

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

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6
7 **ABSTRACT**

8 Signal degradation in coaxial cables and interconnects is a long-standing problem in the
9 practical deployment of time domain reflectometry (TDR) for soil water monitoring. Acclima,
10 Inc. has recently commercialized a TDR sensor (TDR-315)¹ with all electronics required for
11 waveform acquisition embedded in the probe head. We calibrated ten TDR-315 sensors and
12 conventional TDR for apparent permittivity (K_a) and bulk electrical conductivity (σ_a)
13 measurements. Also, soil water content calibrations were completed for a Pullman clay loam
14 soil. Lastly, the sensitivity of K_a to σ_a was examined using a saturated solute displacement
15 experiment with both probe technologies installed in a column packed with Pullman clay loam.
16 A range of σ_a (0.65 to 2.8 dS m⁻¹) was established by equilibrating the column with 0.25 dS m⁻¹
17 CaCl₂ and introducing a step pulse of 7.3 dS m⁻¹ CaCl₂. Permittivity calibrations of the TDR-315
18 could be accomplished with conventional TDR methods and with similar sampling errors.
19 Conventional calibrations of σ_a using long time amplitudes yielded a linear response for $\sigma_a \leq 3$
20 dS m⁻¹ above which the response was nonlinear. The fitted water content calibrations of the
21 Pullman clay loam for the TDR-315 were nearly indistinguishable from conventional TDR
22 calibrations with similar root mean square errors (0.017 to 0.020 m³ m⁻³). Response of the two

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23 measurement technologies in a lossy soil during changing solution conductivities demonstrated
24 that, in contrast to conventional TDR, travel time measured using acquired TDR-315 waveforms
25 was insensitive to σ_a up to 2.8 dS m^{-1} .

26

27 INTRODUCTION

28 In-situ, nondestructive monitoring of soil water is critical for the evaluation of water, energy
29 and solute fluxes in the field. Innovations in electromagnetic methods that make use of the
30 unique electrical properties of water have revolutionized the measurement, study and
31 management of water within the soil profile. Characterization of material properties using time
32 domain reflectometry (TDR), initially for determining the dielectric properties of liquids
33 (Fellner-Feldegg, 1969), has become widely accepted for monitoring soil water since its
34 introduction (Hoekstra and Delaney, 1974) and the seminal work by Topp et al. (1980). The
35 fundamental success of the TDR method for estimating soil water content arises from an
36 apparent permittivity (K_a) response that is less sensitive to bulk electrical conductivity (σ_a)
37 compared with lower frequency ($< 100 \text{ MHz}$) electromagnetic techniques (Robinson et al.,
38 2003). In addition, minimal soil disturbance using open-ended rods, the ability to measure σ_a
39 (Dalton et al., 1986), and the approximately linear relationship between the water content and the
40 square root of K_a (Ferré and Topp, 2002) or the measured travel time (Topp and Reynolds, 1998;
41 Evett et al., 2005) are further advantages of the method.

42 Despite the above successes and refinements of the TDR technique, use under field
43 conditions is cumbersome because of unavoidable signal attenuation and high frequency filtering
44 in coaxial cables, multiplexers, and interconnects (Logsdon, 2000; Casanova et al., 2013). Even
45 with the use of high quality coaxial cables, the bandwidth can narrow to less than 0.5 GHz at the

46 cable termination from an incident pulse bandwidth of 1.75 GHz (Schwartz et al., 2009a).
47 Further signal attenuation, dispersion, and high frequency filtering by dielectric loss
48 mechanisms, especially in saturated, fine-textured soils, will further reduce the effective
49 bandwidth thereby increasing the K_a sensitivity to σ_a and temperature and reducing accuracy of
50 water content estimations (Schwartz et al., 2009a, b). Auxiliary measurements of σ_a and
51 temperature can be combined with travel time measurements in soil specific water content
52 calibrations to account for signal attenuation (e.g. Schwartz et al., 2009b). However, such
53 modifications in the calibration procedure are difficult in practice to apply under field conditions
54 and are not entirely satisfactory under elevated σ_a levels (Schwartz et al., 2013).

55 A TDR sensor (TDR-315) has recently been commercialized by Acclima, Inc. that
56 circumvents the problem of maintaining a high frequency signal over long cable distances. All
57 the electronics required for pulse generation and waveform acquisition are embedded in a
58 miniaturized circuit within the probe head, and processed data is transmitted digitally via SDI-12
59 protocol with cable lengths of at least 60 m possible (SDI-12 Support Group, 2013). The sensor
60 shares some measurement concepts with the earlier time domain transmission (TDT) Acclima
61 sensor (Anderson and Anderson, 2004; Blonquist et al., 2005; Schwartz et al., 2013) but with a
62 greater bandwidth and new electronics to process signals in the reflection mode. Ideally, the
63 TDR-315 would provide the same advantages of conventional TDR without the problems of
64 signal degradation prior to entering the soil test material. However, evaluation of the waveforms
65 and firmware estimated K_a and σ_a over a range of conditions and media are required to ascertain
66 potential limitations of the sensor compared with conventional TDR. Our objectives were to (i)
67 carry out K_a and σ_a calibrations for the TDR-315 using conventional TDR methods, (ii) complete
68 a water content calibration for a fine-textured soil, and (iii) utilize a saturated column

69 displacement experiment to examine the dependency of measured K_a on σ_a while avoiding the
70 confounding effects of soil water content and pore structure changes. In all of these evaluations,
71 TDR-315 responses were compared with conventional TDR.

72

73 MATERIALS AND METHODS

74 *Sensor description*

75 Ten TDR-315 sensors were calibrated and evaluated to ascertain their responses to a range of
76 media as compared with two conventional TDR probes. The TDR-315 sensors consisted of a
77 planar three-conductor transmission line 150 mm in length with the incident pulse transmitted in
78 the center rod and two exterior ground rods (Fig. 1). The sensors had rod diameters of 3.2 mm
79 and a rod separation distance of 19 mm that conforms to the recommended ratio of wire
80 separation to wire diameter less than 10 proposed by Knight (1992). All TDR-315 sensors had
81 the same printed circuit assembly consisting of a step function generator, precision time base
82 generator, 5 ps resolution waveform digitizer, thermistor, and communications circuits potted
83 within the sensor head. The TDR circuit for pulse generation and waveform acquisition was
84 directly coupled to the electrodes. The function generator launches a ~3.5 GHz step pulse with a
85 10 - 90% rise time of 100 ps (20 – 80% rise time of 64 ps). A digitized waveform is constructed
86 by launching a series of step pulses triggered by a timing generator and, for each step pulse,
87 sampling the amplitude of the reflection at successive time increments. A voltage comparator is
88 used to evaluate (digitize) the amplitude of the analog signal compared with reference amplitude
89 at a given time offset. Using a specialized interface, waveforms can be acquired spanning 0 to 20
90 ns at sampling intervals of 5 ps or greater.

