Electromagnetic characterization of organic-rich soils at the microwave L-band with ground-penetrating radar, radiometry and laboratory measurements

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Abstract—**Microwave remote sensing of the environment strongly relies on knowledge of the soil electrical properties. In this study, we characterized organic-rich soils using remote ground-penetrating radar (GPR) and radiometer as well as resonant cavity and waveguide reference methods. Organic-rich soil samples were collected from the HOBE (Hydrological Observatory) test site in the Skjern River Catchment (Denmark) and set up at the TERENO (Terrestrial Environmental Observatories) controlled test site in Selhausen (Germany). GPR and L-band radiometer measurements were performed above the soils during two months in order to cover a wide range of soil moisture conditions. GPR data were processed using full-wave inversion based on layered media Green's functions and radiometer data were inverted using a two-stream radiative transfer model for estimating the soil electrical properties. Results were compared to reference measurements carried out at the IMS laboratory (Laboratoire de l'Intégration du Matériau au Système, France) using two different methods, i.e., the small perturbation method with resonant cavity and the waveguide method. Relatively large differences were observed between the different estimation methods for the real part of the relative dielectric permittivity, while reasonable agreement were obtained with respect to its imaginary part. This was attributed to a higher sensitivity of the real part of the relative dielectric permittivity with respect to soil samples heterogeneities. This study provided valuable insights into the electrical characterization of organic soils to improve space-borne remote sensing data products.**

Index Terms—**complex dielectric permittivity, GPR, microwave remote sensing, organic soil, radiometry**

I. INTRODUCTION

Hydrological states of the terrestrial land surface affects energy and matter fluxes between the atmosphere and the land surface. Accurate knowledge of these transfer processes is highly relevant to improve predictions of weather and environmental disasters, and in general to advance research on climate change. Meeting these challenges requires global information on (amongst others) the hydrological states of the land-surface.

Microwave remote sensing has proven to be a powerful tool to provide soil moisture information at large scale. However, the remote signatures measured at microwave frequency are not only dependent on the soil moisture but also on the surface roughness and the physicochemical properties of the soil, such as texture and organic content. Currently, there is very little information available in the literature regarding the effect of organic soil surface layers on active and passive microwave signals, while a large proportion of the northern land surfaces are covered by organic soils. Furthermore, organic soils in higher latitudes might directly respond to climate change, and therefore, monitoring of their states is of high importance. This was the rational for the European Space Agency (ESA) project SMOSHiLat (Changing Earth Science Network), which aims at improving our understanding of microwave L-band emissions of organic soil surface layers in order to support the quality of ESA's Soil Moisture and Ocean Salinity (SMOS) data in the northern cold climate zone. The experiment described here was carried out in the framework of the SMOSHiLat project.

In that context, the objective of this study is to characterize the electromagnetic properties of organic-rich soils at the microwave L-band with ground-penetrating radar (GPR), radiometry, and laboratory measurements.

II. MATERIALS AND METHODS

A. Experimental setup

The organic soils were collected from the HOBE (Hydrological Observatory) test site in the Skjern River Catchment. The test site is a heathland located in Gludsted, Denmark. The soil is characterized by a first organic layer of 3 to 5 cm depth.

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(a)

(b)

Fig. 1. Undisturbed soil-vegetation blocks excavated form the HOBE test site in the Skjern River Catchment, Denmark (a) and transported in wooden boxes to the TERENO test site in Selhausen, Germany (b).

Within the organic layer, two horizons were distinguished, the OL-OF horizon, which is characterized by dead leaves or needles still recognizable and the OH horizon, which is composed of humified organic matter without recognizable plant structure. The second layer is a mineral layer with a dominant sand fraction (sand: 85%, silt: 14%, clay: 1%). It is worth noting that the transition between the two layers is generally not clear. The vegetation above the soil is mainly composed of moss, heather, crow berry, cranberry, and grass. Forty blocks of undisturbed soil-vegetation were excavated in August 2013 and carefully transported in wooden boxes to the TERENO (Terrestrial Environmental Observatories) test site in Selhausen, Germany (Fig. 1). Each block had an area of about 60 by 70 cm with a height of 8 to 15 cm and 15 to 20 cm for the soil and the vegetation layer, respectively.

