium (e.g., deionized water) should approach the true value of probe impedance as cable length and associated losses approach zero, the true value of probe impedance being that value which results in the correct cell constant value when substituted into Eq. [4].

Earlier, Castiglione and Shouse (2003) reported a theoretical development leading to a method of accounting for cable losses by scaling the reflection coefficient measured in the sample, ρ, with respect to reflection coefficients measured with the probe rods in air, ρ_a, and with the probe rods short circuited, ρ_{sc}:

$$\rho_S = 2\frac{\rho - \rho_a}{\rho_a - \rho_{sc}} + 1 \qquad [5]$$

where ρ_S is the scaled reflection coefficient. The value of σ_a is then

$$\sigma_a = \frac{K_p}{Z_u}\frac{1 - \rho_S}{1 + \rho_S} \qquad [6]$$

Using this approach, we recalculated a representative sample of our data using a cell constant of 3.236, consistent with a probe impedance of 244 Ω. Our original methods overestimated σ_a by 7% when compared with the method of Castiglione and Shouse (2003) (Fig. 3). Using the characteristic probe impedance for zero-length cable of 244 Ω, rather than the variable probe impedances in our original paper, our

Table 1. Linear calibration equations including the bulk electrical conductivity, σ_a, calculated using the methods of Castiglione and Shouse (2003), and the effective frequency, f_{vi}, terms for conventional time domain reflectometry in three soils (3879 observations for each soil). All coefficients were significant ($P = 0.0001$).

Soil	a	b	c	r^2†	RMSE
$\theta_v = a + b[c_o t_t/(2L)] + c[\sigma_a/(2\pi f_{vi}\varepsilon_o)]^{0.5}$					
					$m^3\ m^{-3}$
Combined data, 2005‡	−0.182	0.1271	−0.004933	0.997	0.0100
Combined data, 2006§	−0.182	0.1271	−0.005027	0.997	0.0100
A, 2005	−0.183	0.1311	−0.005855	0.999	0.0061
A, 2006	−0.183	0.1310	−0.005957	0.999	0.0062
B, 2005	−0.158	0.1127	−0.001480	0.997	0.0095
B, 2006	−0.159	0.1130	−0.001606	0.997	0.0095
C, 2005	−0.196	0.1299	−0.005008	0.999	0.0053
C, 2006	−0.197	0.1307	−0.005646	0.999	0.0053

† Value is adjusted coefficient of determination.
‡ From Evett et al. (2005).
§ Computed in 2006 using methods of Castiglione and Shouse (2003) for σ_a.

values of σ_a were almost completely in agreement with those calculated using the methods of Castiglione and Shouse (2003). Interestingly, when we used our original methods but substituted V_R for V_0, σ_a was overestimated by only 1.2%.

Thus, we agree that our use of a length-variable apparent characteristic probe impedance resulted in σ_a error, although the error appears to be less than one-half of the 18% suggested by the analysis of Huisman and Vereecken (2006). Also, our data show a smaller effect of cable resistance on the characteristic probe impedance estimated using Eq. [3] than does their modeling effort. Finally, we disagree with the thought that Eq. [3] has no practical use. Using Eq. [3] with several cable lengths, we have shown that the estimated zero-cable-length impedance is a good estimator of the actual characteristic probe impedance and in good agreement with theory.

To assess the effect of our errors on the TDR calibration equations we published, we recalculated σ_a using the methods of Castiglione and Shouse (2003) and recomputed the calibration equations (Table 1). As suggested by Huisman and Vereecken (2006), very little difference occurred between the new calibration equations and those we published in 2005.

In summary, we thank Huisman and Vereecken (2006) for their thorough look at our work, which spurred us to further our investigations. They have shown the important effects that shorter probes and longer cables can have on measurements of the probe impedance using Eq. [3], and they pointed the way toward using measurements at multiple cable lengths to infer the probe impedance at zero cable length.

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