Clay content and soil moisture mapping using on-ground time-domain GPR

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Abstract

In this research we proposed a new approach to estimate the soil electrical conductivity using direct ground wave recorded by on-ground time-domain GPR. In order to map the field-scale soil water and clay content, we used GPR in bistatic mode in a ~5 ha agricultural field located in Luxembourg for two different weather conditions. Soil core sampling provided the ground-truth partly entire the field with different depths from surface up to 40 cm. We used the phase and amplitude of the direct ground wave signal to retrieve the shallow soil dielectric permittivity and electrical conductivity. Topp's model was applied to convert the soil dielectric permittivity to soil moisture. Then, the aggregate conductivity was derived using the linear and quadratic parallel models. The linear relationship between aggregate conductivity and measured clay content was figured out. The results showed a good agreement for soil moisture and clay content maps and led to 1.2% standard deviation of clay content entire the field.

Keywords: ground penetrating radar, direct ground wave, clay content mapping.

Introduction

Mapping the soil properties such as moisture and clay content with high spatial resolution is essential in agricultur. Surface water content is a key variable to estimate the water and energy fluxes at the land surface. Clay is another fundamentally important substance in soils. In fact, the movement of water within and through the soil and its availability to plants are greatly influenced by the clay content. Soil sampling is common method used to characterize clay content and as well for soil water content at the point scale. Generally this method is restricted to small observation areas and is tedious, and time-consuming.

The electromagnetic tools such as ground-penetrating radar (GPR), electromagnetic induction (EMI), and time domain reflectometery (TDR) have promising potential to estimate the shallow soil electromagnetic properties. In that case, GPR is more suitable to be used as a rapid and non-invasive tool for mapping the electromagnetic soil properties at the field scale with high spatial resolution.

In this paper, the ability of on-ground time-domain GPR for mapping the soil moisture is evaluated. Also a new approach for retrieving soil electrical conductivity using this system is proposed. Finally the petrophysical relationship between clay content and aggregate conductivity are investigated.

In order to map the soil water and clay content, we used the GPR in bistatic mode at the field-scale while soil core sampling provided the reference measurements, at different depths. We used both phase and amplitude of the radar signal focusing on direct ground wave to retrieve the shallow soil dielectric permittivity and electrical conductivity. The Topp model was used to convert soil dielectric permittivity to soil moisture. Using the aggregate conductivity derived by linear and quadratic parallel models led to find the linear relationship with measured clay content. Finally The Kriging interpolation was used to map the soil moisture and clay content.

Materials and methods

The study site. A ~5 ha agricultural field located in the Oësling hills in north part of Grand Duchy of Luxembourg with a mean altitude of 450 m was swept in September 2010. Soil core sampling was performed in 0-10, 10-20, 20-30, and 30-40 cm depths at 30 points entire the field. All the soil samples were used for ground-truth of volumetric water content and only 0-10 and 20-30 cm soil samples were analyzed for clay content because of the costs.

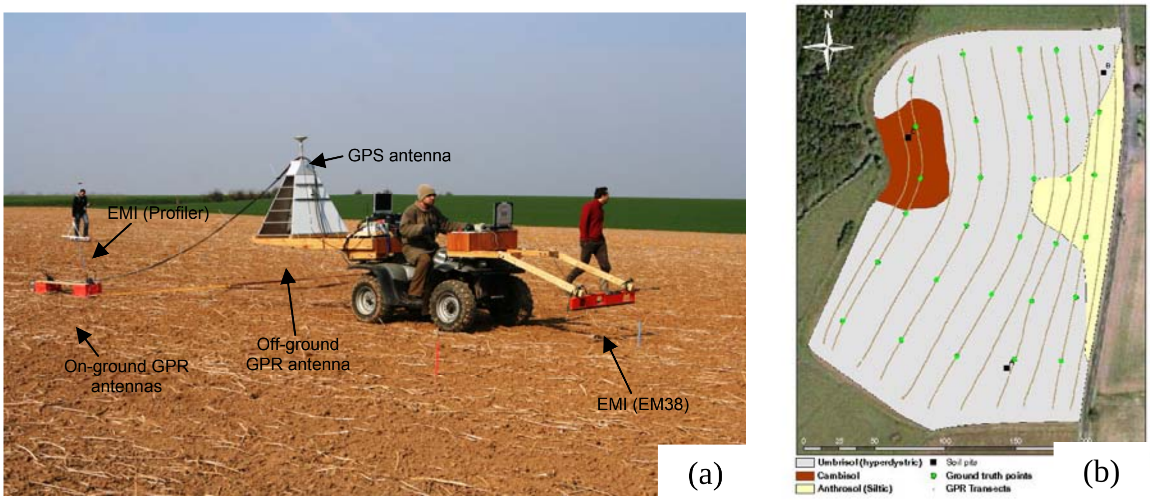

Figure 1: Equipments (a) and the study field profile (b).