To characterize the electromagnetic properties of the different soil layers and of the vegetation, the controlled field laboratory setup for ground-based remote sensing developed by Jonard *et al.* [1] at the TERENO test site in Selhausen was used (Fig. 2). This setup offers the unique possibility of highly controlled acquisitions of microwave electromagnetic properties accompanied by the monitoring of the essential physical state parameters, such as temperature and moisture profiles. This setup includes a L-band radiometer installed at 4 m height with a fixed incidence angle of 36 degrees to measure time series of brightness temperatures at horizontal (H) and vertical (V) polarizations. Furthermore, an ultra wideband off-ground GPR is fixed above the soil surface to measure backscatter at normal incidence. Both instruments are pointing to a 2 x 2 m box filled with sand down to a depth of 1 m. To increase the sensitivity of the radiometer measurements to radiance originating from the sand box and to minimize the influence of radiance from the surrounding area, a wire grid with a mesh size of 0.5 cm was placed around the sand box. A detailed description of the setup is available in Jonard *et al.* [1].

Fig. 2. Controlled field laboratory setup for ground-based remote sensing observations at the TERENO test site in Selhausen, Germany [1].

Several undisturbed soil blocks from the HOBE test site were placed together on top of the sand box and cut to cover the 2 x 2 m area. Below the organic soil, a horizontal metal sheet was installed to control the bottom boundary condition in the microwave emission model and the GPR full-wave model. As a result, regions underneath this metal sheet have no influence on the measured brightness temperature and backscattered radar signal. On the side of the setup, a second area of 2 x 2 m was covered with additional soil blocks to get a reference observation area for destructive soil and vegetation sampling. Periodical radiometer and GPR observations were then carried out during two months, from October to November 2013, in order to collect time series of brightness temperatures and radar data at different soil-vegetation moisture conditions. To realize a large range of soil moisture conditions, the soils were first wetted to near-saturation (about 300 liters per plot). The measurements were then performed under natural drying and wetting conditions. In a next step, GPR and radiometer measurements were performed with the vegetation layer removed, and then with the organic layer removed. Finally, the microwave measurements were carried out above the organic soil layer alone, then above the vegetation layer alone, and the last measurements were performed above the vegetation and the organic layer together.

Simultaneously with the microwave observations, soil moisture, temperature, and electrical conductivity data were recorded using 5TE sensors (Decagon Devices Inc., Pullman, Washington, USA). The 5TE sensors were installed horizontally at three different depths within the investigated soils (three sensors per depth) in the GPR/radiometer observation area as well as in the reference plot. Additional soil moisture measurements were carried out with the ThetaProbe ML2x sensor (Delta-T Devices Ltd, Cambridge, UK) in both plots. Furthermore, soil and vegetation samples were periodically collected from the reference plot to estimate the volumetric water content of the organic and mineral layers and the vegetation water content. The soil volumetric water content measurements were used to calibrate the *in situ* moisture sensors. Soil samples were also collected to carried out laboratory measurements of soil dielectric permittivity and soil physicochemical properties (texture, bulk density, and organic matter content).

B. Remote sensing instruments

The GPR measurements were performed using an ultra wideband stepped-frequency continuous-wave radar connected to a transmitting and receiving double-ridge horn antenna (BBHA 9120 A, Schwarzbeck Mess-Elektronik, Schönau, Germany). The antenna nominal frequency range is 0.8 to 5.2 GHz. The antenna was connected to the reflection port of a vector network analyzer (VNA, ZVL, Rohde & Schwarz, Munich, Germany) with a high quality N-type 50-Ω coaxial cable. Measurements were performed with the antenna aperture situated at an average height of 40 cm above the soil surface with a normal incidence. The resulting raw GPR data consists of the frequency-dependent complex ratio S_{11} between the backscattered electromagnetic field and the incident electromagnetic field. The Green's functions were computed from the S_{11} scatter function using the far-field radar equation of Lambot *et al.* [2], through which antenna effects are accounted for. In order to identify the soil surface dielectric permittivity, inversion in the time domain was performed by focusing on a time window containing the surface reflection only. Soil surface roughness was accounted for in the inversion of the GPR data using the approach of Jonard *et al.* [3] and considering a standard deviation of the surface height σ = 0.005 m, which was in agreement with our visual observations. Inversion of the data was performed in a limited frequency band, i.e., 1 – 2 GHz, and with a frequency step of 4 MHz.

