Geoderma 161 (2011) 225–237

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Mapping shallow soil moisture profiles at the field scale using full-waveform inversion of ground penetrating radar data

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ARTICLE INFO

Article history:
Received 17 February 2010
Received in revised form 18 October 2010
Accepted 26 December 2010
Available online 31 January 2011

Keywords:
Ground penetrating radar
Soil moisture
Digital soil mapping
Layered media

ABSTRACT

Full-waveform inversions were applied to retrieve surface, two-layered and continuous soil moisture profiles from ground penetrating radar (GPR) data acquired in an 11-ha agricultural field situated in the loess belt area in central Belgium. The radar system consisted of a vector network analyzer combined with an off-ground horn antenna operating in the frequency range 200–2000 MHz. The GPR system was computer controlled and synchronized with a differential GPS for real-time data acquisition. Several inversion strategies were also tested using numerical experiments, which in particular demonstrated the potentiality to reconstruct simplified two-layered configurations from more complex, continuous dielectric profiles as prevalent in the environment. The surface soil moisture map obtained assuming a one-layered model showed a global moisture pattern mainly explained by the topography while local moisture patterns indicated a line effect. Two-layered and profile inversions provided consistent estimates with respect to each other and field observations, showing significant moisture increases with depth. However, some discrepancies were observed between the measured and modeled GPR data in the higher frequency ranges, mainly due to surface roughness effects which were not accounted for. The proposed GPR method and inversion strategies showed great promise for high-resolution, real-time mapping of soil moisture at the field scale.

1. Introduction

Soil moisture dynamics is a key component in many researches and applications like precision agriculture, hydrological studies, meteorological and climatological modeling and other environmental studies. In hydrology, soil moisture is a highly sensitive state-variable in runoff, solute transport, evaporation and erosion processes, as it governs the partitioning between runoff and infiltration, and reducing its uncertainty largely improves modeling precision (Zehe et al., 2005). In global circulation models, soil moisture largely controls the energy fluxes between the land surface and the atmosphere (Schumann et al., 2009).

Recent developments in microwave remote sensing of surface soil moisture bring increasing opportunities for extensive soil moisture characterization at different spatial and temporal scales, as new remote sensing data products (e.g., from SMOS and SMAP) become available (Wagner et al., 2007). Nevertheless, a poor agreement still exists between remote sensing derived soil moisture and ground-truth measurements (i.e., gravimetric sampling, time domain reflectometry measurements). Ground-based soil moisture measurement techniques may fail to match the remote sensing retrievals as a result of the different support scales of the techniques, particularly with respect to the depth of characterization, as it was stated by Stevens et al. (2008). In addition, the inherent large spatial variability of soil moisture within a remote sensing pixel implies that a large number of ground measurements must be collected to adequately compare the data. Hence, no absolute relation between the backscattered signals from remote sensing sensors and the surface soil moisture exists, necessitating site-specific calibrations (D'Urso and Minacapilli, 2006; Verhoest et al., 2008).

Furthermore, the value of remotely-sensed surface soil moisture may be limited by a lack of correlation between surface and subsurface soil moisture (Vereecken et al., 2008). As it is directly exposed to atmospheric forcing, surface soil moisture dynamics is a lot more active than subsurface soil moisture. A physical decoupling between surface and subsurface soil moisture may occur considering a wet soil subject to fast evaporation or the propagation of a wetting front in a dry soil, especially in coarse materials. In addition, pedogenetic processes and agricultural practices may lead to vertically-varying soil moisture conditions, according to the different soil layer properties (Schaap et al., 2003). Surface soil moisture may therefore fail to reflect soil moisture conditions in the subsurface that are actually of interest for a lot of processes (Capehart and Carlson, 1997). Some studies have addressed this issue in remote sensing acquisition, using transfer functions based on statistical relationships or physically-based hydrodynamic models to relate the soil moisture profile to the

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0016-7061/$ – see front matter
doi:10.1016/j.geoderma.2010.12.023

remotely-sensed surface soil moisture (Ceballos et al., 2005; Wagner et al., 1999). Nevertheless, soil moisture profile information cannot be inherently inferred from the single-frequency satellite sensors.

In that respect, ground penetrating radar (GPR) has shown further potentialities to increase the extraction of information about surface and subsurface soil moisture (Doolittle et al., 2006; Galagedara et al., 2005; Huisman et al., 2003; Lambot et al., 2008a; Lunt et al., 2005; Serbin and Or, 2005). Characterization of soil moisture in multilayered media using inversion of GPR data was performed by Lambot et al. (2004b), Strobbia and Cassiani (2007) and van der Kruk (2006). In particular, borehole GPR applications can accurately reconstruct 2-D images (tomograms) of the complete soil moisture profile between borehole locations (Binley et al., 2001; Looms et al., 2008), but these techniques remain limited at small-scale (a few meters) studies, as it requires the installation of vertical wells into the soil. Hence, although they showed a good accuracy (e.g., van der Kruk, 2006), these techniques remain largely cumbersome and time-consuming, hampering for the mapping of large areas. Surface soil moisture determination by the surface reflection coefficient method, using off-ground GPR antennas, have shown a potential for proximal soil moisture sensing at a much larger scale compared to the borehole methods (Redman et al., 2002; Serbin and Or, 2003, 2005). However, this method still remains unused in real field applications due to several practical and theoretical limitations. A more practical and accurate GPR approach for mapping surface soil moisture at the field scale is the one developed by Lambot et al. (2004b), which is based on off-ground, zero-offset GPR and full-waveform inverse modeling. Owing to an accurate radar model that accounts for three dimensional wave propagation, antenna effects and antenna-soil interactions, information retrieval from the radar data is inherently maximized in terms of quantity and accuracy. Specific inversion strategies have been developed for the retrieval of soil surface dielectric permittivity and correlated water content (Lambot et al., 2006b) and have been applied to field data (Lambot et al., 2008b). This advanced GPR approach provides high-resolution soil moisture maps at the field scale, thereby bridging the scale gap between small-scale invasive measurement techniques and spaceborne sensors.

