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SOIL MOISTURE AND DIELECTRIC CONSTANT MEASUREMENTS OF ORGANIC SOILS IN THE HIGHER NORTHERN LATITUDES IN SUPPORT OF THE SMOS MISSION

Simone Bircher[1], S. Razafindratsima[2], F. Demontoux[2], M. Andreasen[3], J. Vuollet[4], K. Rautiainen[4], F. Jonard[5], L. Weihermüller[5], P. Richaume[1], A. Mialon[1], J.-P. Wigneron[6], Y. H. Kerr[1]*

1. Centre d'Etudes Spatiales de la Biosphère, Toulouse, France
2. Laboratoire de l'Intégration du Matériau au Système, Bordeaux University, Bordeaux, France
3. Department of Geosciences and Natural Resource Management, University of Copenhagen, Denmark
4. Finnish Meteorological Institute, Helsinki, Finland
5. Institute of Bio- and Geosciences Agrosphere (IBG-3), Forschungszentrum Jülich GmbH, Germany
6. INRA, UMR 1391 ISPA, 33140 Villenave d'Ornon, France

* Corresponding author: simone.bircher@cesbio.cnes.fr

ABSTRACT

The SMOSHiLat project aims at increasing our insufficient understanding of L-band (1.4 GHz) emission behaviour of organic soils in the higher northern latitudes in order to support soil moisture product generation from the Soil Moisture and Ocean Salinity (SMOS) satellite over these regions. Evaluation of two soil moisture sensors (Decagon 5TE and Delta-T ThetaProbe) for organic horizons and L-band dielectric constant measurements are being carried out on samples collected in Denmark, Finland, Scotland and Siberia. Here, focus is on the presentation of the material, applied methods and first results that show consistent trends, in agreement with other studies using TDR sensors. The observed dielectric constants of the organic substrate at a given water content are decreased compared to sandy mineral soils due to high water binding capabilities of the former. The current ongoing data analyses including the derivation of organic calibration functions shall be presented at the symposium.

I - INTRODUCTION

Organic-rich soils are typical for the circumpolar northern cold climate zone (boreal forest/tundra). Due to above-average rising temperatures in the higher northern latitudes, a large amount of these important carbon sinks might be released, possibly causing a significant positive feedback on global warming (e.g. Stokstad 2004). Hydrology plays a key role, but the overall response of these soils remains currently highly uncertain. Thus, there is a strong need to monitor hydrologic states and water redistribution processes in these regions.

The only means to acquire such observations at high temporal resolution and with complete spatial coverage are by spaceborne remote sensing techniques. The European Space Agency's (ESA) Soil Moisture and Ocean Salinity (SMOS) mission (Kerr et al. 2001) carries the first space-borne passive L-band microwave (1.4 GHz) radiometer on board. It acquires global brightness temperatures (TB) from which surface soil moisture is retrieved, taking advantage of the very large difference between the dielectric constant (also referred to as relative permittivity, ε) of dry soil and liquid water. The retrieval algorithm is based on the inversion of the L-band Microwave Emission of the Biosphere (L-MEB) radiative transfer model (Wigneron et al. 2007) using tuning parameters derived from study sites in dry and warm temperate climate zones

In order to improve our understanding of L-band emission of organic soil surface layers and thus, enhance the quality of SMOS soil moisture data in the higher northern latitudes, the ESA project "SMOSHiLat" has been initiated (http://due.esrin.esa.int/stse/projects/stse_project.php?id=179). Its aim is to adapt and calibrate the L-MEB model for organic soils encountered in Northern regions and test it in the SMOS soil moisture prototype retrieval algorithm in view of its implementation in the operational one. In a first step, a database is created including measured and modelled key parameters of the radiative transfer chain from Northern study sites, i.e. L-band TBs and soil dielectric constants, in situ soil moisture, temperature and soil characteristics. In this context, an important issue is soil moisture sensor calibration for organic-rich material to relate the acquired sensor response (a function of ε) to soil moisture. While several studies have investigated the influence of organic matter content on the Time Domain Reflectometry (TDR) sensors (e.g. Topp et al. 1980, Schaap et al. 1996, Jones et al. 2002, Vaz et al. 2013), such analyses are sparse for impedance and capacitance sensors, though the latter are widely used due to their significantly lower costs. Therefore, two sensors, Delta-T ThetaProbe ML2x (impedance) and Decagon 5TE (capacitance)[1], are being calibrated for variable organic matter content using both field and lab measurements from mainly two study sites in Northern Finland and Denmark. While these sensors measure at 100 and 70 MHz, respectively, dielectric constant measurements are also being carried out at the L-band frequency using two

1 Mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the authors

complementary approaches (rectangular wave-guide and resonant cavity techniques).