For the radiometer measurements, we used the ETH L-band radiometer ELBARA II, which is a similar instrument as used by ESA for ongoing SMOS validation and research activities. A detailed description of the ELBARA II radiometer is given by Schwank *et al.* [4]. The ELBARA II measures brightness temperatures within the protected part, i.e., 1400 – 1427 MHz, of the microwave L-band (1 – 2 GHz). The radiometer was attached to a Pickett-horn antenna to perform measurement at H- and V-polarizations. The absolute accuracy of brightness temperatures measured is better than 1 K, and the sensitivity is < 0.1 K. Brightness temperatures were simulated using the same two-stream radiative transfer approach as used in the Microwave Emission Model of Layered Snowpacks (MEMLS) [5]. The used two-stream radiative model is a second-order solution of the radiative transfer equations. It is in agreement with Kirchhoff's law, and it takes into account effects of multiple scattering and multiple reflections across the layers. Due to the reflector placed beneath the relatively thin soil layers, the consideration of multiple reflections is an important feature of the radiative transfer model. Accordingly, the use of a simpler zero-order solution of the radiative transfer equations, such as the Tau-Omega model [6], would not be adequate. Furthermore, the used two-stream approach is an incoherent model, implying that coherent effects caused by the superposition of electric fields with different phases are not considered. However, the use of an incoherent model is more appropriate than using a coherent emission model, as coherent effects are expected to be smeared out by averaging over the beamwidth and bandwidth of a radiometer. This two-stream emission was then inverted to identify the complex dielectric permittivity of the soil layers on the basis of the brightness temperatures measured at H- and V-polarizations. Similarly to the GPR data inversion, roughness was accounted for in the inversion of the radiometer data with σ = 0.005 m and by using the empirical roughness model of Wang and Choudhury [7].

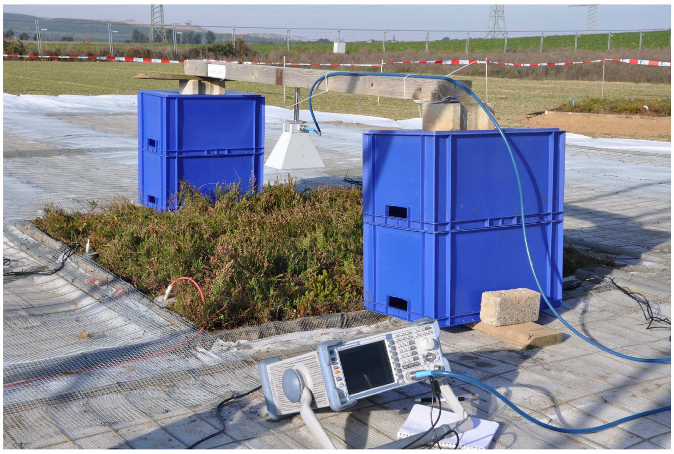
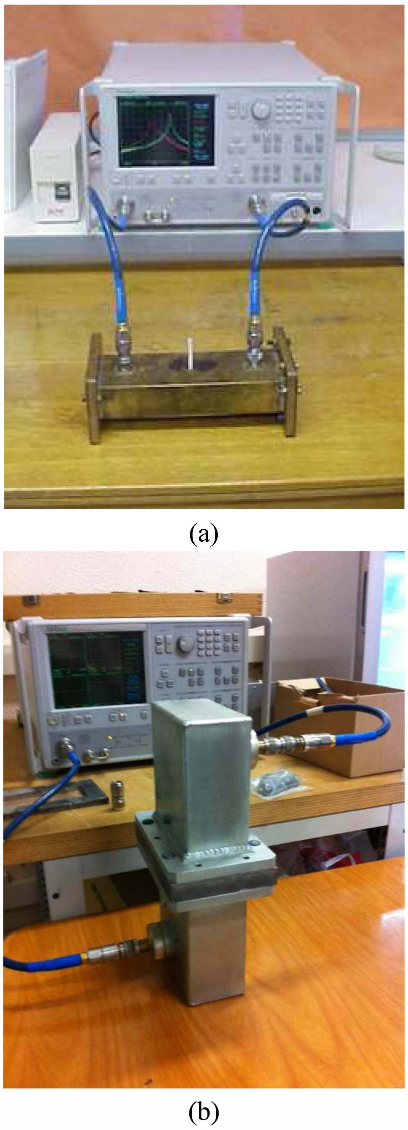


Fig. 3. Picture of the off-ground GPR consisting of a vector network analyzer connected to a horn antenna.

C. Laboratory measurements

Measurements of soil dielectric permittivity were carried out at the IMS laboratory (Laboratoire de l'Intégration du Matériau au Système, France) using two different approaches: the resonant cavity technique based on the small perturbation method [8] and the waveguide technique based on the Nicolson, Ross and Weir method for rectangular waveguide


(a)

(b)

Fig. 4. Laboratory setups used at the IMS laboratory (France) for complex dielectric permittivity measurements: resonant cavity technique (a) and waveguide technique (b).

