Soil Moisture Retrieval Using L-Band Radiometer and Ground-Penetrating Radar

François Jonard, Lutz Weihermüller, Mike Schwank, Harry Vereecken, and Sébastien Lambot

***Abstract*—The objective of this study was to evaluate two remote-sensing methods for mapping the surface soil moisture of a bare soil, namely L-band radiometry using brightness temperature and ground-penetrating radar (GPR) using surface reflection inversion. Invasive time-domain reflectometry (TDR) measurements were used as a reference. A field experiment was performed in which these three methods were used to map soil moisture after controlled heterogeneous irrigation that ensured a wide range of water content. The heterogeneous irrigation pattern was reasonably well reproduced by both remote-sensing techniques. For GPR, the effect of roughness was excluded by operating at low frequencies (0.2-0.8 GHz) that were not sensitive to the field surface roughness. For the radiometer, the effect of roughness was accounted for using an empirical model that required calibration with the reference TDR measurements. The root mean square (RMS) error between soil moisture measured by GPR and TDR was 0.038 m^3 m^{-3} while the RMS error between radiometer (horizontal and vertical polarizations)- and TDR-derived soil water content was 0.020 m^3 m^{-3}. These results suggest that both remote-sensing techniques are promising for field-scale mapping of surface soil moisture over bare soils.**

***Index Terms*—Active and passive remote sensing, GPR, L-band radiometer, soil water content, surface roughness.**

I. Introduction

Soil water content is a key variable for estimating water and energy fluxes at the land surface. Accurate estimates of soil water content are essential in many research fields, including agriculture, hydrology, meteorology, and climatology.

Soil sampling or time-domain reflectometry (TDR) are common techniques used to characterize soil water content at the point scale. These methods are invasive and generally restricted to small observation scales. On the other hand, airborne and spaceborne remote-sensing techniques with either passive microwave radiometry or active radar instruments are the most promising methods for mapping surface soil moisture over larger areas [1], [2]. The choice of whether active or passive systems depends on the tradeoff between advantages and disadvantages of the techniques and the aim of the mission. Active radar instruments, particularly synthetic aperture radar (SAR), can provide high spatial resolution data from space (10-100 m). However, the radar signal is highly sensitive to the geometric structure of the soil surface [3]. In addition, remote-sensing radar measurements are greatly affected by vegetation [2]. Active systems are therefore limited to flat areas with bare soils or low vegetation. On the other hand, numerous studies have also demonstrated the potential of passive microwave remote sensing to retrieve soil moisture [4], [5]. Passive methods provide coarser spatial resolution data (> 10 km), but are less influenced by surface roughness and vegetation cover [2]. Microwave radiometry in the L-band (1 to 2 GHz) is a promising technique to estimate soil moisture and has the advantage of being unaffected by cloud cover and independent of solar radiation [6]. Few techniques are presently available to measure soil water content at an intermediate scale between the local and remote-sensing scales, namely, the field scale [7]. However, they are particularly necessary for improving and validating large-scale remote-sensing data products [8]. In this respect, ground-penetrating radar (GPR) and ground-based microwave radiometry techniques are specifically suited for field-scale characterization.

The objective of this study is to compare L-band radiometer and off-ground GPR to map surface soil moisture at the field scale over a bare soil. Therefore, a 72 x 16 m^2 field was partly irrigated and 144 measurement points were measured by L-band radiometer and off-ground GPR [9]. As a reference ground truth, additional TDR measurements were performed. The effect of soil roughness on the passive microwave signal was also addressed by using an empirical roughness model.

F. Jonard, L. Weihermüller, M. Schwank, H. Vereecken and S. Lambot, Institute of Bio- and Geosciences, Agrosphere (IBG-3), Forschungszentrum Jülich GmbH, 52425 Jülich, Germany. (e-mail: f.jonard@fz-juelich.de, l.weihermueller@fz-juelich.de, h.vereecken@fz-juelich.de, s.lambot@fz-juelich.de).

S. Lambot, Earth and Life Institute, Université catholique de Louvain, Croix du Sud 2 box 2, 1348 Louvain-la-Neuve, Belgium. (e-mail: sebastien.lambot@uclouvain.be).