91 Although full waveforms can be acquired from the TDR-315 using a specialized interface,
92 the design intent is to return to the user only processed data elements. A microprocessor executes
93 firmware stored in on-board memory to acquire the pertinent waveform features, measure
94 temperature, calculate the apparent permittivity (K_a) and bulk electrical conductivity (σ_a), and
95 transmit this information to compliant data loggers using the Serial Digital Interface (SDI)
96 protocol at 1200 baud (SDI-12). Measurement of propagation time is achieved efficiently by first
97 generating a waveform using coarse time increments and identifying a window containing the
98 reflection at the end of the transmission line. This portion of waveform is sampled at finer time
99 resolution for precise determination of the time, t_2 , at which the pulse arrives at the end of the
100 probe. The time of pulse arrival within the medium, t_1 , is evaluated at a calibrated offset from the
101 launch of the incident wave to determine propagation time, $t_2 - t_1$. Probes are individually
102 calibrated to report accurate K_a and σ_a , and volumetric water content is calculated using a
103 standard mixing model.

104 Firmware associated with acquisition of the long time amplitude and the σ_a calibration was
105 still under development for the initial eight sensors evaluated in this study (serial numbers (SN) 1
106 to 6, 684 and 713). In four sensors (SN 684, 713, 729, and 731), the long time amplitude was
107 acquired approximately 3 μ s after the incident wave launch and based on microprocessor cycles
108 whereas in the initial six sensors (SN 1 to 6) this measurement was unavailable. In the final two
109 sensors (SN 729 and 731) the σ_a was calculated based on the long time amplitude and the Giese
110 and Tiemann (1975) thin section approach. All waveforms were acquired in quadruplicates.

111 *Conventional TDR*

112 Two conventional TDR probes, each with a 8.5-m low-loss coaxial cable (LMR-240, Times
113 Microwave Systems, Wallingford, CT), were evaluated for comparison with the TDR-315
114 sensors. The probes had rod diameters of 3.2 mm, an outer rod separation distance of 60 mm,
115 and a length of approximately 150 mm. Waveforms were acquired using a cable tester (model
116 1502C, Tektronix, Beaverton, OR) with an open-ended 1.75 GHz bandwidth and a 10 – 90% rise
117 time of 200 ps. Waveforms were collected in quadruplicate with waveform averaging set to 4
118 samples in the 1502C. A coaxial cable length of 8.5 m was used in this study because it more
119 properly represented the attenuated signal used to acquire travel times for estimation of soil
120 water contents in the field than would an arbitrarily short cable. The bandwidth associated with
121 the 10–90% rise time of the TDR pulse that arrives at the end of the 8.5-m cable into the probe
122 was estimated to be 820 MHz (Schwartz et al., 2013).

123

124 *Apparent permittivity calibration*

125 The TDR-315 sensors were calibrated for apparent permittivity (K_a) using waveforms
126 acquired at 20 ps intervals in air and deionized water. Conventional TDR was also calibrated in
127 the same manner using 251-point waveforms in air and water (13.5 and 53.4 ps intervals,
128 respectively). Amplitudes, V , acquired from the TDR-315 were converted to reflection
129 coefficients, ρ as

130
$$\rho = \frac{2 \cdot V - V_0}{V_0} \quad (1)$$

131 where V_0 is the measured amplitude at long times (20 ns) in air (open circuit). Limitations
132 associated with the timing circuit prevented the routine acquisition of amplitudes at times greater
133 than 20.4 ns. Short circuit measurements with the TDR-315 by design yield an amplitude of zero

134 at long times. Travel time for both conventional and digital TDR was evaluated using adaptive
135 waveform interpretation with Gaussian filtering (AWIGF) as described by Schwartz et al.
136 (2014). Three AWGIF algorithm parameters were adjusted to accommodate the differences
137 between the TDR-315 and conventional TDR systems. After scaling amplitudes using Eq. (1),
138 AWIGF was implemented for TDR-315 waveforms using a characteristic noise level $\alpha = 0.25$ ns
139 rather than the 0.142 ns (Schwartz et al., 2014) to account for differences between the TDR-315
140 step pulse generator and the step pulse generator used in metallic cable testers with conventional
141 TDR. In addition, the standard deviation of the Gaussian kernel for the evaluation of t_1 was set to
142 two-thirds of the value used in conventional TDR. This was necessary because the t_1 evaluation
143 for TDR-315 is based on an offset from launch of the incident step pulse rather than, in
144 conventional TDR, the impedance change generated as the signal leaves the cable, with the
145 former having a more abrupt transition. Lastly, the measured maximum amplitude gradient in air
146 associated with the rising limb of the reflection at the termination of the transmission line was set
147 to 1.2 ns^{-1} . All other parameters were set equivalent to the default values used for interpretation
148 of conventional waveforms using the 1502C cable tester (Schwartz et al., 2014).

149 A calibration in air and water was used to determine an offset t_c and the electrical length L_e of
150 both conventional TDR and TDR-315 probes (Heimovaara, 1993; Schwartz et al., 2014). In
151 conventional TDR probes, t_c is the time between t_1 and the intersection of the tangent lines to the
152 rising limb of the first reflection and the preceding baseline (t_{x1}). Similarly, for TDR-315 sensors,
153 t_c is the time between t_1 and the launch time of the incident wave also evaluated at the
154 intersection of the tangent lines of the step pulse and the preceding baseline (Fig. 2). Calibrations
155 in water were completed at $20 \pm 2^\circ\text{C}$ with the temperature dependent apparent permittivity

156 calculated using the empirical expressions of Stogryn (1971; 1995) assuming an effective
157 frequency of 1 GHz.

158

159 *Bulk electrical conductivity calibration*

160 Conventional TDR and TDR-315 probes were calibrated for bulk electrical conductivity
161 sensing in CaCl₂ solutions with electrical conductivities ranging from 100 μS m⁻¹ (deionized
162 water) to 7.3 dS m⁻¹. Electrical conductivity of solutions was measured using a bench top meter
163 (WTW Inolab, White Plains, NY) with conductivity reported at ambient temperatures (20°C ±
164 2°C). Bulk electrical conductivity (σ_a) using the conventional TDR probes was determined using
165 the method of Lin et al. (2008) using open (air) and short circuit measurements to evaluate the
166 scaled reflection coefficient ρ_{scale} at 3 μs that accounts for the instrumental error and cable
167 resistance (Castiglione and Shouse, 2003). After rescaling, the Giese and Tiemann (1975)
168 method

$$169 \quad \sigma_a = \frac{K_p}{Z_s} \left(\frac{1 - \rho_{scale}}{1 + \rho_{scale}} \right) \quad (2)$$

170 was applied to find the slope of the relationship K_p/Z_s using zero-intercept linear regression
171 where K_p is the probe constant (m⁻¹) and Z_s is the source impedance (Ω). Electrical conductivity
172 calibrations for the TDR-315 sensors were completed using the reflection coefficient (Eq. 1)
173 evaluated at 20 ns (all sensors) and at 3 μs (SN 684,713,729, and 731). Noting that

$$174 \quad \frac{1 - \rho}{1 + \rho} = \frac{V_0}{V} - 1 \quad (3)$$

175 when the short circuit amplitude is zero, the Giese and Tiemann Eq. (2) was also used to evaluate
176 the slope K_p/Z_s for TDR-315 calibrations. Firmware-calculated σ_a was being developed
177 concurrently with testing of TDR-315 sensors and was not implemented in SN 1 to 6, 684, and

178 713. However, firmware in sensors with SN 729 and 731 reported σ_a based on a factory
179 calibration and these values were compared to measured conductivity values of CaCl₂ solutions.

