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Validation of ground penetrating radar full-waveform inversion for field scale soil moisture mapping

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SUMMARY

Ground penetrating radar (GPR) is an efficient method for soil moisture mapping at the field scale, bridging the scale gap between small-scale invasive sensors and large-scale remote sensing instruments. Nevertheless, commonly-used GPR approaches for soil moisture characterization suffer from several limitations and the determination of the uncertainties in GPR soil moisture sensing has been poorly addressed. Herein, we used a proximal GPR method based on full-waveform inversion of ultra-wideband radar data for mapping soil moisture and we evaluated uncertainties in the soil moisture maps by three methods. First, GPR-derived soil moisture uncertainties were computed from GPR data inversions, according to measurements and modeling errors, and to the sensitivity of the electromagnetic model to soil moisture. Second, the repeatability of soil moisture mapping was evaluated. Third, GPR-derived soil moisture was compared with ground-truth measurements (soil core sampling). The proposed GPR method appeared to be highly precise and accurate, with a spatially averaged GPR inversion uncertainty of 0.0039 $m^3 m^{-3}$, a repetition uncertainty of 0.0169 $m^3 m^{-3}$, and an uncertainty of 0.0233 $m^3 m^{-3}$ when compared with ground-truth measurements. These uncertainties were mapped and appeared to be related to some local model inadequacies and to small-scale variability of soil moisture. In a soil moisture mapping framework, the interpolation was found to be the main source of the observed uncertainties. The proposed GPR method was proven to be largely reliable in terms of accuracy and precision and appeared to be highly efficient for soil moisture mapping at the field scale.

1. Introduction

The importance of accurate soil moisture characterization at various temporal and spatial scales for hydrologic, climatic, and agriculture applications has boosted the development of different soil moisture sensing techniques. Reviews of soil moisture measurement techniques, including descriptions of the sensors, applications, and research outlooks are given by Robinson et al. (2008a,b), and Vereecken et al. (2008). The development of soil moisture remote sensing technologies in recent years (Wagner et al., 2007) offers new opportunities for hydrological applications, as soil moisture data covering large areas become available. At much smaller scales, in situ sensors such as time domain reflectometry (TDR) and capacitance probes are revealing their best potential in recently deployed wireless sensors networks (Bogena et al., 2010), which allow for collection of huge amounts of soil moisture data at an unprecedented temporal resolution. Nevertheless, the small sampling volume of these invasive sensors (∼dm) can be hardly compared with the larger footprint of remote sensing instruments, even for high-resolution active radar sensors (∼10 m), given the inherent high spatial variability of soil moisture at the radar footprint scale.

With an intermediate support scale (∼m), ground penetrating radar (GPR) for soil moisture sensing may bridge the scale gap between invasive sensors and remote sensing instruments. A review about recent GPR developments can be found in Slob et al. (2010), while a complete review of GPR applications for soil moisture sensing was given in Huisman et al. (2003). Numerous studies used the now well-established GPR ground-wave techniques for soil moisture determination (e.g., Huisman et al., 2002; Grote et al., 2003; Galagedara et al., 2003, 2005; Lunt et al., 2005; Grote et al., 2010). Recently, some authors proposed innovative soil moisture retrieval techniques using the same GPR sensors. In that respect, van der Kruk (2006) and van der Kruk et al. (2010) developed an inversion method of dispersed waveforms trapped in a surface waveguide (i.e., when soil is layered by freezing, thawing or by a wetting front) for retrieving its dielectric permittivity and thickness. Benedetto (2010) used a Rayleigh scattering based method for directly determining the soil moisture, without the need of a petrophysical relationship and calibration of the GPR system.

Off-ground (i.e., proximal or air-launched) GPR systems offer particularly promising perspectives in terms of proximal soil

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sensing, as antennas can be rapidly moved over the soil surface when mounted on mobile platforms. Using an approach similar to satellite remote sensing of soil moisture, the retrieval of soil moisture using off-ground GPR is based on the measurement of the soil surface reflection. Few studies have applied such an off-ground GPR approach for soil moisture sensing in field conditions (Chanzy et al., 1996; Redman et al., 2002, 2003; Serbin and Or, 2003, 2005). Based on a full-waveform inversion of GPR data and an accurate GPR system modeling, the off-ground GPR system developed by Lambot et al. (2004, 2006b) has shown excellent potentialities for surface soil moisture sensing and mapping in field conditions (Weihermüller et al., 2007; Lambot et al., 2008; Jadoon et al., 2010; Jonard et al., 2011; Minet et al., 2011). The method relies on an accurate radar model that, in particular, accounts for antenna and antenna–soils interactions.

