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, \( \sigma_e \), using time domain reflectometry (TDR) waveforms. In our original paper (Evett et al., 2005), we suggested that the TDR calibration model for water content \((\theta_0, \text{m}^3 \text{m}^{-3})\) could be improved by including \( \sigma_e \) and the effective frequency, \( f_v \), of the TDR pulse:

\[
\theta_0 = a + b \left[ \varepsilon_r c_v t_s / (2L) \right] + c \left[ \sigma_e / (2\pi f_v \varepsilon_0) \right]^{0.5}
\]

where \( \varepsilon_r \) is the permittivity of free space \((8.854 \times 10^{-12} \text{ F m}^{-1})\), \( c_v \) is the speed of light in a vacuum \((299792458 \text{ m s}^{-1})\), \( L \) is the TDR probe length \((\text{m})\), \( t_s \) is the pulse travel time \((s)\), and \( a, b, \) and \( c \) are linear regression fitting parameters. We defined an effective frequency, \( f_v \), 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 we used to determine \( \sigma_e \).

We calculated \( \sigma_e \) using methods given by Wraith (2002):

\[
\sigma_e = \frac{\varepsilon_r c_v Z_0}{u} \left[ \frac{2(V_0 - V_r)}{V_F - V_r} - 1 \right]^{0.5}
\]

where \( V_0, V_F, \) and \( V_r \) are relative voltages measured from the wave form (Fig. 1), \( Z_0 \) is the characteristic impedance of the probe \((\Omega)\), \( Z_o \) is the characteristic impedance of the cable \((50 \Omega \text{ in our case})\), 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 \( V_{\text{min}} \) in deionized water using

\[
Z_0 = Z_0 \varepsilon_r^{0.5} \frac{V_{\text{min}}}{2V_0 - V_{\text{min}}}
\]

where \( \varepsilon_r \) is the permittivity of water, and \( V_0 \) and \( V_{\text{min}} \) 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 \((6.4-10 \text{ m})\) and with the multiplexers included in the circuit. We found that \( Z_0 \) ranged from 260 to 267 \( \Omega \) for cable lengths ranging from 6.4 to 10.0 m, respectively. In so doing, we thought to correct the cell constant \((\varepsilon_r c_v Z_0 / L \text{ in Eq. [2]})\) 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].

To show that cable length and probe length affect the apparent probe impedance estimated using Eq. [3], thus causing inaccurate estimates of \( \sigma_e \), 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 \( \Omega \text{ m}^{-1} \). Our measurements indicate a lesser effect of 2.3 \( \Omega \text{ m}^{-1} \) (Fig. 2). Because of this, the bulk

![Fig. 1. Plot of a waveform and its first derivative from a Tektronix 1502C TDR cable tester set to begin at -6.5 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, \( V_r, V_{\text{min}}, V_0, \) 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 \( V_{\text{min}} \) was used for \( V_r \).](image-url)