A Reevaluation of TDR Travel Time Estimation in Soils and Geological Media

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Abstract

Time domain reflectometry (TDR) is an established method for the determination of apparent dielectric permittivity and water content in soils. Using current waveform interpretation procedures, signal attenuation and variation in dielectric media properties along the transmission line can significantly increase sampling error in estimating the time, t_2, at which the pulse arrives at the end of the probe. Additionally, manual adjustment of waveform analysis parameters is frequently required in current software to accommodate changes in media properties when processing large time series of TDR measurements. Our objectives were to reevaluate conventional propagation time analysis and difficulties with these methods, introduce the AWIGF (adaptive waveform interpretation with Gaussian filtering) algorithm that circumvents these problems, and compare interpretation methods using waveforms obtained with different TDR instruments and under widely varying media properties. The AWIGF algorithm filters signal noise using Gaussian kernels with an adaptively estimated standard deviation based on the maximum gradient of the reflection at the termination of the probe. Two fitted parameters are required to scale the smoothing level for a given step pulse generator. Additionally, the maximum second derivative is used to evaluate t_2. AWIGF determined t_2 was compared with TACQ, a standard waveform interpretation algorithm. The strategies of AWIGF permitted the determination of t_2 without parameter adjustment when the loss characteristics of the media changed, such as an increase in soil water content and bulk electrical conductivity. Using the new method, the sampling error of t_2 was less than 0.06 ns over a wide range of media properties and less than or equal to that obtained with TACQ. In strongly attenuated waveforms, the water content sampling error determined with AWIGF was 0.005 m^3 m^{-3} compared with 0.038 m^3 m^{-3} obtained using TACQ.

Difficulties with conventional travel time analysis

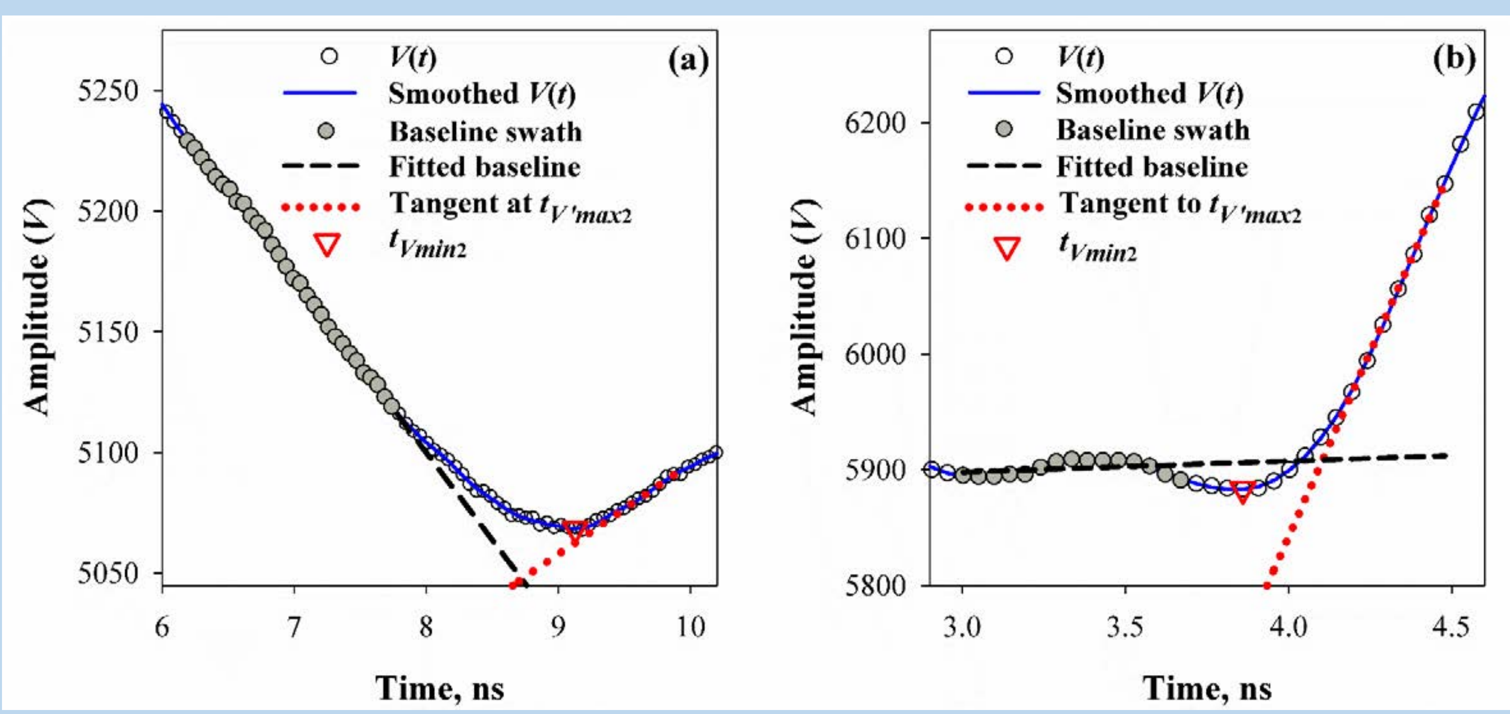
- Frequent under- or over-estimation of time t_2 at the probe termination when estimated using the intersection of a fitted baseline and the tangent to the maximum amplitude gradient $t_{V'max2}$ (Fig. 1a and 1b)
- The optimal smoothing window applied to the second reflection will increase with increasing signal attenuation because of the inherently lower signal to noise ratio (Fig 1d and 1e)
- Manual adjustment of waveform analysis parameters is frequently required to accommodate changes in media properties when processing large time series of TDR measurements