The validation of the GPR technology for soil moisture retrieval implies a comprehensive assessment of the uncertainties in retrieval methods. The methods for assessing the uncertainties vary greatly in the literature and are dependent on the GPR system. Most of the studies attempted to calibrate or validate GPR measurements by comparing the GPR estimates with another measurement technique assumed to be the ground-truth (mainly TDR or soil sampling). Using the ground-wave technique, Huisman et al. (2001) compared GPR and TDR estimates of soil moisture with gravimetric sampling measurements and found similar root mean square error (RMSE) around 0.03 $m^3\ m^{-3}$. The sources of errors were also identified and the dominant error was attributed to the petrophysical relationship (i.e., the empirical relationship between the relative dielectric permittivity of the soil and soil moisture). In a controlled outdoor experiment, Wijewardana and Galagedara (2010) compared the volumetric soil moisture content estimated with direct ground wave of GPR with gravimetrically measured water content values for raised bed agricultural field and found a RMSE of 0.0184 $m^3\ m^{-3}$. In controlled laboratory conditions, Lambot et al. (2004) found a very low RMSE of 0.0066 $m^3\ m^{-3}$ between water content from sampling measurements and off-ground GPR using a linear approximation of the frequency-dependent effective electrical conductivity. However, in field conditions and using the same off-ground GPR, Jadoon et al. (2010) found a RMSE of 0.025 $m^3\ m^{-3}$ between TDR and GPR estimates. The errors were mainly attributed to the different support scales of the instruments with respect to the small-scale within-field variability. As well as for remote sensing, the different support scales and the large vertical and lateral variations of soil moisture in real conditions may actually preclude the use of small-scale ground-truthing to fully validate the GPR sensors for soil moisture.

In that respect, Jacob and Hermance (2004) assessed the repeatability of GPR common mid-point (CMP) measurements using information from the same CMP measurements and from several independent CMP measurements performed at the same location. Using a cross-borehole GPR, Alumbaugh et al. (2002) obtained a RMSE in volumetric soil moisture of 0.005 $m^3\ m^{-3}$ between repeated measurements. Recently, Bikowski et al. (2010) and Minet et al. (2010b) assessed the posterior distributions of GPR-derived soil properties by a Markov Chain Monte Carlo technique, when using GPR methods based on inverse modeling of GPR data. This permitted to quantify confidence intervals around the inverted parameters by accounting for errors associated with the GPR data processing.

In this study, we propose to comprehensively evaluate the reliability of the GPR system developed by Lambot et al. (2004) for soil moisture mapping in field conditions and to quantify the soil moisture uncertainties. A mobile proximal GPR was used over a 2.5 ha agricultural field to map the soil moisture at high spatial resolution. We evaluated the reliability of the GPR technique by three independent uncertainty assessment methods. First, soil moisture uncertainties were derived from the inversion of the GPR data for each point by the computation of modeling error and soil moisture sensitivity. Second, three repetitions of the acquisition were performed, in order to assess the repeatability of the technique, by comparison with the spatial interpolation uncertainties. Third, soil moisture core sampling were performed in order to compare the GPR estimates with reference soil moisture measurements, allowing for the evaluation of the petrophysical model. These three independent soil moisture uncertainty assessment methods were compared and the different sources of errors were identified.

2. Materials and methods

2.1. Study site

We surveyed a 2.5-ha agricultural field situated in the loess belt area in the center of Belgium, near Louvain-la-Neuve (4°41′8″E, 50°35′59″N) (Fig. 1). The soil type is uniformly a silt loam and elevation ranges from 130 to 144 m above sea level. According to the national Belgian soil database (Orshoven and Vandenbroucke (1993)), soil particle fractions are 4% sand, 82% silt, and 14% clay for a soil sampling point situated at 500 m from the field. The GPR acquisition took place at the end of the winter on 18 March 2010 in moderately wet conditions. According to a rain gauge station situated 2 km away from the field, no rainfall was recorded for the previous 11 days, but evaporation was limited due to low temperatures, as the average temperature was 3 °C for that period. The field was covered by low-grown winter wheat, with a canopy height lesser than 5 cm (see Fig. 2). The surface roughness was low, with an amplitude around 5 cm, as the field was finely plowed for wheat sowing four months before the campaign and subsequent rainfalls flattened the soil surface during the winter.

2.2. Soil moisture sensing by GPR

2.2.1. GPR setup

The GPR principle for soil moisture sensing is based on the propagation of an electromagnetic wave, which is governed, for non-magnetic soils, by the relative dielectric permittivity ε and electrical conductivity *EC*. As the relative dielectric permittivity of water ($\varepsilon_w \approx 80$) is much larger than that of the soil particles ($\varepsilon_s \approx 5$) and air ($\varepsilon_a = 1$), GPR is primarily sensitive to soil moisture.

The GPR system we used was set up with a vector network analyzer (VNA) (ZVL, Rohde and Schwarz, Münich, Germany) connected to an ultra-wideband monostatic horn antenna (BBHA 9120 F, Schwarzbeck Mess-Elektronik, Schönau, Germany) situated off the ground at around 1.1 m height. In accordance with the operating bandwidth of the antenna, the VNA emulated a stepped-frequency electromagnetic wave from 200 to 2000 MHz, at a frequency step of 6 MHz. For this off-ground configuration, antenna and soil–antenna interactions effects are modeled using frequency-dependent transfer functions for a far-field antenna configuration (Lambot et al., 2006a; Jadoon et al., 2011).

For field acquisition, we used an all-terrain vehicle (ATV) holding the GPR system, a differential global positioning system (DGPS) (Leica GPS1200, Leica Geosystems), and a PC (Fig. 2). The PC automatically integrates the DGPS position, launches GPR measurements, and saves all the measured data. Real-time GPR measurements were performed at a regular spacing of two meters along the same track, according to DGPS measurements, which are known with a horizontal precision of about 3 cm. The ATV followed 12 parallel tracks with a spacing of 5 m between the acquisition tracks (see Fig. 1) and a driving speed of about 5 km/h. The GPR antenna footprint where soil moisture was measured had a diameter of about 1.5 m and a sampling depth around 5 cm. Three repetitions of