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A TDR-waveform approach to estimate soil water content in electrically conductive soils

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ABSTRACT

Time domain reflectometry (TDR) has been widely used by the scientific community as a reliable method to indirectly measure the volumetric water content (θ) of soils, and in most soils TDR can provide observations of θ at high temporal resolution with acceptable accuracy. This technique induces an electrical wave in waveguides inserted into the soil, estimates the soil bulk dielectric permittivity (ε) based on an interpretation of the reflected electromagnetic signal, and then relates ε with θ. In electrically conductive soils, the reflected signal can be highly attenuated by the effect of the soil's bulk electrical conductivity, resulting in very large errors in the estimation of θ; the traditional TDR methodology is thus subject to large errors and uncertainties. This work presents a simple and empirical waveform interpretation methodology based on variables less sensitive to the soil's electrical conductivity than those used in the traditional TDR methodology. This approach extends the applicability of TDR sensors with reliable and accurate measures of θ, making it possible to more accurately measure soil water contents in settings that have traditionally been difficult to observe, and without modifying the TDR sensors.

1. Introduction

Soil water content refers to the water stored in the soil's unsaturated zone, and is the source of natural water for agriculture and natural vegetation (Dobriyal et al., 2012). It influences many processes related to agricultural production and plant growth (Power, 2010; Lekshmi et al., 2014), as well as a wide range of soil processes (Huang et al., 2010). Water content also affects the physical properties and biological community of the soil, acting as a control on microbial activity and biogeochemical cycling (Robinson et al., 2008). Soil water content also controls several near-surface geophysical processes (Robinson et al., 2003a; Hernández-López et al., 2014). For instance, it influences the energy and water balance of a basin through its effects on evapotranspiration, runoff and soil infiltration, and it is a key driver in both surface and subsurface hydrology and land-atmosphere interactions (Entekhabi et al., 1996). Therefore, accurately measuring and monitoring soil water content at high temporal and spatial scales improves our understanding, management and control of processes that are directly applicable to disciplines as wide-ranging as agriculture, hydrology, mining, geology and environmental engineering.

Soil salinization is a worldwide problem that results in loss of agricultural productivity, which is caused by a combination of factors such as poor land management, removal of trees, and crude irrigation practices (Darwish et al., 2005; Devkota et al., 2015). Typically, in most irrigated and rainfed circumstances the soil bulk electrical conductivity (BEC) does not exceed $\sim 2\ \mathrm{dS\,m^{-1}}$, but in many arid zones it can be higher than $\sim 10\ \mathrm{dS\,m^{-1}}$ (Darwish et al., 2005). Measuring soil water content in saline (or electrically conductive) soils is an important issue for salt-tolerant agricultural operations (Hook et al., 2004), for soil respiration (Yan and Marschner, 2014), and for developing water and salt transport models (Chen et al., 2014).

It is difficult to measure soil water content, especially *in situ*. Most current measurement methods are indirect methods which measure other soil properties (e.g., electrical or thermal properties), and infer a water content from those measurements. Because the observed properties are bulk properties of the soil, indirectly measured water contents are typically volumetric water contents, hereafter be referred to as θ. Detailed discussion of current measurement methods can be found elsewhere (Robinson et al., 2008). Time domain reflectometry (TDR), which infers θ from a reflected electromagnetic wave induced in the soil, is widely

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utilized because it provides good accuracy in a variety of soils, is easy to implement and to calibrate (a standard calibration is sufficient for many soils), provides excellent temporal resolution, and is a relatively non-invasive and non-polluting method (Jones et al., 2002).

In TDR, an electromagnetic pulse is launched through a coaxial cable that ends in a metallic probe embedded in the soil. The waveform, a relationship between reflection coefficient and travel time or apparent distance, is recorded as a series of amplitude values at regularly space time intervals. The waveform is then analyzed to determine the travel time of the pulse along the electrodes surrounded by soil (Schwartz et al., 2014). This travel time is divided by the electric length of the electrodes to obtain the propagation velocity, which is then related to the bulk dielectric permittivity of the medium (ε). The dielectric permittivity can then be related to θ due to the large difference between the permittivity of the air ($\varepsilon_a \approx 1$), the solid phase of the soil ($\varepsilon_s \approx 3$–5), and the water ($\varepsilon_w \approx 80$). Topp et al. (1980) proposed the following third-order polynomial equation to relate θ and ε:

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2}\varepsilon - 5.5 \times 10^{-4}\varepsilon^2 + 4.3 \times 10^{-6}\varepsilon^3 \quad (1)$$