180

181 *Soil water content calibration*

182 Water content calibrations of the Ap horizon (0 – 0.15 m) of the Pullman clay loam (fine,
183 mixed, superactive, thermic Torrertic Paleustoll) were carried out for six TDR-315 sensors (SN 1
184 to 6) and two conventional TDR probes. The Pullman Ap horizon has a clay content of
185 approximately 390 g kg⁻¹ dominated by smectite and mica (Soil Survey Staff, 2008; Schwartz et
186 al., 2009). Packed columns (0.101 m inside diameter by 0.20 m long Schedule 40 rigid polyvinyl
187 chloride) were prepared using soil sieved through a 12.7-mm by 12.7-mm mesh screen. A range
188 of volumetric water contents was achieved by combining air-dry soil with different ratios of
189 deionized water, thoroughly mixing to achieve uniformity, and packing the mixture into the
190 columns to ~160 mm in 20-mm increments. After packing, the probe and sensor rods were
191 installed vertically into the prepared soil columns. Waveforms were acquired at room
192 temperature (20°C), at 6°C (in a refrigerator), and at 40°C (in a water-jacketed incubator) after
193 permitting the packed columns to equilibrate for one day at each temperature regime. The
194 refractive mixing model (Birchak et al., 1974), which assumes a linear relationship between the
195 square root of K_a and water content, was fitted to measured apparent permittivity using measured
196 volumetric water contents. All temperature regimes were included in the calibrations so that the
197 errors associated with the fitted model would be more representative of non-isothermal field
198 conditions. Slopes of the permittivity response to temperature for the Pullman clay loam
199 calibration were evaluated for each water content level using the general linear model analysis of
200 covariance (SAS, 2009) assuming equal slopes among column replicates.

201 *Solute displacement*

202 The dependence of measured apparent permittivity (K_a) on σ_a in a lossy soil was examined
203 for both the TDR-315 and conventional TDR using a near saturated solute displacement
204 experiment. Air-dry Pullman soil was packed in a 0.2 m diam. by 0.20 m long Schedule 40
205 polyvinyl chloride column in increments of 20 mm to a depth of 0.19 m. A single TDR-315
206 sensor was installed at a soil depth of 130 mm through a slot machined into the wall of the
207 column with approximately 20 mm of the 60 mm long sensor head containing the circuitry
208 embedded within the soil. Once the sensor was installed, the slot containing the sensor head was
209 sealed with room temperature vulcanizing silicon gasket maker to prevent water from seeping
210 out of the column. Subsequently, soil was carefully packed above the sensor. A single TDR
211 probe with a rod length of 150 mm was installed at a soil depth of 50 mm with the 30 mm long
212 probe head embedded entirely within the soil and the coaxial cable inserted through a hole in the
213 column wall that was sealed to prevent seepage. The remaining soil was packed above the TDR
214 probe to a depth of 190 cm, leaving 10 mm for ponding of water above the soil surface.

215 The column was slowly saturated with 1.0 mM CaCl_2 ($\sigma_s = 0.25 \text{ dS m}^{-1}$ at 25°C) through a
216 bottom inlet. Once the column was saturated, downward, vertical flow was established by
217 maintaining a 5-mm head of influent solution above the soil surface using a Mariotte bottle.
218 After equilibration of the flow concentration at the bottom inlet, the influent solution was
219 switched to $\sim 35 \text{ mM CaCl}_2$ ($\sigma_s = 7.3 \text{ dS m}^{-1}$ at 25°C) and the displacement experiment was
220 continued until effluent attained 7.2 dS m^{-1} after which the influent was again switched back to
221 1.0 mM CaCl_2 . The displacement experiment was completed at a near constant temperature (20
222 $\pm 1^\circ\text{C}$) for a duration of 12 days after saturation. Further details of the methodology are provided
223 by Schwartz et al. (2013).

224 RESULTS AND DISCUSSION

225 Waveforms acquired with the TDR-315 in air and deionized water (Fig. 2) exhibited features
226 similar to conventional TDR (Schwartz et al., 2014) except for the inclusion of the rising edge of
227 the step pulse launched approximately 0.20 ns prior to the pulse arrival within the medium.
228 Waveform distortions immediately after the incident step pulse that oscillated around the steady state
229 unloaded amplitude (overshoot and ringback) were evident in the trace in air (Fig. 2). These features
230 were present in the relevant portions of the waveform required to evaluate travel time in low
231 permittivity media. The waveform interpretation algorithm AWIGF was modified to ensure that
232 the identified time of the amplitude derivative maximum was associated with the time at which
233 the pulse arrives at the end of the transmission line (t_2) rather than overshoot features. This
234 simply involved providing the algorithm with the physical probe length to set the beginning time
235 of the t_2 search window as $0.6 (2 L)/c$ where c is the speed of light and L is physical probe length.
236 With this modification, the algorithm had no difficulties in identifying t_2 in low permittivity
237 media. The sample standard deviation for the bulk permittivity in water averaged 0.063 and
238 0.068 relative permittivity units for the TDR-315 and conventional TDR, respectively. The mean
239 of the sample standard deviation in air for the TDR-315 (0.003) was less than that obtained for
240 conventional TDR (0.009) likely because of greater resolution afforded by the faster rise time of
241 the TDR-315 step pulse generator. Electrical length L_e and offset t_c for permittivity calibrations
242 of the TDR-315 and conventional TDR were remarkably similar (Table 1). Variations in
243 calibrated L_e among TDR-315 probes resulted from small variations in the physical rod length
244 and the timing circuit. Probes with serial numbers 684, 713, 729 and 731 exhibit slightly larger
245 offsets (t_c) and earlier pulse launches because of the inclusion of additional rod length within the
246 epoxy head. These manufacturing variations are accommodated in the commercial sensors by the
247 factory calibration process.

248 The electrical conductivity (EC) calibrations for conventional TDR probes were linear (Fig.
249 3) with r^2 values exceeding 0.9998 and non-significant y-intercepts ($P > 0.180$). Likewise, the
250 TDR-315 EC calibrations using the 20 ns long time amplitudes were linear with r^2 values
251 exceeding 0.9988, suggesting that the Giese and Tiemann (1975) thin-section approach for
252 estimation of electrical conductivity was appropriate for these sensors. However, the TDR-315
253 response deviated from linear at electrical conductivities less than 0.2 dS m^{-1} (Fig. 3), yielding
254 significant linear regression y-intercepts ($P < 0.05$). This nonlinearity was likely due to the
255 settling of amplitudes at these low attenuation levels occurring at times greater than 20 ns. Slopes
256 of the EC responses were similar among conventional TDR probes and TDR-315 sensors (Table
257 1), although the theoretical probe constant K_p of the conventional TDR probes (4.31 m^{-1}) was 1.2
258 times greater than that of the TDR-315 (3.59 m^{-1}) because of the greater rod spacing of the
259 former. Long time reflection coefficients evaluated from the $3 \mu\text{s}$ amplitudes reported by the
260 firmware of the newer probes (serial numbers 684,713,729 and 731) were linear at low
261 conductivities, had y-intercepts not significantly different from zero, and slightly greater r^2
262 values. However, EC calibrations using these amplitudes at $3 \mu\text{s}$ departed from a linear response
263 at electrical conductivities greater than 3 dS m^{-1} (Fig. 3). Firmware in two of the latest probes
264 evaluated (SN 729 and 731) reported σ_a based on a factory calibration that accounted for this
265 nonlinearity in the response at $\sigma_a > 3 \text{ dS m}^{-1}$. Electrical conductivity reported by the nonlinear
266 factory calibration had a relative error of $\leq 6.5\%$ in the 0.01 to 7.3 dS m^{-1} range, which was
267 similar to the error observed for the conventional TDR probes evaluated in this study ($\leq 5.0\%$).
268 Of note, however, is that TDR-315 firmware estimates of σ_a are independently predicted values
269 (calibration coefficients and errors were evaluated using different EC data) and, accordingly,

270 would be expected to have greater error compared with error associated with the conventional
271 TDR fit where the same EC data was used for calibration and the determination of error.