In this paper, the sensor calibration and L-band dielectric constant measurements are presented and discussed. As analyses are still ongoing, here focus is on the presentation of the study sites, material and applied methods. Some preliminary results are shown and an outlook is given on the work that will be presented during the symposium.

II – STUDY SITES

An overview over the study locations is given in Figure 1. This experiment includes primarily the two main SMOSHiLat test sites in Finland (Finnish Meteorological Institute, FMI), and Denmark (Hydrologic Observatory, HOBE). The FMI's Arctic Research Centre is situated in Sodankylä in the boreal (coniferous forest) zone of Northern Finland. The prevailing soil type is podsol of mainly very sandy texture and overlying organic surface layers. Samples were collected from a heathland area within a forest clearing as well as under spruce. At both locations, a Decagon 5TE soil moisture and soil temperature station with sensors at 5, 10, 20, 40, and 80 cm depths, respectively, is placed.

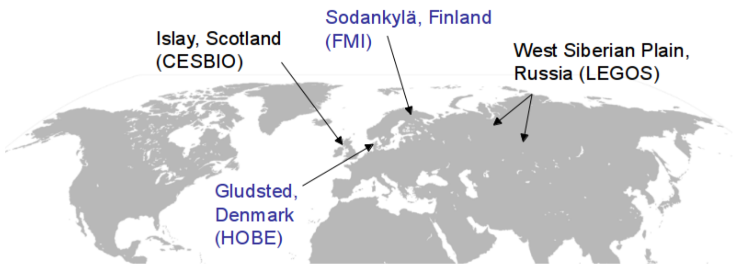

Figure 1: Overview over all sampling locations

In Denmark, the selected HOBE test site is situated within the Gludsted spruce plantation in the Skjern River Catchment. Soil samples were mainly collected in the forested parts and to a small amount in a heathland area. The naturally occurring soil type is again podsol of coarse sandy texture with pronounced organic surface layers. Several soil moisture and soil temperature stations are distributed in the forest, including Decagon 5TE sensors at 5, 25 and 55 cm depths of the mineral soil as well as in the organic surface layer.

Furthermore, organic samples were collected in two peatlands on the Island Islay in Western Scotland, GB, (Centre d'Etudes Spatiales de la Biosphère, Toulouse), and on the West Siberian Plain, Russia, from a tundra area and a bog as well as a forest farther south (Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Toulouse).

III – MATERIAL AND METHODS

III - A - Soil Moisture Calibration

Calibration of the electromagnetic sensors, Delta-T ThetaProbe ML2x (impedance) and Decagon 5TE (capacitance), is being carried out. The ThetaProbe ML2x is a soil moisture sensor with four 6-cm long rods building an array whose impedance varies with a medium's water content (Delta-T Devices Ltd., 1999). The voltage output is proportional to the soil's dielectric constant and related to water content using the manufacturer's calibration curves for mineral and organic substrates. The probe has been widely evaluated and some calibration functions for organic material were derived (see Vaz et al. 2013). The Decagon ECH2O 5TE uses the capacitance method to measure around three 5.2 cm long prongs (Decagon Devices Inc., 2014). From the raw sensor output the dielectric constant is estimated dividing by 50. By default, the Topp equation for mineral soils (1980) is used to calculate soil moisture. Thus far, calibration for organic material has only been conducted by Vaz et al. (2013) for a plant potting mix. Curves for natural organic soils are lacking. The dielectric constants observed by 5TE sensors and ThetaProbes correspond mainly to the real part (ε'), but as the measurements are sensitive to the imaginary part (ε'') to some extent (e.g. Blonquist et al. 2005), the term “apparent dielectric constant” (ε_a) is used.

