Evaluation of a Direct-Coupled TDR for Determination of Soil Water Content and Bulk Electrical Conductivity

R.C. Schwartz[1], S.R. Evett[1], S.K. Anderson[2], D.J. Anderson[2]
[1]USDA-ARS, Bushland, TX
[2]Acclima, Inc., Meridian, ID

Introduction

Signal degradation in coaxial cables and inter-connects is a long-standing problem in the practical deployment and calibration of time domain reflectometry (TDR) for soil water content monitoring. Acclima, Inc.[1] has recently commercialized a TDR sensor (TDR-315) with all electronics required for waveform acquisition embedded in the probe head thereby avoiding signal degradation. Our objectives were to (i) carry out apparent permittivity (K_a) and bulk electrical conductivity (σ_a) calibrations for the TDR-315 using conventional TDR methods, (ii) complete a water content calibration for a fine-textured soil, and (iii) utilize a saturated column displacement experiment to examine the dependency of measured K_a on σ_a while avoiding the confounding effects of soil water content changes. In all of these evaluations, TDR-315 responses were compared with conventional TDR.

Sensor Description

- **Planar three-conductor transmission line 150 mm in length, rod separation distance of 19 mm, and rod diameters of 3.2 mm (Fig. 1).**
- **Potted sensor head consisting of a step function generator, precision time base generator, 5 ps resolution waveform digitizer, thermistor, and SDI-12 communications circuits.**
- **Function generator launches a 3.5 GHz step pulse with a 10 – 90% rise time of 100 ps.**
- **Firmware in on-board memory acquires pertinent waveform features, measures temperature, calculates travel time, K_a, and σ_a, and transmits the information to compliant data loggers using SDI-12.**
- **Full waveforms can be acquired using a specialized interface. Timing circuit limitations restricts amplitude sampling to 20.4 ns. Four sensors (SN 684 to 731) had firmware to sample amplitudes at 3 µs based on microprocessor cycles.**

[1]The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of an product or service to the exclusion of others that may be suitable.

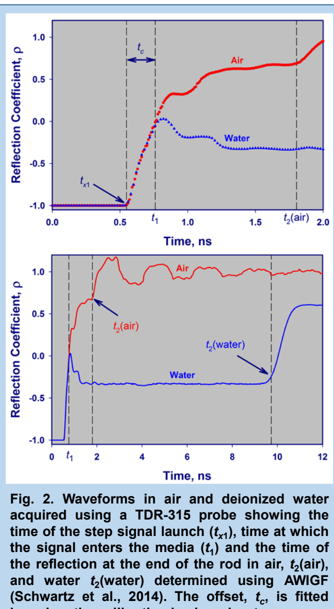

Fig. 2. Waveforms in air and deionized water acquired using a TDR-315 probe showing the time of the step signal launch (t_{x1}), time at which the signal enters the media (t_1) and the time of the reflection at the end of the rod in air, t_2(air), and water t_2(water) determined using AWIGF (Schwartz et al., 2014). The offset, t_c, is fitted based on the calibration in air and water.