272 The fitted water content calibration for the Pullman clay loam derived from AWIGF K_a
273 estimates using the TDR-315 corresponded closely to the conventional TDR calibration also
274 using AWIGF to evaluate travel time (Fig. 4). The TDR-315 firmware-calculated K_a averaged
275 95% of the TDR-315 AWIGF-calculated K_a and the two estimates were closely correlated ($r^2 =$
276 0.997). Accordingly, the water content calibration obtained from the firmware estimate of K_a was
277 remarkably similar to the AWIGF derived calibrations (Fig. 4). Slopes and intercepts of the three
278 water content calibrations were similar, with RMSE values that ranged from 0.017 to 0.020 m^3
279 m^{-3} . At the three lowest water contents evaluated for soil water calibrations (0.04, 0.17, and 0.24
280 $\text{m}^3 \text{m}^{-3}$; Fig 4), both conventional TDR and the TDR-315 K_a response to temperature were
281 positive exhibiting slopes ranging from 0.005 to 0.028 $^{\circ}\text{C}^{-1}$. Except in one case (conventional
282 TDR at $\theta = 0.17 \text{ m}^3 \text{ m}^{-3}$), these temperature responses were significant ($P < 0.05$) and indicative
283 of a mechanistic process, possibly related to the change in bound water with temperature (Or and
284 Wraith, 1999). At near saturated water content ($\theta = 0.47 \text{ m}^3 \text{ m}^{-3}$), the slope of the $K_a -$
285 temperature response was positive for conventional TDR (0.054 $^{\circ}\text{C}^{-1}$) similar to that reported by
286 Schwartz (2009) and likely due to sensitivity to σ_a that varies with temperature (Evetts et al.,
287 2005). In contrast, the $K_a -$ temperature response was negative for the TDR-315 (-0.074 $^{\circ}\text{C}^{-1}$).
288 We interpret this behavior for the TDR-315 to indicate that near saturation, the thermodielectric
289 response was dominated by bulk water resulting in a decrease in K_a with temperature (Or and
290 Wraith, 1999). The factory water content calibration reported by the firmware tended to
291 underestimate soil water content and had a root mean square error of 0.0324 $\text{m}^3 \text{ m}^{-3}$ that was
292 greater than that of the soil specific calibrations (Fig. 4).

293 A characteristic feature of all displacement experiments in previous evaluations (Schwartz et
294 al., 2013) and in this study was an increase in conventional TDR measured K_a as the high
295 concentration CaCl_2 solute front migrated past the probe rods followed by a decline in K_a after
296 the injection of the final 0.25 dS m^{-1} solution (Fig. 5). The measured response arises because of
297 the contribution of low frequency conductive losses to K_a imparted by a lower effective
298 measurement frequency compared with the incident signal (Hook et al., 2004; Schwartz et al.,
299 2013). Apparent permittivity estimated with AWIGF using conventional TDR increased from 32
300 to 40 after introduction of the 7.3 dS m^{-1} CaCl_2 step pulse (Fig. 5). In contrast, K_a estimated
301 using the TDR-315 and also evaluated using AWIGF was insensitive to σ_a (Fig. 5). Both of the
302 above AWIGF-derived estimates of K_a use the default method whereby t_2 is conditionally
303 evaluated using the maximum of the second derivative (Schwartz et al., 2014). Of note, the
304 AWIGF-calculated K_a for the TDR-315 using the conventional method to estimate t_2 (denoted as
305 t_{x2} which is the intersection of the tangents to the baseline and rising limb) resulted in a slight
306 dependence on σ_a (Fig. 5). Likewise the TDR-315 firmware estimates of K_a were slightly
307 sensitive to σ_a and were subject to reduced precision at $\sigma_a > 2 \text{ dS m}^{-1}$ (Fig. 5). Sensitivity of
308 firmware-calculated K_a to σ_a likely results from evaluation of t_2 using t_{x2} . At greater
309 conductivities, we recommend that waveforms be sampled by the firmware using finer time
310 resolutions to improve K_a estimates. The cause of the insensitivity of the TDR-315 measured K_a
311 to σ_a was evident from the waveforms at a high σ_a (2.8 dS m^{-1}). The slope of the reflection at the
312 termination of the rods was four times greater for the TDR-315 waveform compared with that for
313 conventional TDR (Fig. 6) indicating that a greater proportion of the high frequency signal
314 component was preserved by the TDR-315.

315 CONCLUSIONS

316 Waveforms acquired using the TDR-315 sensor over a wide range of media properties were
317 similar to those from conventional TDR and interpretable using the same algorithm with minor
318 adjustments in parameters to account for differences in the step pulse. Calibration of K_a could be
319 accomplished with the conventional TDR method using air and water as two known
320 permittivities. The conventional Giese and Tiemann (1975) approach for σ_a calibration gave a
321 linear response to $\sigma_a < 3 \text{ dS m}^{-1}$ for long-time amplitudes obtained at $3 \mu\text{s}$. At greater
322 conductivities, the response became nonlinear. Firmware successfully accounted for the
323 nonlinearity and reported electrical conductivities to within 6.5% of a benchtop meter. The fitted
324 water content calibrations for the Pullman clay loam using the firmware-reported K_a and the
325 AWIGF-calculated travel time were both nearly indistinguishable from conventional TDR
326 calibrations. The response of K_a to σ_a in a saturated Pullman clay loam exhibited by the two
327 sensor technologies differed markedly. Waveforms acquired by the TDR-315 probe retained a
328 greater proportion of high frequency components as compared to conventional TDR as was
329 inferred by a greater slope of the reflection at the rod termination. This resulted in AWIGF-
330 derived permittivity measurements from the TDR-315 that were insensitive to σ_a up to 2.8 dS/m
331 and a corresponding pore water conductivity of 7.3 dS/m . In contrast, measured K_a using
332 conventional TDR increased by 25% over the same range in conductivities. Firmware-calculated
333 K_a for the TDR-315 was satisfactory compared with estimates evaluated using AWIGF, although
334 waveforms should be sampled by the firmware at higher time resolutions when $\sigma_a > 2 \text{ dS m}^{-1}$.
335 Based on these observations, the TDR-315 would be more suitable for measurement of soil water
336 contents in saline or salt affected soils than is conventional TDR. Considering that measured K_a
337 is insensitive to σ_a for the range evaluated in this study, exhibited temperature responses of K_a

338 for the TDR-315 Pullman water content calibrations are therefore a result of bound water effects
339 and, unlike conventional TDR in lossy, fine-textured soils, not a combination of both σ_a and
340 bound water. For high accuracy water content measurements, we recommend soil specific
341 calibrations using the firmware reported K_a .