Most calibration measurements on different mineral and organic soil horizons were conducted at the Finish and Danish sites in the lab. At the HOBE forest site a field experiment was also carried out in order to validate the lab approach. To avoid increasing water content underestimation towards the dry end due to shrinkage effects of the organic matter (e.g. Schaap et al., 1996) the material was previously saturated. Subsequently, it was allowed to undergo a natural dry down in order to consider the changing volume during the sampling process. In case of lab calibration, saturated bulk densities were estimated in the field and the collected material packed accordingly in large buckets. In the center of each bucket one 5TE sensor was installed horizontally with the blade in vertical direction to avoid ponding of water. These measurements were logged continuously, while ThetaProbe readings and gravimetric samples were taken sporadically. The latter were oven-dried at 105 ºC during 24 hours and at 85 ºC during 48 hours for the mineral and organic material, respectively. The chosen organic drying temperature was estimated as the point around which mass loss due to charring balanced the effects of residual water due to the strong water binding capabilities of organic matter (O'Kelly, 2004). The estimated gravimetric water content was converted into the volumetric. Texture and organic content data were obtained using standard procedures. At the Finish sites and the Danish forest site, calibration samples were taken close to 5TE network stations at the respective sensor depths. The field experiment took place at one of the latter. Three Decagon 5TE sensors were installed in the organic horizon and logged permanently. The soil was saturated and during the dry-down ThetaProbe readings and gravimetric samples kept being taken. These field data include some further 5TE-ThetaProbe-gravimetric sample couples available from organic layers around other network stations within the plantation.

In order to increase the number of calibration points and thus, the scope of validity, some additional measurements were added: Few data were acquired during a radiometer experiment for which purpose a large soil patch (organic and A-horizon) from heathland within the Gludsted plantation was transported to the Research Center Jülich, Germany (Jonard et al. 2014). Furthermore, some ThetaProbe measurements together with gravimetric sampling were taken from the Scottish and Siberian samples in the lab.

An Overview of all calibration samples and their characteristics is given in Table 1. Layers with soil organic matter content (SOM) greater than around 34 % (e.g. Zanella et al. 2011) are considered organic horizons. Dry bulk densities range from 0.05-0.4 and 1.0-1.5 g/cm3 for the organic and mineral samples, respectively. Sand fractions always constitute more than 80 % of the total soil mass. Couples of sensor output and sample volumetric water content of all data are plotted for the two sensor types in order to evaluate the manufacturer's calibration curves and if required derive new ones.

III - B - L-band Dielectric Constant Measurements

L-band dielectric constant measurements are being carried out at the Laboratoire de l'Intégration du Matériau au Système (Bordeaux, France) using two complementary approaches: The resonant cavity is based on the small perturbation method (Boudouris 1964) and measures sample-induced changes of resonance parameters of the transmission coefficient curve (resonance frequency and quality factor). The Nicolson, Ross and Weir rectangular waveguide technique (Weir 1974) estimates the complex coefficients of transmission and reflection. In both cases the real and imaginary parts of the dielectric constant (ε', ε'') are computed. The former method is more precise but restricted to fixed frequencies, while the latter can measure over a wider range and uses larger samples, better

Table 1: Overview of the calibration samples collected from organic and mineral horizons. N=Number of readings.

		Location	Land cover	Type	Layer depth [cm]	SOM [%]	N 5TE	N ThetaProbe
Organic	HOBE_Forest_O_F	Gludsted, DK	Forest	Field	0-5	69-93	19	13
	HOBE_Forest_O1_L			Lab	0-5	69	11	11
	HOBE_Forest_O2_L			Lab	0-5	31	11	11
	HOBE_Heath_O_F		Heath	Field	0-5	NaN	2	8
	FMI_Forest_O_L	Sodankylä, FI	Forest	Lab	0-5	36.6	7	7
	SIB_O_L	Siberia, RU	Tundra/bog	Lab	0-10	NaN	0	3
	ISL_O_L	Islay, GB	Bog	Lab	0-10	NaN	0	17
Mineral	HOBE_Forest_M_L	Gludsted, DK	Forest	Lab	10-15	8	11	11
	HOBE_Heath_M_F		Heath	Field	10-15	NaN	4	7
	FMI_Forest_M_L	Sodankylä, FI	Forest	Lab	10-15	15	6	6
	FMI_Heath_M1_L		Heath	Lab	0-5	7	5	5
	FMI_Heath_M2_L			Lab	10-15	5	4	4

accounting for the material's heterogeneity. Classification of the measured organic samples was undertaken according to Zanella et al. (2011, Table 2). A range of different humus types of both terrestrial and semi-terrestrial regimes (rarely/frequently water-saturated, respectively) were sampled. For comparison, the underlying mineral A-horizons and overlying vegetation layers were also acquired at the Danish and Finish sites.