Determination of travel time using an adaptive smoothing approach (AWIGF)

1. Smooth the waveform with normalized, discrete Gaussian kernels using a fixed standard deviation σ for the determination of t1, the time of pulse arrival within the media
2. Calculate an adaptively scaled σ based on the ratio of the maximum amplitude gradient associated with the reflection at the termination of the transmission line and the equivalent maximum gradient obtained with the probe in air
3. Smooth the waveform again with Gaussian kernels using the σ calculated in (2) to yield the smoothed waveform $h(t)$ and its smoothed derivative $h'(t)$ and second derivative $h''(t)$
4. Find $t_{V'max2}$, the time of the maximum amplitude gradient in $h'(t)$ associated with the reflection at the termination of the transmission line
5. Determine the position of the local minimum t_{Vmin2} evaluated from zero crossings of $h'(t)$ preceding $t_{V'max2}$ (Fig. 2d and 2e)
6. Find $t_{V''max2}$, the maximum in $h''(t)$ and the point of maximum convexity associated with the reflection at the termination of the transmission line (Fig. 2c, 2d and 2e)
7. Calculate t_{x2} as the intersection of tangent lines at $t_{V'max2}$ and t_{Vmin2}. If t_{Vmin2} does not exist (Fig. 2c), evaluate t_{x2} based on the intersection of the tangent at $t_{V'max2}$ and a linear fit to a baseline swath (Fig. 2b)
8. Evaluate t_2 as

$$t_2 = \begin{cases} t_{V''max2} & \text{for} \quad t_{Vmin2} \le t_{V''max2} \le t_{x2} \\ t_{Vmin2} & \text{for} \quad t_{Vmin2} > t_{V''max2} \\ t_{x2} & \text{for} \quad t_{V''max2} > t_{x2} \end{cases}$$