Instrumentation. We used a time-domain GPR system equipped with two transmitting (Tx) and receiving (Rx) 400 MHz bow-tie antennas with Tx and Rx offsets of 0.15 and 1.1 m, respectively, thereby setting up a multi-offset system. The different gain functions for each channel were enabled in 5 points in order to use the maximum capacity of radar dynamic range. Time window was limited up to 50 ns for each channel. A dGPS receiver and survey wheel were used for positioning (see Figure 1a). The instruments were mounted on a mobile platform and eleven transects were followed entire the field by N-S orientation. In order to avoid the non-desired signals, the GPR antennas were situated about 5 m apart from the platform.

Measurements were performed in both relatively dry and wet conditions (after a precipitation event). Each profile was completely performed by a person for less than one hour.

The approach description. In this work, we present an approach similar to the single trace analysis (STA) method to retrieve the soil permittivity and a new approach to estimate the soil electrical conductivity using the radar signal amplitude.

The Tx sends a Riker-type pulse to the ground and the reflected or propagated pulses are recorded by Rx of channel 1 and Rx of channel 2 (see figure 2). The strongest pulse recorded by channel 1 is the combination of the direct Tx-Rx coupling and DGW (crossing the ground from Tx-channel 1 to Rx-channel 1). Also because of the antenna electrical shields and contact with the ground, the strongest pulse recorded by channel 2 is DGW from Tx-channel 1 to Rx-channel 2. The delay between highest picks of the signals of channel 1 and channel 2 is related to the averaged dielectric permittivity of a portion of ground which is situated between antennas (assuming that the ground is homogeneous). Equation 1 illustrates the relative dielectric permittivity (ε_r) of ground as a function of Δt (propagation time) and Δx (Tx-Rx offset) where c is the speed of the light in free space.

$$\varepsilon_r = (c.\frac{\Delta t}{\Delta x})^2 \qquad (1)$$

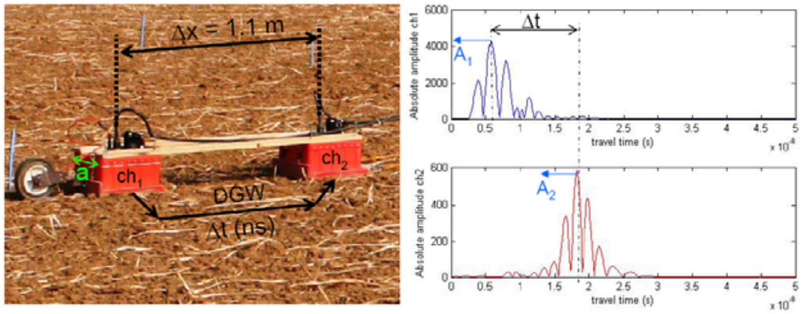

Figure 2: Bistatic radar antenna was used for detecting DGW.

In order to estimate the soil electrical conductivity we assumed the simple TEM wave propagation equation in a homogeneous medium illustrated in Equation (2) only for x-directed electric field:

$$E_x = E_{x0} e^{-\alpha z} \cos(\omega t - \beta z) \tag{2}$$

Where E_x is the electric field, E_{x0} is the excitation field, α is the medium losses factor, z is the propagated distance from the source, ω being the angular frequency of source, and β is the phase factor. As it is well-known, the medium losses factor, α, is a function of electromagnetic properties such as permittivity, permeability, and specially conductivity. Equation (3) illustrates the inversed relationship of σ and α as a function of frequency.

$$\sigma = \omega\varepsilon \sqrt{\left(\frac{2(\frac{\alpha}{\omega})^2}{\mu\varepsilon} + 1\right)^2 - 1} \tag{3}$$

In order to calculate α, we should find the consequent peaks for Equation (2) when $cos(\omega t\text{-}\beta z)$ equals 1. As shown in Figure 2, the amplitude of signals at the determined times are the desired points (A_1 and A_2). It is worth noting that the TEM signal is radiated from Tx-channel 1 following a 3-dimentional radiation pattern, and Rx-channel 2 will receive only a portion of energy. Equation 4 calculates α as a function of A_1, A_2, Δx_1 and Δx_2 for a multi-offset system where Δx_1 and Δx_2 are Tx-Rx_1 and Tx-Rx_2 offsets, respectively.

$$\alpha = \frac{-1}{\Delta x_2 - \Delta x_1} \ln\left(\frac{A_2}{A_1}\sqrt{\frac{\Delta x_2}{\Delta x_1}}\right) \tag{4}$$

Results and discussion

Soil moisture maps. Figure 3 shows the dry and wet θ-maps with same colour-scales. Both maps are relatively consistent but comparison with ground-truths showed different penetration depth for DGW which is dependent to the soil moisture (results are not presented). For instance the best retrieved penetration depth for dry-land is about 30 cm and for wet-land is about 10 cm which is logical having less penetration in wet land.