In case of the resonant cavity, glass tubes were filled with air dried material (5.2 cm^3) using pre-defined in situ bulk densities. Different water contents were added to span the entire wetness range. Two tubes per step were prepared and each was measured three times at room temperature and frozen conditions, respectively. For the wave-guide measurements, teflon containers (60 and 125 cm^3 depending on material's composition) were used. The samples having different soil water contents were measured twice at room temperature and under frozen conditions, respectively, turned 180 degrees between the two measurements to account for heterogeneity effects. Due to labor-intensity, the ideal preparation from the wet-end was only undertaken in case of semi-terrestrial samples exhibiting the strongest shrinkage effects. For both methods a calibrated vector network analyzer was used. The measurements in different substrates, using the two complementary methods, are currently being analyzed and compared.

Table 2: Overview over organic samples collected for L-band dielectric constant measurements

Location	Land cover	Water regime	Type	Horizons
Gludsted, Denmark	Coniferous forest (spruce)	Terrestrial	Mor	OL-OF-OH
	Heathland	Terrestrial	Moder	OL-(OF)-OH
Sodankylä, Finland	Coniferous forest (spruce)	Terrestrial	Mor	OL-OF-OH
	Heathland	Terrestrial	Mor	OL-OF-OH
West Siberia, Russia	Tundra	Semi-terrestrial	Hydromor	(OLg)-OFg-(OHg)
	Bog	Semi-terrestrial	Histomor	hf
	Forest	Terrestrial	Mor	OL-OF-OH
Islay, Scotland, GB	Peat	Semi-terrestrial	Histomor	hf-hm

IV – RESULTS/DISCUSSION

IV - A - Soil Moisture Calibration

Figure 2 shows Decagon 5TE and ThetaProbe output plotted against the sample water content, separately for organic and mineral horizons (listed in Table 1), together with the manufacturer's default curves. For the 5TE sensor, ϵ_a is used as the raw output is only logged by Decagon-fabricated devices. Color codes go from highest to lowest SOM content. Despite a significant dispersion, a clear and consistent trend is visible in the organic data from all locations. For both sensor types, there is good agreement between the field and lab measurements from the HOBE forest site. The 5TE sensor response at a given water content is significantly lower for organic material than indicated by the default mineral function. This behavior was likewise observed in respective TDR studies (e.g. Topp et al. 1980, Jones et al. 2002). It has been explained by the substantial bound water fraction in high surface-area porous organic matter where interfacial forces render water molecules rotationally hindered, leading to reduced ϵ_a. In contrast, and opposite to the manufacturer curve's trend, our organic ThetaProbe measurements consistently show an increased sensor output at a given water content, and the response seems to saturate around 1000 mV. The mineral data with SOM < 10% scatters around the default curves. While the ThetaProbe data of SOM > 10% follow this pattern, the 5TE sensor shows a tendency towards decreased ϵ_a but with weaker shape than for organic horizons.