9. Calculate travel time as $t_2 - t_1$



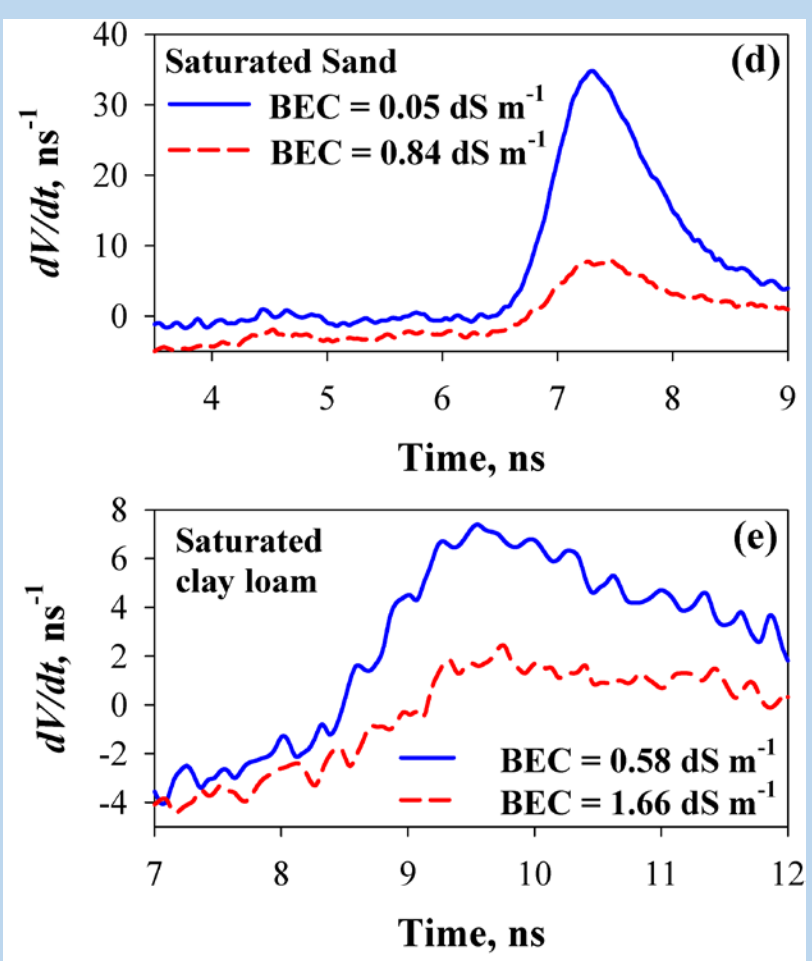


Fig. 1. Waveform interpretation difficulties associated with conventional methods for determining the propagation time in TDR amplitude traces. In (a), the intersection of the fitted baseline swath and the tangent to the maximum amplitude gradient $t_{V'max2}$ occurs prior to the local minimum t_{Vmin2}. In (b), nonuniform water content along the transmission line results in a fitted baseline that causes an overestimation of propagation time. As bulk electrical conductivity (BEC) and hence attenuation of the reflection at the probe termination increases (d and e), noise levels are approximately constant yet the signal response of the amplitude derivative declines indicating a decrease in the signal to noise ratio and the need for greater smoothing.