Methods

- Ten TDR-315 sensors and two TDR probes were calibrated and evaluated in a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll)
- Conventional TDR probes, each with a 8.5-m low-loss coaxial cable, were 150 mm in length with a rod separation distance of 30 mm and rod diameters of 3.2 mm. Waveforms were acquired using a cable tester (1502C, Tektronix, Beaverton, OR) with a 10 – 90% rise time of 200 ps (1.75 GHz bandwidth). The bandwidth of the pulse arriving at end of 8.5-m cable was estimated to be 820 MHz.
- Amplitudes, V, acquired from the TDR-315 were converted to reflection coefficients, ρ, as
$$\rho = \frac{2 \cdot V - V_0}{V_0}$$
where V_0 is the measured amplitude at long times (20 ns) in air.
- Travel time of acquired waveforms was evaluated using adaptive waveform interpretation with Gaussian filtering (AWIGF)[2] as described by Schwartz et al. (2014).
- A calibration in air and water was used to determine an offset t_c and electrical length L_e of both conventional TDR and TDR-315 probes (Fig. 2; Table 1).
- Conventional TDR probes and TDR-315 sensors were calibrated for bulk electrical conductivity in $CaCl_2$ solutions (100 µS m^{-1} to 7.3 dS m^{-1}). The Giese and Tiemann (1975) relationship was applied to find the slope K_p/Z_s where K_p is the probe constant (m^{-1}) and Z_s is the source impedance (Ω). Long time reflections were evaluated at 3 µs (conventional TDR and four TDR-315 sensors) and at 20 ns (all TDR-315 sensors).
- Water content calibrations of the Ap horizon of the Pullman clay loam were carried out for six TDR-315 sensors and two conventional TDR probes at room temperature (20 °C), 6 °C, and at 40 °C. All temperature regimes were included in calibrations.
- A near saturated solute displacement experiment was used to evaluate the dependence of measured apparent permittivity K_a on σ_a in a Pullman clay loam over a range of solution conductivities from 0.25 to 7.3 dS m^{-1}.

Results – K_a and σ_a Calibrations

- **Permittivity calibration of the TDR-315 in air and water could be accomplished with conventional TDR methods (Fig. 2; Table 1).**
- **The conventional Giese and Tiemann (1975) approach for σ_a calibration using amplitudes acquired at ~3 µs gave a linear response for σ_a < 3 dS m^{-1} with nonlinear responses at greater conductivities (Fig. 3).**
- **TDR-315 firmware successfully accounted for σ_a nonlinearity at σ_a > 3 dS m^{-1} with errors less than 6.5%.**

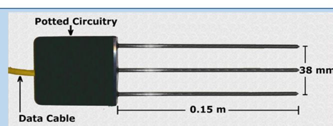

Fig. 1. Illustration of a TDR-315 sensor showing electrode length and spacing, sensor head containing the circuitry, and the 3-wire communications cable.

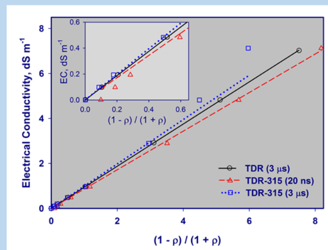

Fig. 3. Electrical conductivity (EC) calibrations for the long time reflection coefficient, ρ, in $CaCl_2$ solutions for the TDR and TDR-315. Inset shows calibration response at low EC levels.

Table 1. Apparent permittivity and bulk electrical conductivity calibration parameters for the TDR-315 and conventional TDR. Electrical length (L_e) and offset (t_c) are derived from the air-water calibration. The probe constant divided by the source impedance (K_p/Z_s) is derived from the slope of the long time amplitude calibrations at 20 ns and 3 µs.

Serial Number	Physical Length	L_e	t_c	K_p/Z_s 20 ns	K_p/Z_s 3 µs
	m	m	ns	S m^{-1}	
----- Acclima TDR-315 -----					
1	0.150	0.1494	0.189	0.0840	
2	0.150	0.1496	0.207	0.0917	
3	0.150	0.1489	0.203	0.0978	
4	0.150	0.1493	0.206	0.0918	
5	0.150	0.1493	0.224	0.0923	
6	0.150	0.1498	0.168	0.0815	
684	0.145	0.1523	0.243	0.0873	0.0963
713	0.145	0.1521	0.229	0.0850	0.0987
729	0.145	0.1535	0.262	0.0858	0.0974
731	0.145	0.1537	0.236	0.0877	0.0970
----- Conventional TDR (Tektronix 1502C) -----					
	0.150	0.1550	0.194		0.0937
	0.151	0.1570	0.192		0.0914