[9] (Fig. 4). Measurements with the resonant cavity technique were performed at 1.26 GHz and with samples of about 2.6 cm^3, while measurements with the waveguide technique were performed from 1.3 to 1.5 GHz using larger sample volumes (60 cm^3 and 125 cm^3), which allows to better account for the soil heterogeneity [10]. For both approaches, measurements were performed at room temperature and using a VNA (Anritsu 37325A, Anritsu, Morgan Hill, CA, USA). Each measurement was repeated two times for the waveguide technique and three times for the resonant cavity technique.

In addition to these electromagnetic measurements, vegetation and soil (organic and mineral layers) water contents were determined using the oven drying method. For the soil samples, we used a drying temperature of 85°C during 48 hours. This temperature was used in order to avoid charring the organic fraction, which may occur at the standard drying temperature of 105°C [11]. The vegetation samples were dried at 60°C during also 48 hours.

III. RESULTS AND DISCUSSIONS

In this paper, the permittivities derived from the radiometer and the GPR measurements performed above the single layer configuration, i.e., one soil layer above the metallic plate, are presented and compared to laboratory measurements. Within the organic layer, two horizons were distinguished, the OL-OF and the OH horizons. For the laboratory measurements, samples were collected from the OL-OF and OH organic horizons. However, for technical reasons, it was not possible to separate these two horizons for use in the field measurements.

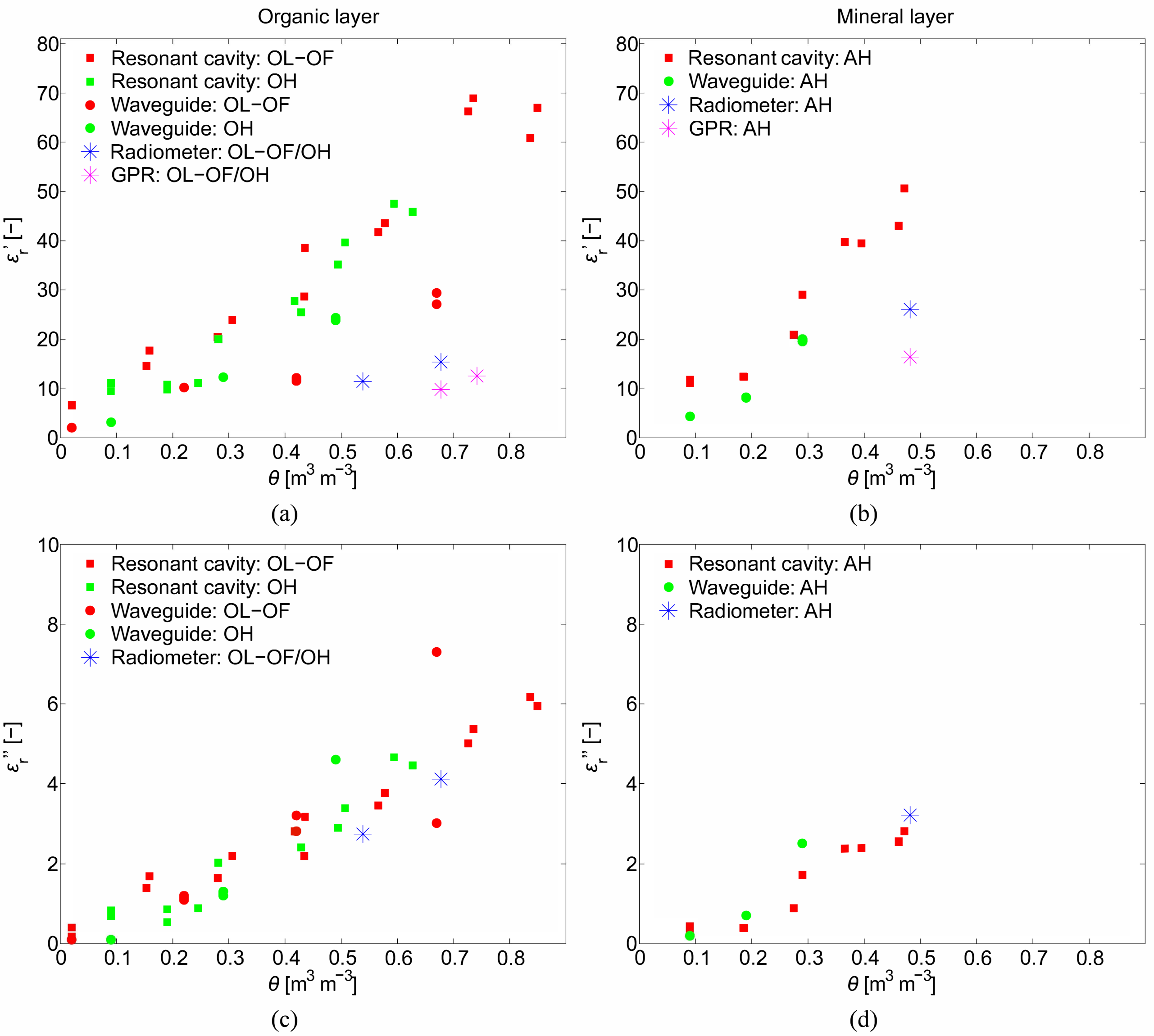
Figures 5(a)-(b) show the real part of the relative dielectric permittivity ε_r' estimated by the different field and laboratory techniques for the organic and mineral layers. The estimated values of ε_r' from the field data (GPR and radiometer) are significantly lower compared to the laboratory estimates for both soil layers (organic and mineral). As it can be expected, ε_r' of the organic layer derived from field measurements are closer to corresponding ε_r' derived from laboratory measurements on samples collected from the OL-OF horizon (first horizon of the organic layer) in comparison with samples of the OH horizon. Indeed, GPR and radiometer signals are mainly influenced by the top layer of the observed soil. Furthermore, considering the OL-OF horizon for the laboratory measurements, the waveguide technique shows closer estimations to the field measurements compared to the resonant cavity technique, which can be explained by the larger sampling volume used for the waveguide technique. In general, all techniques show a decrease of ε_r' with an increase of organic matter content. The relatively large differences observed between the remote and the laboratory estimations of ε_r' may be attributed to scale issues raised by the soil heterogeneity and the significantly different sensing volumes of the field and laboratory techniques.