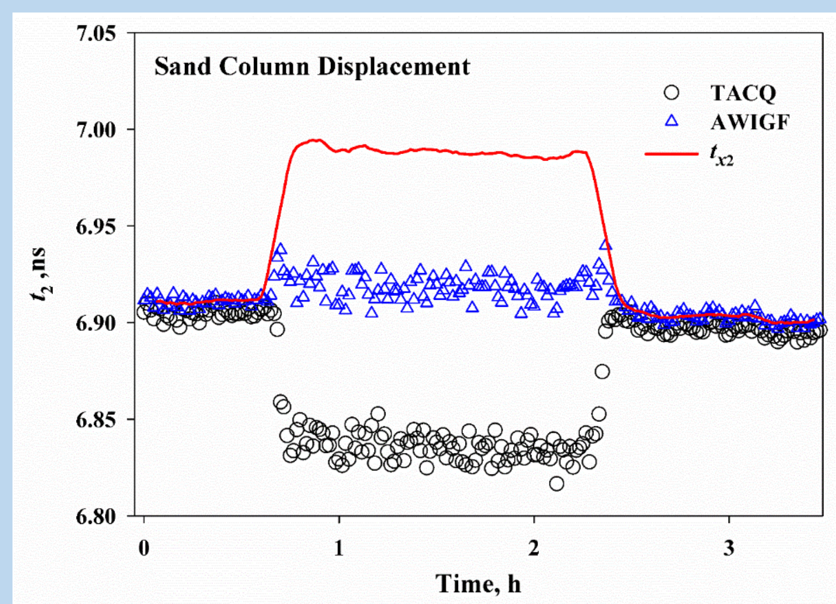


Fig. 3. Measured time, t_2, at the probe termination determined using TACQ and AWIGF for a TDR probe in saturated sand and undergoing changes in bulk electrical conductivity during column displacement.

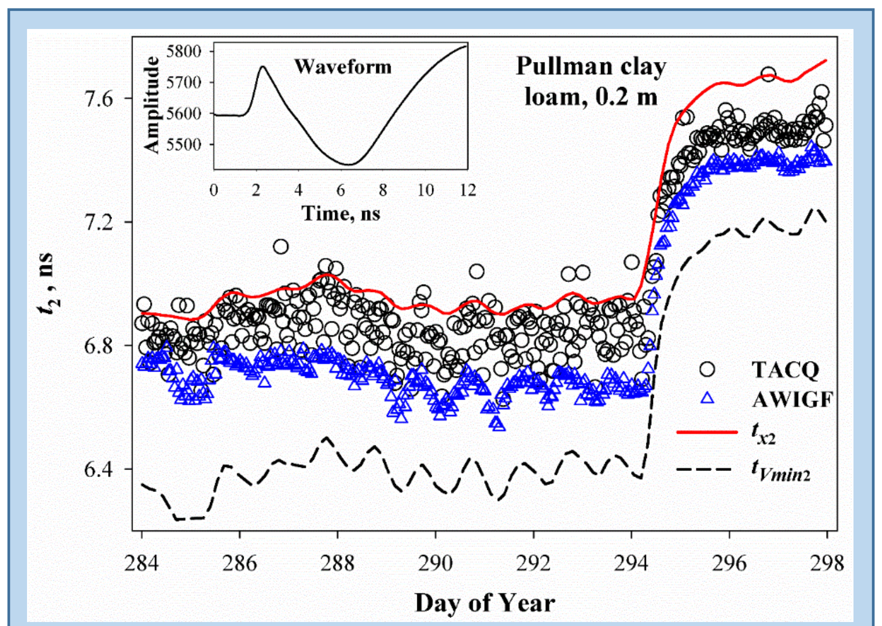


Fig. 4. Measured time, t_2, at the probe termination determined using TACQ and AWIGF for a TDR probe in a Pullman clay loam and undergoing wetting in the field.