342

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351

352 **REFERENCES**

353 Anderson, S.K., and H.S. Anderson. 2004. Method and apparatus for determining moisture
354 content and conductivity. U.S. Patent 6831468 B2. Date issued: 14 December.

355 Birchak, J.R., C.G. Gardner, J.E. Hipp, and J.M. Victor. 1974. High dielectric constant
356 microwave probe for sensing soil moisture. Proc. IEEE 62:93–98.

357 Blonquist, J.M., Jr., S.B. Jones, and D.A. Robinson. 2005. A time domain transmission sensor
358 with TDR performance characteristics. J. Hydrol. 314:235–245.
359 doi:10.1016/j.jhydrol.2005.04.005

360 Casanova, J.J., R.C. Schwartz, S.R. Evett, and S. K. Anderson. 2013. Directly coupled vs.
361 conventional time domain reflectometry in soils. *Applied Engr. Agric.* 29(5): 771-777.

362 Castiglione, P. and P.J. Shouse. 2003. The effect of ohmic cable losses on time domain
363 reflectometry measurements of electrical conductivity. *Soil Sci. Soc. Am. J.* 67:414-424.

364 Dalton, F.N., and M.Th. van Genuchten. 1986. The time-domain reflectometry method for
365 measuring soil water content and salinity. *Geoderma* 38:237-250.

366 Evett, S.R., J.A. Tolk, and T.A. Howell. 2005. TDR laboratory calibration in travel time, bulk
367 electrical conductivity, and effective frequency. *Vadose Zone J.* 4:1020-1029..
368 doi:10.2136/vzj2005.0046

369 Ferré, T.P.A. and G.C. Topp. 2002. Time Domain Reflectometry, pp. 434-446. In J.H. Dane, J.H.
370 and G.C. Topp (Eds.), *Methods of Soil Analysis. Part 4. Physical Methods.* Madison, WI.

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

374 Heimovaara, T.J. 1993. Design of triple-wire time domain reflectometry probes in practice and
375 theory. *Soil Sci. Soc. Am. J.* 57:1410-1417. doi:10.2136/sssaj1993.03615995005700060003x

376 Hoekstra, P. and A. Delaney. 1974. Dielectric properties of soils at UHF and microwave
377 frequencies. *J. Geophys. Research* 79:1699-1708.

378 Hook, W.R., T.P.A. Ferré, and N.J. Livingston. 2004. The effects of salinity on the accuracy and
379 uncertainty of water content measurements. *Soil Sci. Soc. Am. J.* 68:47-56.

380 Knight, J.H. 1992. Sensitivity of time domain reflectometry measurements to lateral variations in
381 soil water content. *Water Resour. Res* 28:2345-2352.

382 Lin, C.-P, C.C. Chung, J.A. Huisman, and S.-H. Tang. 2008. Clarification and calibration of
383 reflection coefficient for electrical conductivity measurement by time domain reflectometry.
384 Soil Sci. Soc. Am. J 72:1033-1040.

385 Logsdon, S.D. 2000. Effect of cable length on time domain reflectometry calibration for high
386 surface area soils. Soil Sci. Soc. Am. J. 64:54-61.

387 Or, D. and J.M. Wraith. 1999. Temperature effects on soil bulk dielectric permittivity measured
388 by time domain reflectometry: A physical model. Water Resour. Res. 35:371-383.

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

392 SAS Institute. 2009. SAS/STAT online documentation. Version 9.2. SAS Inst., Cary. NC.

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

395 Schwartz, R.C., J.J. Casanova, M.G. Pelletier, S.R. Evett, and R.L. Baumhardt. 2013. Soil
396 permittivity response to bulk electrical conductivity for selected soil water sensors. Vadose
397 Zone J. doi:10.2136/vzj2012.0133.

398 Schwartz, R.C., Evett, S.R. and Bell, J.M. Complex permittivity model for time domain
399 reflectometry soil water content sensing. II. Calibration. 2009a. Soil Sci. Soc. Am. J. 73(3):
400 898-909. 2009.

401 Schwartz, R.C., Evett, S.R., Pelletier, M.G., and Bell, JM. 2009b. Complex permittivity model
402 for time domain reflectometry soil water content sensing. I. Theory. Soil Sci. Soc. Am. J.
403 73(3):886-897. 2009.

404 SDI-12 Support Group. 2013. SDI-12 A Serial-Digital Interface Standard for Microprocessor-
405 Based Sensors. Version 1.3. River Heights, Utah. [http://www.sdi-
406 12.org/current%20specification/SDI-12_version1_3%20January%2026,%202013.pdf](http://www.sdi-12.org/current%20specification/SDI-12_version1_3%20January%2026,%202013.pdf)
407 Stogryn, A.P. 1971. Equations for calculating the dielectric constant of saline water. IEEE Trans.
408 Microw. Theory Tech. 19:733–736.
409 Stogryn, A.P. 1995. The microwave permittivity of sea and fresh water. GenCorp Aerojet,
410 Azusa, CA.
411 Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil-water
412 content: Measurement in coaxial transmission lines. Water Resour. Res. 16:574-582.
413 Topp, G.C. and W.D. Reynolds. 1998. Time domain reflectometry: a seminal technique for
414 measuring mass and energy in soil. Soil Till. Res 47:125-132.
415

416 **FIGURE CAPTIONS**

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

419
420 Fig. 2. Waveforms in air and deionized water acquired using a TDR-315 probe showing the time
421 of the step signal launch (t_{x1}), time at which the signal enters the media (t_1) and the time of the
422 reflection at the end of the rod in air, $t_2(\text{air})$, and water $t_2(\text{water})$ determined using AWIGF
423 (Schwartz et al., 2014). The offset, t_c , is fitted based on the calibration in air and water.

424
425 Fig. 3. Electrical conductivity (EC) calibrations for the long time reflection coefficient, ρ , in
426 CaCl_2 solutions for the TDR and TDR-315. Inset shows calibration response at low EC levels.

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428 Fig. 4. Refractive mixing model soil water content calibrations of the Pullman clay loam (0.0 to
429 0.15 m) for conventional TDR and TDR-315 using AWIGF-estimated travel times and the
430 apparent permittivity (K_a) calibration (Fig. 2) and the TDR-315 using firmware estimated K_a .
431 Calibrations include permittivity measurements at all three temperature regimes. Also shown is
432 the Acclima factory soil water content calibration.

433
434 Fig. 5. Response of electrical conductivity and apparent permittivity during column displacement
435 for conventional TDR and TDR-315 sensors in a Pullman clay loam. Apparent permittivities for
436 the TDR-315 are plotted using two AWIGF methodologies to estimate the time at which the
437 pulse arrives at the end of the transmission line (t_2): the default method that uses the maximum of
438 the second derivative and the conventional method that uses the intersection of the tangents to

439 the baseline and rising limb (t_{x2}). In addition, firmware-calculated apparent permittivities are
440 also plotted. A lag in the TDR-315 response compared with conventional TDR is due to differing
441 heights within the soil column.