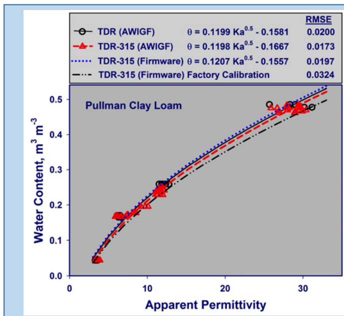

Fig. 4. Refractive mixing model soil water content calibrations of the Pullman clay loam (0.0 to 0.15 m) for conventional TDR and TDR-315 using AWIGF-estimated travel times and the apparent permittivity (K_a) calibration (Fig. 2) and the TDR-315 using firmware estimated K_a. Calibrations include permittivity measurements at all three temperature regimes. Also shown is the Acclima factory soil water content calibration.

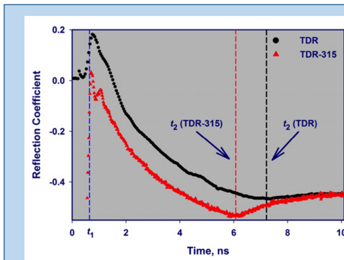

Fig. 6. Waveforms of conventional TDR and the TDR-315 at a bulk electrical conductivity (σ_a) of 2.8 dS m^{-1} and the AWIGF-evaluated time at which the pulse arrives at the end of the transmission line (t_2). The waveforms have been horizontally adjusted in time so that the time at which the step pulse enters the media (t_1) is identical.

Results – Evaluation in a lossy soil

- **Refractive mixing model water content calibrations for the Pullman clay loam using TDR-315 firmware -reported K_a and the AWIGF-calculated travel time were both nearly indistinguishable from conventional TDR calibrations (Fig. 4).**
- **AWIGF -derived K_a from the TDR-315 were insensitive to σ_a up to 2.8 ds m^{-1} (pore water conductivity of 7.3 dS m^{-1}). In contrast, K_a estimated with AWIGF using conventional TDR increased from 32 to 40 (Fig. 5).**
- **Firmware- derived K_a from the TDR-315 exhibited a slight sensitivity (28 to 31) to σ_a likely due to the method of travel time evaluation (Fig. 5).**
- **TDR-315 waveforms retained a greater proportion of high frequency components as compared to conventional TDR as inferred by a greater slope of the reflection at the rod termination (Fig. 6).**

References

Giese, K., and R. Tiemann. 1975. Determination of the complex permittivity from thin-sample time domain reflectometry improved analysis of the step waveform. Adv. Mol. Relax. Processes 7:45-59.

Schwartz, R.C., J.J. Casanova, J.M. Bell, and S.R. Evett, S.R. 2014. A reevaluation of TDR propagation time determination in soils. Vadose Zone J. doi:10.2136/vzj2013.07.0135

[2]The algorithm AWIGF (matlab script) is available upon request from the author: robert.schwartz@ars.usda.gov

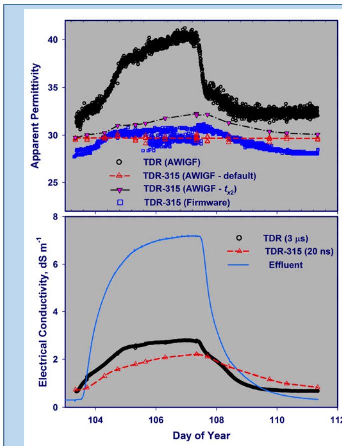

Fig. 5. Response of electrical conductivity and apparent permittivity during column displacement for conventional TDR and TDR-315 sensors in a Pullman clay loam. Apparent permittivities for the TDR-315 are plotted using two AWIGF methodologies to estimate the time at which the pulse arrives at the end of the transmission line (t_2): the default method that uses the maximum of the second derivative and the conventional method that uses the intersection of the tangents to the baseline and rising limb (t_{x2}). In addition, firmware-calculated apparent permittivities are also plotted. A lag in the TDR-315 response compared with conventional TDR is due to differing heights within the soil column.