On the Effectiveness of GPR Early-time Analysis for Mapping Soil Water Content

Remke L. Van Dam*, CEFET-MG, PPG Civil Engineering, Belo Horizonte, Brazil
Jonathan Algeo, Rutgers University Newark, Earth & Environmental Sciences, Newark, NJ, United States
Lee D. Slater, Rutgers University Newark, Earth & Environmental Sciences, Newark, NJ, United States
Andrew M. Binley, University of Lancaster, Lancaster, United Kingdom
Christopher W. Watts, Rothamsted Research, Harpenden, United Kingdom

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Abstract

Ground-penetrating radar (GPR) early-time signal (ETS) analysis is a recently proposed method for assessment of the very near-surface. It uses the frequency and amplitude characteristics of the direct air- and ground-waves of bi-static antenna systems, which have been shown to be correlated with soil dielectric properties.

To study the effects of antenna frequency and processing methodology on the method's effectiveness for soil moisture mapping, we carried out a controlled irrigation experiment at a field site in the United Kingdom, and collected time-lapse GPR along a transect to monitor changes in dielectric properties. To corroborate our results, we collected time-lapse electrical resistivity tomography (ERT) data and soil cores.

All collected data, including data from three GPR antenna frequencies, show clear soil wetting in response to the irrigation. Our results show that the ETS carrier frequency amplitude (CFA) has a deeper depth-of-investigation than the more commonly used average envelope amplitude (AEA). Also, where typically the first positive half cycle has been taken as the de-facto ETS, our results show that a different time window may produce better results.

Introduction

Soil moisture is a critical variable in many environmental, ecology, and engineering fields. Its spatial distribution and temporal changes are typically measured using in-situ point sensors or remote sensing, which have several limitations. In contrast, geophysical methods allow for non-invasive insight into near-surface conditions and processes over a wider range of scales and have become increasingly common for soil moisture mapping and monitoring (Binley et al., 2015).

Among geophysical tools, ground-penetrating radar (GPR) is well suited for mapping and monitoring soil moisture, because propagation and reflection of the electromagnetic (EM) signals depend on dielectric properties of the soil. These dielectric properties, in turn, are governed by textural properties and water content.

Most GPR applications use systems with two antennas in the frequency range of around 0.1 to 1 GHz. Common approaches for measuring soil moisture with GPR either use the arrival time of the transmitted signal from a reflector at known depth, or the travel time of the direct ground wave between two antennas spaced at a distance where it has separated from the direct air wave (Huisman et al., 2003). In both cases, the travel time is first converted to signal velocity and relative permittivity, and then to soil moisture content using a pedotransfer function or mixing model (e.g., Van Dam, 2014).

Recently, it has been observed that some characteristics of the overlapping direct air- and ground-waves of closely spaced bi-static antennas also correlate with dielectric properties of the material. These signal characteristics include signal amplitude and wavelength (e.g., Sbartaï et al., 2006) and more complex attributes such as the instantaneous amplitude (Pettinelli et al., 2007) and so-called carrier frequency amplitude (Comite et al., 2016).

The depth-of-investigation (DOI) of this early-time signal (ETS) is proportional to the wavelength of the signal, which varies with soil dielectric properties. Most available models and experimental data predict a DOI of ¾ wavelength or less (e.g., Grote et al., 2010; Pettinelli et al., 2014).

Compared to traditional approaches for soil moisture assessment using GPR, ETS analysis has some distinct benefits, including the ability to use shielded antenna pairs. Additionally, the ETS method allows for soil moisture assessment in clay-rich soils where signal attenuation typically limits the usefulness of GPR (Algeo et al., 2016).

ETS analysis being relatively new, there are still various unanswered questions about the method. Here we study the effects of GPR signal frequency, different signal attributes, and processing on the ETS method's effectiveness for field-scale soil moisture mapping.