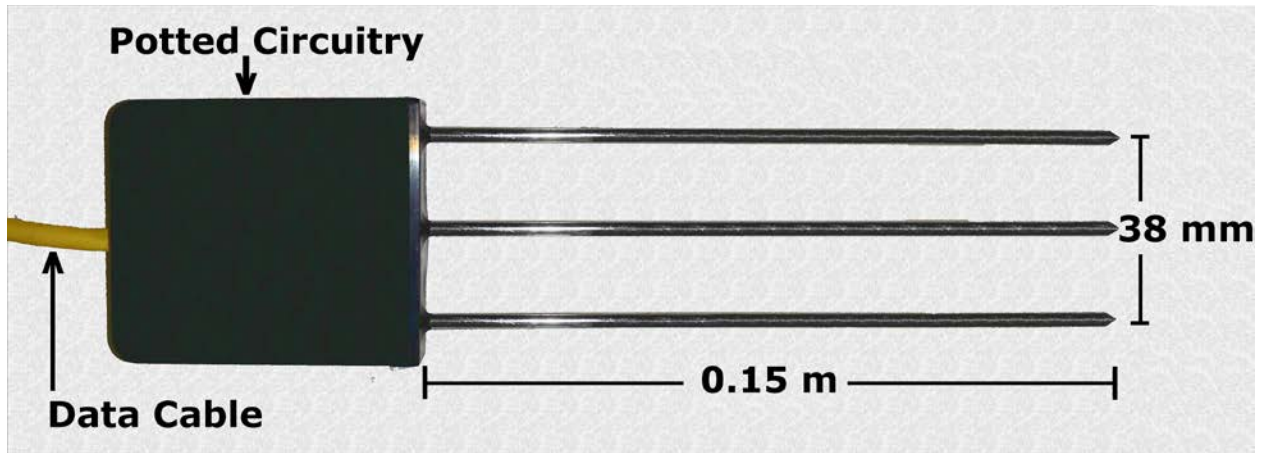
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443 Fig. 6. Waveforms of conventional TDR and the TDR-315 at a bulk electrical conductivity (σ_a)
444 of 2.8 dS m^{-1} and the AWIGF-evaluated time at which the pulse arrives at the end of the
445 transmission line (t_2). The waveforms have been horizontally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

447 Table 1. Apparent permittivity and bulk electrical conductivity calibration parameters for the
 448 TDR-315 and conventional TDR. Electrical length (L_e) and offset (t_c) are derived from the air-
 449 water calibration. The probe constant divided by the source impedance (K_p/Z_s) is derived from
 450 the slope of the long time amplitude calibrations at 20 ns and 3 μ s in CaCl_2 electrolytic solutions
 451 ($100 \mu\text{S m}^{-1}$ to 7.3 dS m^{-1}). The calibration slope for TDR-315 sensors at 3 μ s was obtained from
 452 the linear range at less than or equal to 3 dS m^{-1} CaCl_2 .
 453

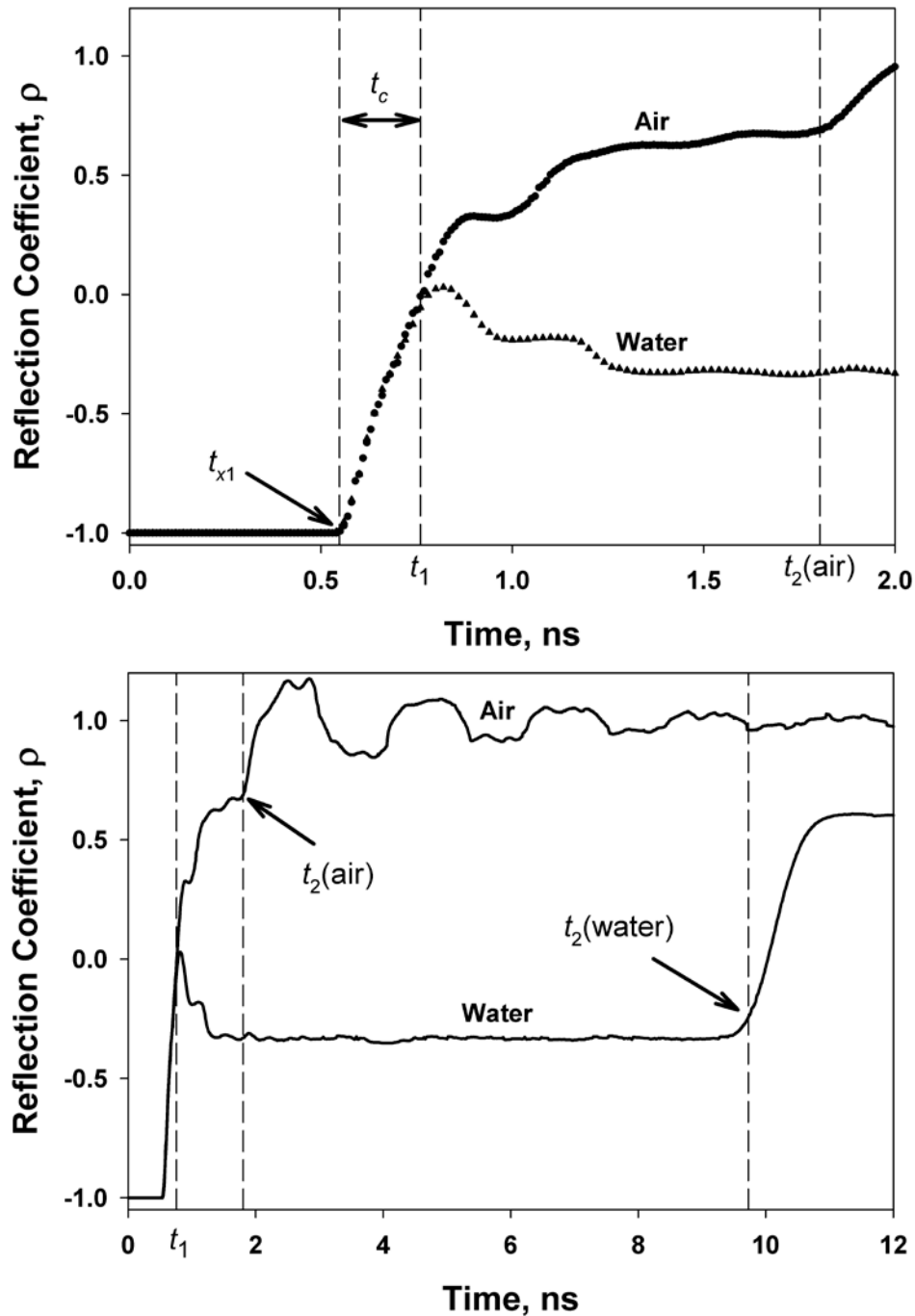
Serial Number	Physical Length m	L_e m	t_c ns	K_p/Z_s 20 ns dS m^{-1}	K_p/Z_s 3 μ s dS m^{-1}
----- Acclima TDR-315 -----					
1	0.150	0.1494	0.189	0.840	
2	0.150	0.1496	0.207	0.917	
3	0.150	0.1489	0.203	0.978	
4	0.150	0.1493	0.206	0.918	
5	0.150	0.1493	0.224	0.923	
6	0.150	0.1498	0.168	0.815	
684	0.145	0.1523	0.243	0.873	0.963
713	0.145	0.1521	0.229	0.850	0.987
729	0.145	0.1535	0.262	0.858	0.974
731	0.145	0.1537	0.236	0.877	0.970
----- Conventional TDR (Tektronix 1502C) -----					
	0.150	0.1550	0.194		0.937
	0.151	0.1570	0.192		0.914