M. Schwank, Section 5.1 "Geoecology and Geomorphology", German Research Centre for Geosciences GFZ, Telegrafenberg, 14473 Potsdam, Germany. (e-mail: schwan@gfz-potsdam.de).

II. Materials and Methods

A. Experimental Setup

The experiment was conducted on July 14, 2009 on an agricultural field at the Selhausen test site of Forschungszentrum Jülich, Germany (longitude 50°87 N, latitude 6°45 E, and elevation 105 m above sea level). The measurements were performed three months after the last plowing event on a compacted bare soil.

GPR, L-band radiometer, and TDR data were collected on a 72 x 16 m^2 experimental plot consisting of 8 transects with 18 measurement points each (measurement spacing: 2 and 4 m in the x- and y-direction, respectively) (Fig. 1). In order to produce a wide range of water contents, the plot was partially irrigated with different quantities of water in two different areas using a fire hose one day before the experiment.

The radiometer and the off-ground GPR were mounted on the back of a truck (Fig. 2). The radiometer antenna aperture was situated about 2 m above the soil surface and directed with

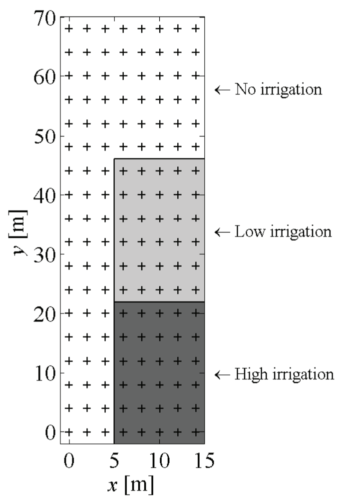

Fig. 1. Sampling grid (72×16 m^2) consisting of 8 transects, each comprising 18 measurement points (in total 144 measurement points). The delineated areas correspond to areas with different levels of irrigation: $\cong 8$ l m^{-2} (high irrigation, dark-gray), $\cong 4$ l m^{-2} (low irrigation, light-gray), and no irrigation (white) (after Jonard *et al.* [9]).

Fig. 2. GPR and L-band radiometer mounted on a truck to measure surface soil relative dielectric permittivity (after Jonard *et al.* [9]).

an observation angle of 53° relative to the vertical direction. The GPR antenna aperture was about 1.2 m above the ground with normal incidence. Invasive time-domain reflectometry (TDR) measurements were used as a reference. For each type of measurement (GPR, radiometer, and TDR), the model of Topp *et al.* [10] was used to relate the soil volumetric water content [θ (in m^3 m^{-3})]) to the soil relative dielectric permittivity.

B. Microwave Sensors

The radar system is based on international standard vector network analyser technology, thereby setting up stepped-frequency continuous-wave GPR. The radar was combined with an off-ground, ultra-wideband, and highly directional horn antenna acting simultaneously as transmitter and receiver. The raw GPR data consisted of the frequency-dependent complex ratio S_{11} between the backscattered electromagnetic field and the incident electromagnetic field and were measured sequentially at 301 stepped operating frequencies over the range 0.2-2 GHz with a frequency step of 6 MHz. For the modeling of the GPR signal, we used the full-wave model of Lambot *et al.* [7] which includes antenna propagation phenomena through a system of linear transfer functions in series and parallel. The model takes into account antenna-soil interactions and assumes the air-subsurface system as a three-dimensional multilayered medium, for which Maxwell's equations are solved exactly. The dielectric permittivity was retrieved using inversion of the radar data in the time domain, focusing on the surface reflection [11].

The radiometer used in this study was the L-band microwave radiometer JÜLBARA from Forschungszentrum Jülich specifically designed for field-scale application in surface soil moisture experiments [9]. Brightness temperatures were measured at horizontal (subscript H) and vertical (subscript V) polarizations in the frequency range 1.400-1.427 GHz. The radiometer was equipped with internal cold (278 K) and hot (338 K) loads for calibration preceding each measurement. The measurements were recorded with 10 s integration time. The estimated absolute accuracy of the radiometer was ± 1 K with a sensitivity better than 0.1 K. To correct for instrumental noise, external calibration was performed by directing the radiometer toward the sky and comparing the measured brightness temperature with the theoretical radiance [12]. The brightness temperature measured with the radiometer was used to derive the soil surface dielectric permittivity and the correlated volumetric water content by using the radiative transfer model described in Jackson *et al.* [13].