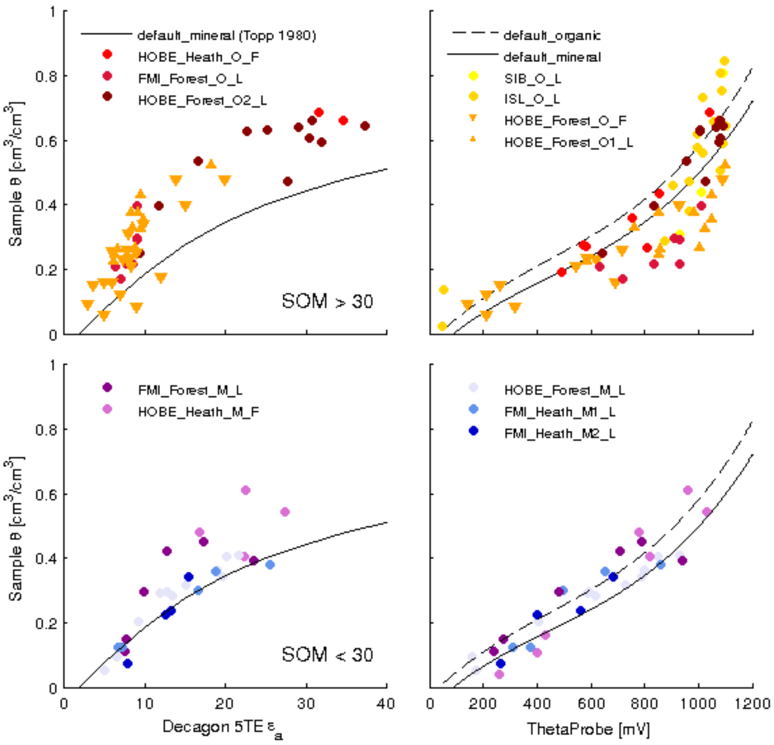

Figure 2: 5TE apparent dielectric constant ε_a (left) and ThetaProbe output [mV] (right column) against volumetric water content Θ (gravimetric samples) for organic (top) and mineral horizons (bottom row) with color codes from highest to lowest SOM content (yellow – dark red and purple - dark blue, respectively). For SOM% see Table 1.

IV - B - L-band Dielectric Constant Measurements

Figure 3 illustrates an example of the first L-band dielectric constant measurements (real/imaginary parts) using an

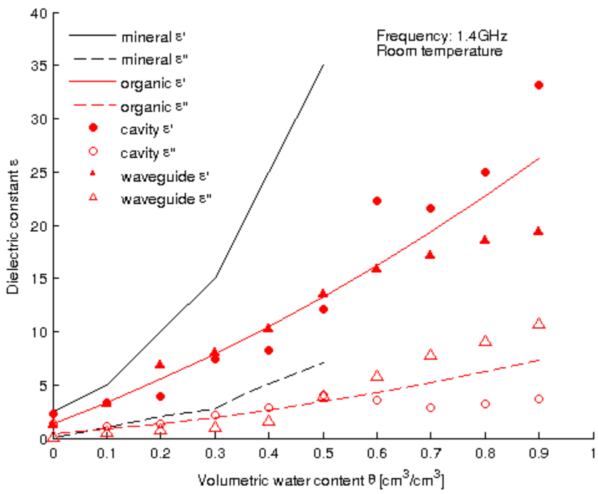

Figure 3: L-band dielectric constants (ε'/ε"), for an average mineral soil (Hallikainen et al., 1985) and fitted through preliminary wave-guide and cavity measurements of organic soil from the Sodankylä forest site.

organic sample from the Sodankylä forest site. Data is depicted over the entire wetness range including corresponding estimates for an average mineral soil after Hallikainen et al. (1985). Resonant cavity (1.48 GHz), and wave-guide (1.4 GHz) observations are in reasonable agreement. Consistent with the calibration data, lower values are observed for the organic material compared to the mineral soil.

V – CONCLUSIONS/OUTLOOK

Measurements of the two soil moisture sensors Decagon 5TE and Delta-T ThetaProbe for organic surface layers as well as sandy A-horizons from different sites in Denmark, Finland, Scotland and Russia show consistent trends. While the data from mineral horizons with low soil organic matter content are in good agreement with the manufacturer's default functions, adapted organic calibration functions are currently being derived. At the same time, other organic calibration curves, mainly derived for TDR sensors, are being tested. L-band dielectric constant measurements spanning a variety of humus types and water regimes, and using wave-guide as well as resonant cavity techniques are currently being analyzed. Existing work such as TDR observations in similar frequency domains will be considered. Also, the sensitivity of the organic matter's dielectric constant to varying frequency, notably between L-band and standard measurement frequencies of capacitance and impedance soil moisture probes (~50-100 MHz) shall be studied. These investigations will be presented during the Fourth International Symposium on Soil Water Measurements. In a next step, new SMOS soil moisture products will be retrieved over Northern regions using L-band dielectric constants adapted to measured values, and compared to re-calibrated in situ data.

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