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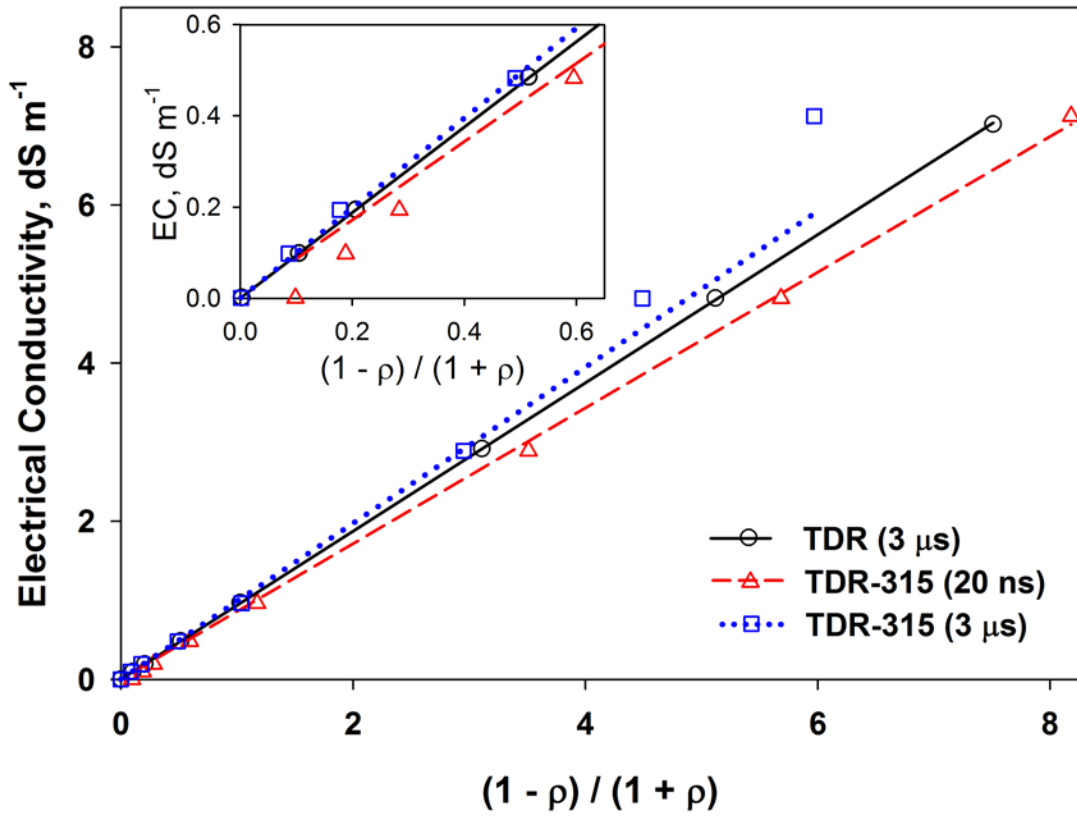