III. Results and Discussion

Surface soil water contents estimated from GPR, TDR, and radiometer (at H and V polarizations) measurements are plotted in Fig. 3. The overall soil moisture patterns were reasonably well reproduced by the three techniques. However, significant differences in the absolute moisture values retrieved were observed. These discrepancies can be attributed to different sensing depths and areas, and different sensitivities to soil surface roughness. For GPR, the effect of roughness was excluded by operating at low frequencies (0.2-0.8 GHz) that were not sensitive to the field surface roughness according to Rayleigh's criterion. For radiometer, the effect of roughness was accounted for in the modeling of the microwave emission by using a model based on the semi-empirical approach of Wang and Choudhury [14]. This model was calibrated by using reference TDR measurements as described in Jonard *et al.* [9]. The root mean square (RMS) error between volumetric soil moisture measured by GPR and TDR was 0.038 m^3 m^{-3} while the RMS error between radiometer and TDR was 0.020 m^3 m^{-3} for both polarizations (Fig. 3).

For a direct comparison of the results obtained from the different measurement methods, the GPR- and radiometer-derived soil water contents are plotted with respect to the TDR results (Fig. 4). It can be observed that GPR-derived soil water contents systematically overestimate the TDR measurements.

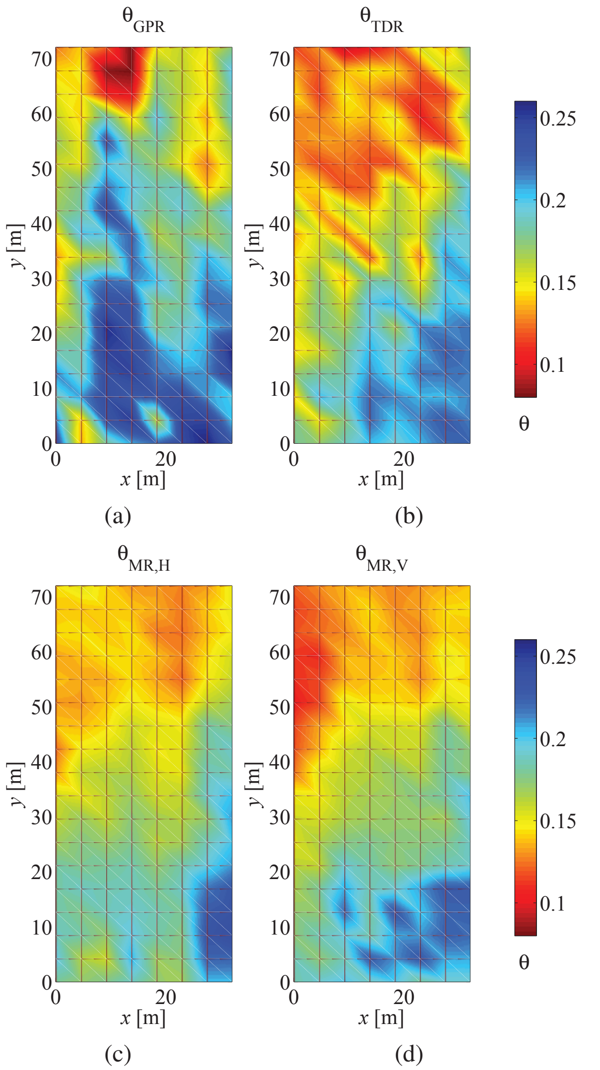

Fig. 3. Volumetric water content maps obtained using (a) off-ground GPR, (b) TDR, (c) radiometer at H polarization, and (d) radiometer at V polarization.

Additionally, the data points are highly scattered resulting in a low correlation coefficient (r^2) of 0.39 compared to the radiometer results ($r^2 = 0.66$ and 0.65 for H and V polarizations, respectively). However, the slope of the regression is similar for the GPR- and radiometer (H polarization)-derived soil water contents ($\sim$0.63) while the slope is closer to 1 for the radiometer (V polarization) results (0.73). The observed discrepancies between the GPR, radiometer, and TDR estimations may be attributed to different sensing depths and areas, and different sensitivities with respect to soil surface roughness. It is worth noting that TDR measurements were affected by the presence of numerous stones in the field, especially in the upper part, thereby leading to significant measurement errors (typically underestimations). The GPR measurements may also be affected by dielectric layering near the soil surface, which may lead to constructive and destructive interferences, and, thereby, to over- or underestimations of the surface dielectric permittivity [15].