Clay content map. Following the presented procedure for calculating electrical conductivity, we estimated the effective conductivity entire the filed exactly at the same depth as the derived water content. To extract the aggregate conductivity from effective conductivity, we used two well-known models namely quadratic parallel and linear models (Tabbagh 2006) represented in Equations (5) and (6), respectively:

$$\sqrt{\sigma_e} = \theta\sqrt{\sigma_w} + (1-\theta)\sqrt{\sigma_{ag}} \tag{5}$$

$$\sigma_e = \theta\sigma_w + (1-\theta)\sigma_{ag} \tag{6}$$

Where σ_e is the effective electrical conductivity derived by GPR, σ_w is the electrolyte conductivity which here was assumed equal to 0.05 S/m, σ_{ag} is the aggregate conductivity, and θ is volumetric water content also derived by GPR. Logically there should be relationship between the aggregate electrical conductivity and hydraulic conductivity which is dependent of the capillary size and therefore dependent of the aggregate size, *i.e.*, there should be relationship between aggregate conductivity and clay content. We assumed a linear relationship between clay content and aggregate conductivity illustrated in Equation (7):

$$C_{clay} = a.\sigma_{ag} + b \tag{7}$$

Where C_{clay} is clay content expressed in percentage. Figure 4 shows a good agreement for this equation to the estimated σ_{ag} and C_{clay} ground-truths. Also the plot shows no benefit to use linear- or quadratic parallel-model for cancelling the electrolyte conductivity.

Conclusions

In this paper the ability of on-ground time-domain GPR for mapping water and clay contents was investigated. For this case, measurements were performed in a ~5 ha agricultural field. The STA for DGW helped to retrieve soil dielectric permittivity and using the signal amplitude led to estimate soil electrical conductivity. Results showed consistent maps for soil moisture with different penetration depths dependent to the land moisture. In order to estimate the clay content, a linear relationship between clay content and aggregate conductivity was figured out.

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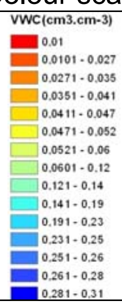
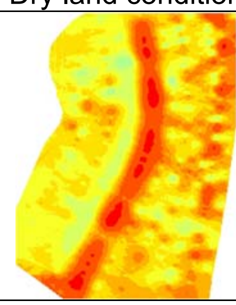
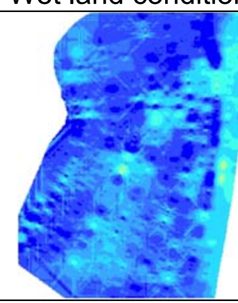
<tr><td>
</td><td></td><td></td></tr>
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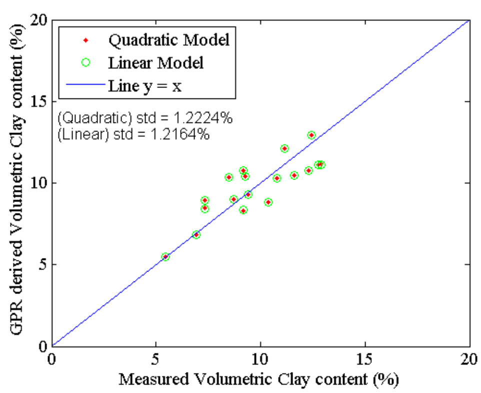
Figure 3: Soil moisture maps derived by on-ground GPR using STA for dry- and wet-weather conditions.



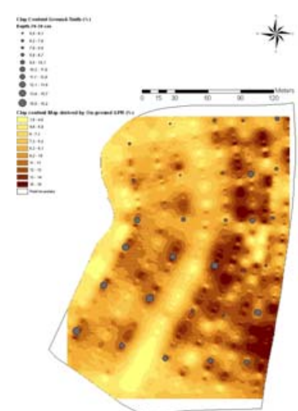


Figure 4: GPR derived volumetric clay contents versus ground-truths.

Acknowledgements

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