Following Lambot et al. (2004b) and Minet et al. (2010), we propose to investigate the retrieval of soil moisture vertical profiles by full-waveform inversion of GPR data acquired in an 11-ha agricultural field. The field was situated in the loess belt region in central Belgium (Walhain), consisting mainly of loamy soils. Soil moisture conditions were described by three models, i.e., a one-layered, a two-layered and a continuously-variable profile model. Numerical experiments are first presented, that evaluate GPR inversions assuming the two-layered soil model facing continuous soil moisture profile conditions. Then, GPR inversions of the field data were performed with the three models, the two-layered and profile inversions being limited to some parts of the field where specific profile conditions were observed. The surface soil moisture map from the one-layered inversion is presented and interpreted in the light of in-situ observations. Soil moisture maps from two-layered and profile inversions are compared, as well as soil moisture profiles. Finally, the errors of the approach with respect to the field conditions are discussed.

2. GPR forward and inverse modeling

2.1. GPR system modeling

GPR is based on the propagation of an electromagnetic wave into the ground, which is governed by its electromagnetic parameters, i.e., the dielectric permittivity ε, the electrical conductivity σ and the magnetic permeability μ. As the dielectric permittivity of water ($\varepsilon_w \approx 80$) is much larger than the one of the soil particles ($\varepsilon_s \approx 5$) and air ($\varepsilon_a = 1$), the GPR wave propagation in the soil is principally determined by its water content.

Following Lambot et al. (2004b, 2006b), the GPR system was set up with a vector network analyzer (VNA) connected to an ultra wideband monostatic horn antenna situated off the ground. The VNA emulates a stepped-frequency continuous wave radar, that is, the GPR measurements are performed in the frequency domain. For this configuration, all antenna effects can be filtered out using the following equation where the GPR antenna is modeled as a linear system (Lambot et al., 2004b):

$$S_{11}(\omega) = H_i(\omega) + \frac{H(\omega)G_{xx}^{\uparrow}(\omega)}{1 - H_f(\omega)G_{xx}^{\uparrow}(\omega)} \quad (1)$$

where $S_{11}(\omega)$ is the quantity measured by the VNA, $H_i(\omega)$ is the antenna return loss, $H(\omega)$ is the antenna transmitting–receiving transfer function, $H_f(\omega)$ is the antenna feedback loss, $G_{xx}^{\uparrow}(\omega)$ is the transfer function of the air-subsurface system, the so-called Green's function, and ω is the angular frequency. A specific calibration of the radar antenna permits to determine the three frequency-dependent transfer functions $H_i(\omega)$, $H(\omega)$, $H_f(\omega)$ and thus to obtain the $G_{xx}^{\uparrow}(\omega)$ from the raw measurements $S_{11}(\omega)$.

The electromagnetic model calculating the Green's function simulates the response of the soil illuminated by the GPR antenna, depending on the soil electromagnetic properties. It represents an exact solution of the 3-D Maxwell's equations for electromagnetic wave propagation in a multilayered medium. The consideration of a 3-D model is essential to take into account spherical divergence (geometric spreading) in wave propagation. The soil can be discretized in multiple layers with homogeneous electromagnetic properties, i.e., the dielectric permittivity ε, the electrical conductivity σ and the thickness of each layer h. A continuously variable medium can be modeled using layer thicknesses that are smaller than one tenth the wavelength. The reader is referred to Lambot et al. (2004b, 2006b) for additional details on this model.

2.2. Petrophysical relationships

In this study, the petrophysical relationships between the soil moisture and its electromagnetic properties are described, respectively, by (1) the model of Ledieu et al. (1986) to derive the volumetric soil moisture θ from the relative dielectric permittivity ε_r:

$$\theta = a\sqrt{\varepsilon_r} + b \quad (2)$$

with $a = 0.1264$ and $b = -0.1933$ for a specific soil, and by (2) the model of Rhoades et al. (1976) to relate the soil electrical conductivity σ to the soil moisture:

$$\sigma = \left(c\theta^2 + d\theta\right)\sigma_w + \sigma_s \quad (3)$$

where the parameters were set to $c = 1.85$, $d = 3.85 \times 10^{-2}$, $\sigma_w = 0.075\ \mathrm{Sm}^{-1}$ and $\sigma_s = 5.89 \times 10^{-4}\ \mathrm{Sm}^{-1}$. These parameters were determined in the laboratory for a specific soil subject to different water contents and salinities. Both dielectric permittivity and electrical conductivity are thus related to the soil moisture by these specific relationships throughout all the study. The petrophysical relationship of Ledieu et al. (1986) was chosen for its simplicity in the development of Eq. (6). It is worth noting that the soil specific parameters in Eqs. (2) and (3) may actually vary within the field depending on soil texture and structure variations. However, the $\theta - \varepsilon$ relationship variation is expected to be relatively small due to the very strong correlation between these two variables and, as discussed below, σ has a small effect on the estimation of the soil surface dielectric permittivity. The assumptions made for these petrophysical relationships are therefore expected not to affect our results.