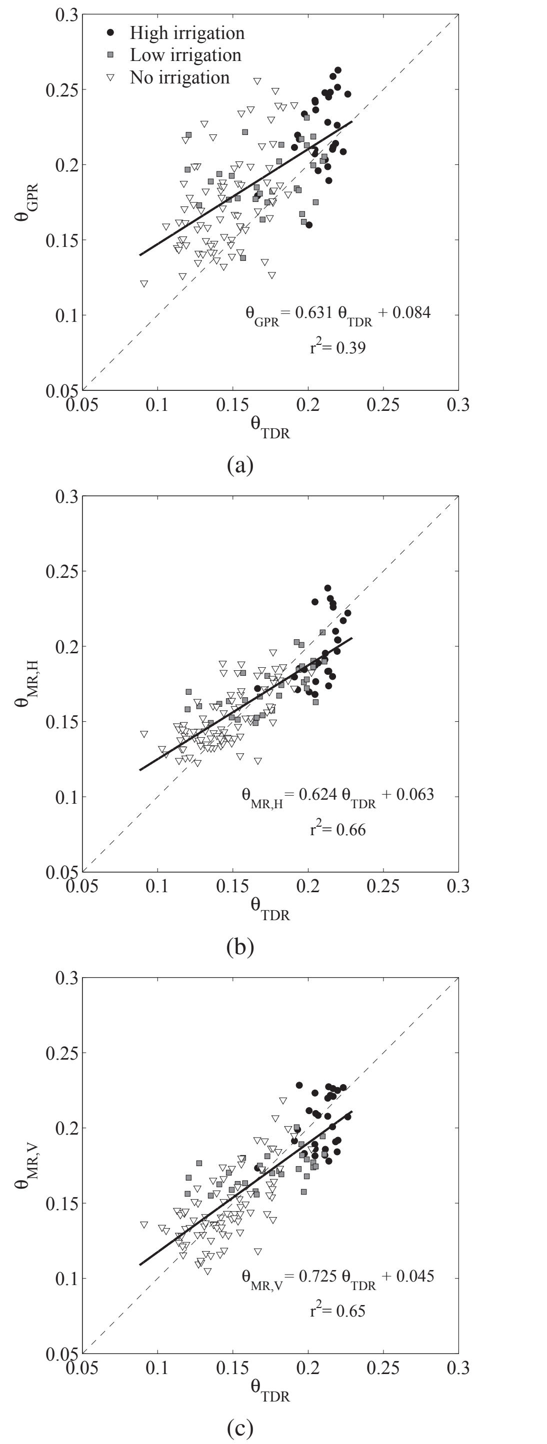

Fig. 4. Volumetric soil water content from (a) GPR versus TDR, (b) radiometer (H polarization) versus TDR, and (c) radiometer (V polarization) versus TDR (after Jonard *et al.* [9]).

IV. Summary and Conclusion

This paper compares ground-based L-band radiometer and off-ground GPR to map surface soil moisture at the field scale over a bare soil. Radiometer and GPR measurements were collected over an area of 72×16 m^2 at the Selhausen test site of Forschungszentrum Jülich (Germany). As a reference ground truth, additional TDR measurements were performed within the footprints of the radiometer and the GPR. The results show that relatively accurate measurements were obtained with both methods, L-band radiometry using brightness temperature and GPR using surface reflection inversion. The observed discrepancies were attributed to different sensing depths and areas, and different sensitivities with respect to soil surface roughness.

The results of this study provided valuable insights into the development and application of field scale characterization techniques that could be used for improving airborne and spaceborne remote-sensing data products for the retrieval of surface soil moisture. Future research will focus on the potential radiometer and GPR synergies for improved soil moisture estimates, as for the NASA's upcoming Soil Moisture Active Passive (SMAP) mission for instance.

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