In this experiment, the waveguide technique seems to be more reliable than the resonant cavity technique because of its larger sampling volume and also its smaller ε_r' derived values in dry conditions (below 5 for the waveguide technique and between 6 and 12 for the resonant cavity technique), which is more consistent with values found in literature [12].

From Fig. 5(c)-(d), it can be seen that the laboratory measurements of the imaginary part of the relative dielectric permittivity ε_r" are well reproduced by the field radiometer measurements, with a reasonable assumption made for the roughness (σ = 0.005 m). However, it is not possible to estimate ε_r" from the GPR data using the surface reflection analysis. In a next step, a full-wave GPR inversion will be performed to retrieve ε_r" in addition to ε_r'.

IV. CONCLUSION

In this study, organic-rich soils were characterized using ground-penetrating radar (GPR) and radiometer as well as reference laboratory measurements. GPR data were processed using full-wave inversion based on layered media Green's



(a) (b)

(c) (d)

Fig. 5. Real and imaginary part of the relative dielectric permittivity (ε_r' and ε_r", respectively) of organic (a-c) and mineral (b-d) soil layers measured in laboratory (resonant cavity and waveguide techniques) and in the field (radiometer and GPR techniques) for different soil moisture (θ) conditions.

functions and radiometer data were inverted using a two-stream radiative transfer model in order to estimate the soil electrical properties. Results were compared to laboratory measurements carried out using two different methods: the small perturbation method with resonant cavity and the waveguide method. Relatively large differences were observed between the different estimation methods for ε_r', while reasonable agreement were obtained with respect to ε_r". This was attributed to a higher sensitivity of ε_r' with respect to soil samples heterogeneities.

Further research will focus on inverse and forward modeling of the radiometer and GPR signals for a two- and a three-soil layer configuration (vegetation layer, organic layer, and mineral layer). Differences observed between laboratory and field measurements of ε_r' will also be investigated. In particular, effect of soil surface roughness, soil bulk density, bound and free water within the soil will be analyzed.

This study provides valuable insights into the characterization of organic soils, which can be used to improve the quality of space-borne remote sensing data products obtained, for instance, by the SMOS mission in the northern cold climate zone. Moreover, this study focuses on radar and radiometric behaviors of organic soils which is also of high interest for the upcoming NASA's Soil Moisture Active and Passive (SMAP) mission.

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