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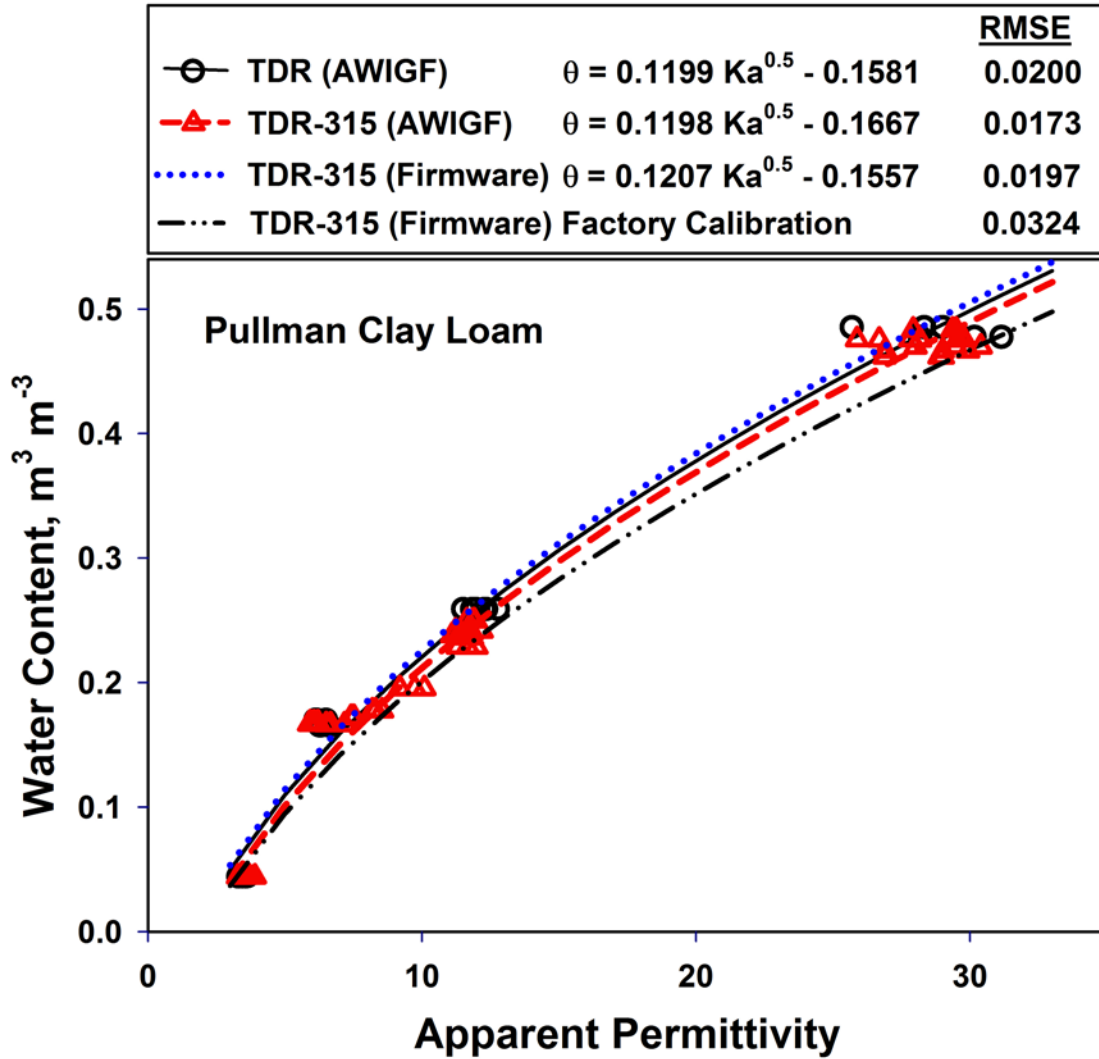
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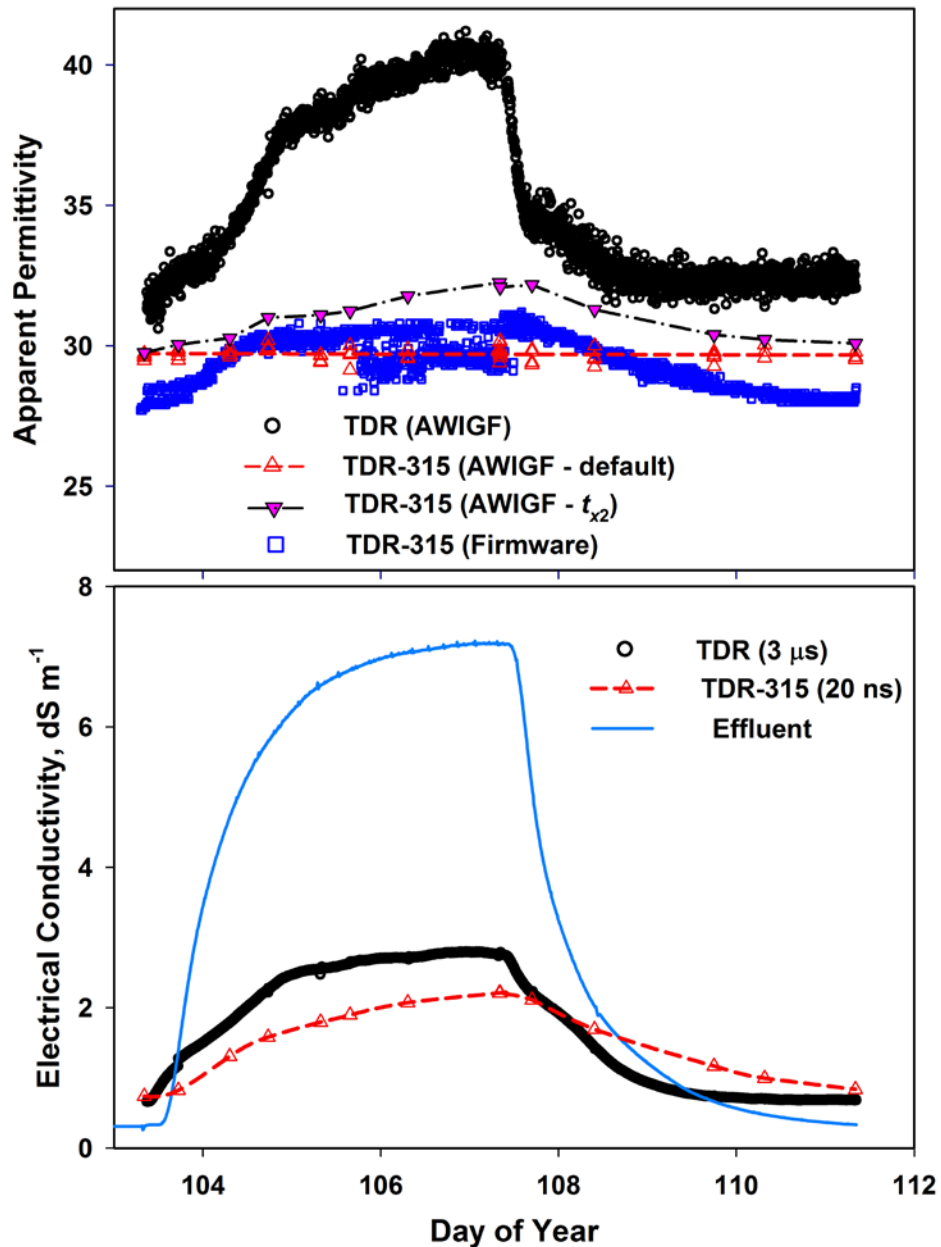
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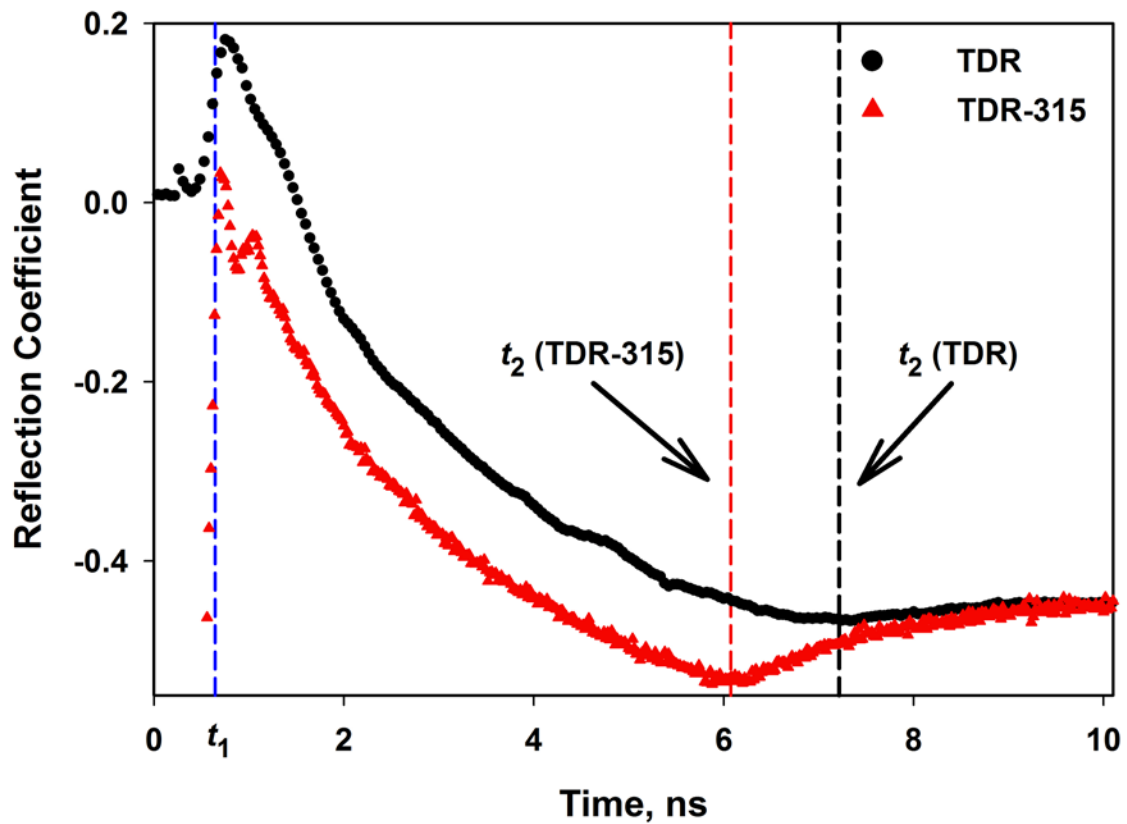
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