Method

We carried out a controlled irrigation experiment at a field site with loamy sand in Woburn, Bedfordshire, UK, and collected time-lapse GPR to monitor changes in dielectric properties. To corroborate our results of soil moisture changes with depth and time, we collected time-lapse electrical resistivity tomography (ERT) data and repeated soil cores for soil gravimetric samples at different depths.

The infiltration experiment was carried out over an area of 5 x 3 m, centered on a 16-m long transect for time-lapse geophysical measurements. The site was wetted incrementally, to gradually increase near-surface moisture content. Geophysical measurements were conducted prior to irrigation, and following each of the wetting events. GPR measurements were conducted using 200 MHz, 400 MHz, and 1 GHz bi-static antennas from Groundvue. The ERT measurements were conducted using an IRIS Syscal Pro system with electrodes spaced at 32 cm. One continuous soil core was taken following each wetting event, and sampled at 10 cm increments.

Our GPR ETS analysis focused on the effect of GPR signal frequency and on two ETS attributes:

Average Envelope Amplitude (AEA) – The AEA attribute is obtained using a Hilbert transform of the selected portion of the trace (usually the first positive half-cycle), and has been successfully used in several research studies (e.g., Pettinelli et al. 2007; Di Matteo et al., 2013; Algeo et al., 2016). The result is typically given as AEA^{-1}, which correlates positively with soil water content.

Carrier Frequency Amplitude (CFA) – The CFA is a recently proposed attribute to extend ETS water content estimates more reliably across a wider range of soil types and saturation levels (Comite et al., 2016). It is obtained using a Fast Fourier transform (FFT) of the selected portion of the trace and has an inverse correlation with soil water content.

Results

Wetting of the soil in response to the incremental irrigation was successfully visualized using difference inversions of time-lapse ERT data (Figure 1). The soil core data confirmed that the gravimetric water content near the surface increased from 5% to 15% due to the irrigation and that the wetting front reached a depth of approximately 50 cm in 3 hours.

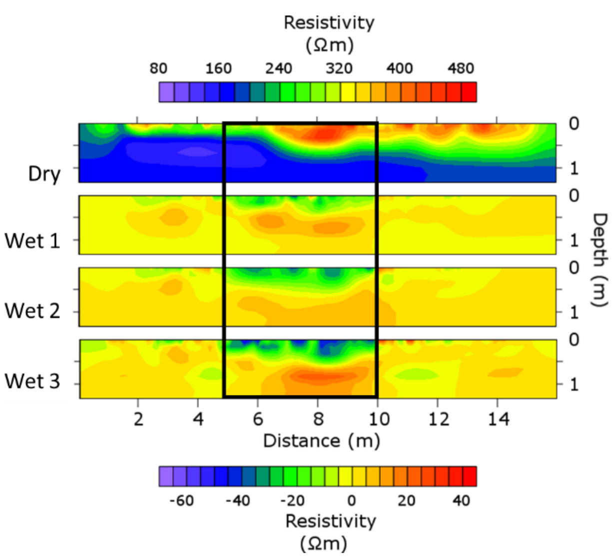

Figure 1. *Results of ERT inversions for data collected on July 26, 2016. The top panel shows the background dataset, collected before irrigation. The lower three panels show the difference inversions for three incremental wetting events, where the color scale gives the change in resistivity relative to the background dataset. The black box represents the irrigated zone.*

The GPR ETS results, comparing the AEA^{-1} and CFA signal attributes are shown in Figure 2. For both attributes, at low frequencies, the lateral variation of normalized amplitude values displays a smoother behavior, reflecting the larger area of influence for the longer wavelengths and further spaced antennas as compared to higher frequency antennas.