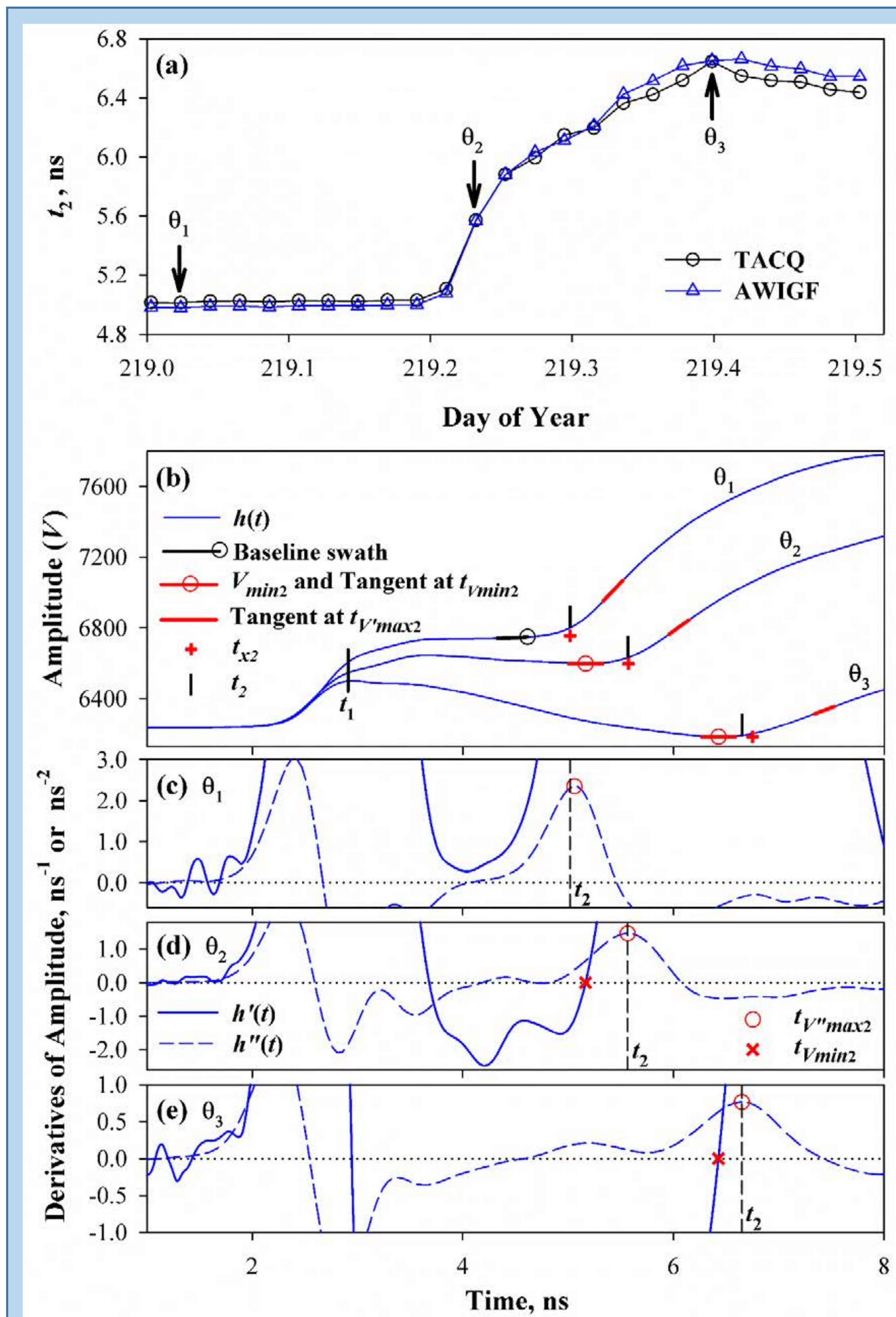


Fig. 2. (a) Measured time, t_2, at the termination of the transmission line determined using TACQ and AWIGF for a TDR probe inserted in an air-dry soil and undergoing wetting and (b) smoothed waveform amplitude traces for three soil water contents (θ_1 = 0.046, θ_2 = 0.091, and θ_3 = 0.175 m^3 m^{-3}). The smoothed first and second derivatives of the waveform amplitudes for the three water contents are shown in (c), (d), and (e). Here, V_{min2} is the local amplitude minimum at t_{Vmin2}, $t_{V'max2}$ is the maximum derivative associated with the second reflection, t_{x2} is the intersection of the AWIGF determined tangents at t_{Vmin2} and $t_{V'max2}$, and $t_{V''max2}$ is the time at the maximum second derivative.

Results

- AWIGF[1] permitted the determination of t_2 without parameter adjustment when loss characteristics of the media changed, such as with an increase in bulk electrical conductivity and soil water content (Figs. 3 and 4, respectively)
- For a given class of pulse generator (e.g. Tektronix 1502C), user intervention and adjustment of waveform interpretation parameters was not required for all test cases examined
- AWIGF had sampling errors of t_2 less than 0.06 ns over a wide range of media properties and less than or equal to that obtained with TACQ (which had a sampling errors of up to an order magnitude greater)

[1]The algorithm AWIGF is written in matlab and available upon request from the author at robert.schwartz@ars.usda.gov or rcschwartz1@gmail.com.