Eq. (1) has errors less than 0.013 $m^3\,m^{-3}$ for a wide range of soils (Jones et al., 2002), although the accuracy of this method is also influenced by probe length (Jones and Or, 2004). Traditional TDR methods infer the value of ε by determining the beginning and the end of the sensor's rods to relate them with the travel time of the electromagnetic pulse. However, as shown below, the detection of the end of the rods is not possible in electrically conductive soils, due to the large attenuation levels of the electromagnetic pulse associated to conductive losses, precluding the use of this methodology on these soils (Mojid et al., 2003; Robinson et al., 2003a,b; Hook et al., 2004; Evett et al., 2005; Friedman, 2005; Schwartz et al., 2014; Lekshmi et al., 2014). Typically, when the BEC exceeds $\sim$3 dS m^{-1}, the errors become large and TDR methods cannot provide accurate volumetric water content estimates (Jones and Or, 2004). Plastic coated rods have been designed to reduce high attenuation levels of the waveform in electrically conductive soils (Nichol et al., 2002). But it has been shown that the coat break easily when inserting the TDR probe (Chen et al., 2014), and also affects the frequency dependence of the electric field at the interface between the media and coating material, deteriorating the measurements' accuracy (Richert, 2009). Therefore, many TDR methods are thus limited to soils with bulk electrical conductivity values up to $\sim$5 dS m^{-1} in the best case of short and high-frequency sensors (Blonquist et al., 2005). Even more, these sensors are not only affected by salinity but also by other factors such as temperature (Wraith and Or, 1999; Evett et al., 2005) and mineralogy (Regalado et al., 2003), highlighting the need for individual calibrations of the ε–θ relationship to correct for these factors.

To address the effect of electrical conductivity of the media, current TDR sensors simultaneously measure the BEC and ε, making it possible to include the BEC in new models to estimate θ, and to quantify dielectric losses to improve ε measurements (Bittelli et al., 2008). Schwartz et al. (2014) developed an adaptive-waveform interpretation that reduces the impact of signal noise and attenuation due to changes in θ or BEC without the need for user-parameters adjustment. This approach is useful when analyzing large time series, where the soil conditions may change considerably, but the method did not extend the electrical conductivity range in which the sensor can operate correctly. Frequency domain analysis has been used to extend TDR volumetric water content measurements in highly saline soils (Heimovaara, 1994; Hook et al., 2004; Jones and Or, 2004). For instance, Jones and Or (2004) extended the permittivity range in highly saline soils using Discrete Fast Fourier Transformation and two approaches to interpret the waveform data: a scatter function and a resonant frequency analysis. Chen et al. (2007) proposed the surface reflection coefficients method to measure water content in soils with high electrical conductivity by taking into account the information related to the electromagnetic wave reflection at the soil surface. Time domain transmission (TDT), which is analogous to TDR, has been utilized to investigate the effects of salinity on the accuracy and uncertainty of volumetric water content measurements (Hook et al., 2004). Hook et al. (2004) concluded that investigations using conventional TDR instruments could not obtain reliable data at high levels of salinity because of the poorer signal-to-noise ratio of such instruments and the interference of multiple reflections characteristic of TDR techniques. Hook et al. (2004) also found that the variability of the travel time of a TDT pulse increased with the pore water salinity. This result suggests that it would be very difficult to construct a simple and unique correction for the effects of salinity on the measurement of volumetric water content. In particular, to determine θ from ε measurements in electrically conductive (or saline) soils, the analysis should consider the losses that give rise to the imaginary component of the dielectric permittivity (Hook et al., 2004; Robinson et al., 2008). Hence, such analysis has to consider both the real and imaginary parts of the dielectric permittivity (Hook et al., 2004), which is a difficult undertaking and is beyond the scope of this paper.

This work presents an approach that can be used to extend the electrical conductivity operation range of TDR without modifying the probes. Here, we show that when an electromagnetic pulse is attenuated, accurate estimates of θ can still be obtained by identifying new aspects of the TDR waveform without including the point at the end of the sensor's rods, and without explicitly determining the permittivity of the media. Although developing a unique relationship to correct for the effects of salinity on the measurements of θ would be very difficult as the variability of the travel time of an electromagnetic pulse increases as soil salinity increases (Hook et al., 2004; Schwartz et al., 2014), there are other aspects to the TDR waveform that have not to date been examined. Thus, the objective of this work is to develop a simple and empirical methodology for determining θ based on a new dimensionless waveform interpretation that uses variables other than those commonly considered by current methods.

2. Materials and methods

2.1. Traditional analysis of the TDR waveform

Conventional TDR analysis utilizes a relationship between ε and θ based on the effective travel time of an electromagnetic pulse through a probe embedded in the soil. The theoretical travel time of a TDR-generated electromagnetic pulse to cross the probe can be expressed as (Topp et al., 1980; Jones et al., 2002):

$$t = \frac{2L\sqrt{\varepsilon}}{c} \quad (2)$$

where L is the length of the probe's waveguides; t is the travel time for the pulse to traverse the length of the probe (down and back: $2L$); and c (=3 × 10^8 m s^{-1}) is the electromagnetic pulse velocity in vacuum. Note however that the travel time of the electromagnetic pulse must be evaluated not based on the measured length of the waveguides (L), but on their electrical length, also known as the apparent length (L_a). The L_a is based on travel time measurements in a material of known permittivity, e.g., water of known temperature. To estimate L_a, TDR systems determine a relationship between the amplitude (V_1) of the electromagnetic signal after partial reflection along a transmission line as function of time, and the