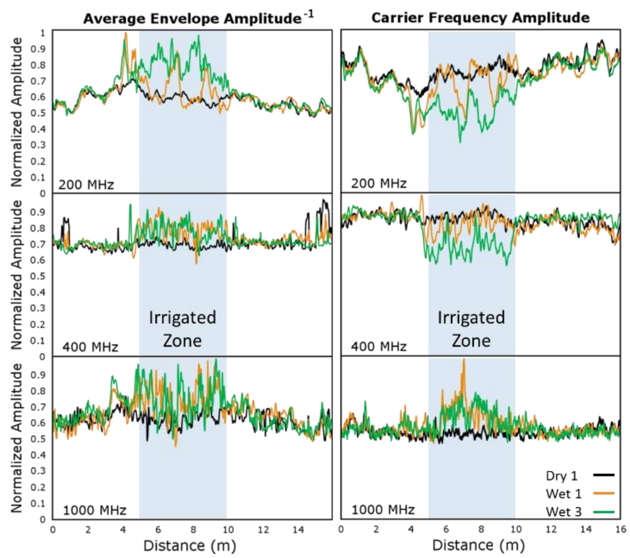

Figure 2. *Results of GPR ETS analysis for different antenna frequencies and wetness conditions on July 26, 2016. Dry 1 is the background measurement; Wet 1 and Wet 3 were collected following the first and third incremental irrigation event, respectively. The AEA^{-1} attribute is shown on the left; the CFA attribute is shown on the right. ETS analysis used the first positive half cycle of each trace.*

The AEA^{-1} attribute displays a positive correlation with wetting, as expected. Only the 200 MHz antenna clearly shows the increased soil wetness after the third irrigation event. The two higher frequencies display a similar variability in normalized amplitude values between the first and third wetting event. This suggests that the depth-of-investigation of the 400 MHz and 1 GHz signal is too small to record the increased depth of the wetting font.

The CFA attribute displays a negative correlation with wetting, as expected, but only for the 200 and 400 MHz antennas. Both frequencies show an increased wetness after the third irrigation event. This suggests that the CFA attribute allows for a greater DOI than the AEA^{-1} attribute, where only the 200 MHz antenna recorded the increased and deeper wetting.

The CFA result for the 1 GHz antenna is unexpected, because the correlation with water content is positive. Further analysis of the 1 GHz data shows that the length and position of the time window used for ETS analysis influences the results (Figure 3). While the first one-third of the first positive half cycle gives the expected correlation for both AEA and CFA attributes, the last one-third produces the reverse effect for the CFA attribute (for the AEA attribute there is no correlation). ETS analysis for the second one-third of the first positive half cycle displayed no correlation with either the AEA and CFA attributes. The reverse correlation for the CFA attribute at the last one-third of the first positive half cycle is possibly due to interference with the infiltrating water from each most recent wetting event, but the exact cause has not been determined.

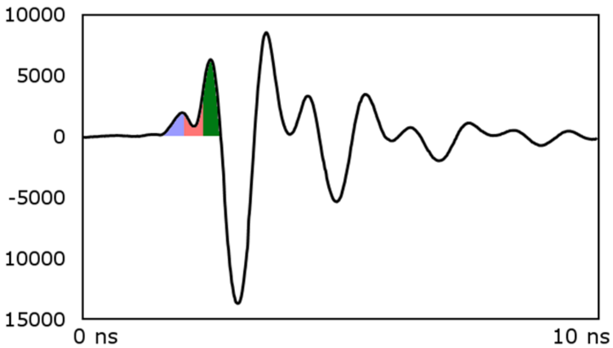

Figure 3. *1 GHz GPR trace with three equal portions of the first positive half cycle highlighted.*

Conclusions

An irrigation experiment was conducted to study the effects of signal frequency and processing method on the effectiveness of ETS analysis to map soil moisture content in field soils.

The GPR ETS data generally vary according to the expected relationships, where the lower antenna frequencies produce smoother results and allow recording of the increased penetration of the wetting front.

The CFA attribute is shown to have a greater depth-of-investigation than the more commonly used AEA attribute. Also, where the first positive half cycle of each trace is typically used for ETS analysis, our results show that a shorter time window may produce better results.

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