GROUND WATER SURVEY WITH A NEW CAPACITANCE PROBE

Idris Bexi, Xavier Chavanne, Jean-Pierre Frangi
Equipe Géomatériaux & Environnement
Institut de Physique du Globe de Paris / Université de Djibouti

ABSTRACT

Original in-situ HF technique of material dielectric characterization in the 1-20 MHz have been developed and validated in order to estimate the moisture content of soils. The 1-20 MHz device is based on 2 electrodes put into the soil and separated from a distance of up to 30 cm. As the probe system is able to investigate several layers constituting a stacking of electrodes, a moisture profile of the soil can be obtained. The system is based on the determination of the complex impedance (ratio voltage/current through the soil impedance) in a variable frequency from 1 to 20 MHz. The measurement requires a calibration on several soil types to reach acceptable accuracy for water content. The design and data processing as well as preliminary results obtained from laboratory experiments are presented.

Keywords: dielectric measurement, impedance, permittivity, conductivity, moisture content, soil, capacitor, electromagnetic waves

INTRODUCTION

Soil moisture is a key variable in controlling the exchange of water and heat energy between the land surface and the atmosphere through evaporation and plant transpiration. The unsaturated zone between the Earth's soil surface and the water table –known as the "vadose" zone – is penetrated by the roots of vegetation, which take up some of the water. Hence, the amount of water in this zone, which determines the "soil moisture", varies with time as a function of the amount of precipitation and the root water take-up, governed by the degree of vegetation cover, the energy being received from the Sun, and run-off and percolation. As the properties of the soil determine its storage capacity and the transport process within the soil, such a topic concerns a wide range of scientists: hydrologists, climatologists, geophysicists, agronomists, geomorphologists. Among various techniques currently used (gravimetric, nuclear, electromagnetic, tensiometric, hygrometric, remote sensing processes), electromagnetic methods appear particularly attractive as they allow to infer soil moisture content by measuring the effective real or imaginary parts of the complex permittivity at different locations using reflected or transmitted waves [1, 2, 3, 4, 5]. Such techniques are generally divided into two categories, surface and drill-hole based measurements, which use open-ended transmission line or free-space methods. Among surface techniques, new developments have been performed which concern a capacitive probe HYMENET. This probes appear as a particularly simple and efficient tools to characterize the dielectric properties of the near surface of soft soils in broad frequency bands [0.1; 20] MHz.

In the present study, the dielectric characterization of soils and particularly their volumetric moisture content rely on the estimation of the real permittivity because of the great difference between the relative permittivity of water close to 80, and the relative permittivity of common dry soils ranging from 4 to 15. Afterwards, a non trivial relation between the real permittivity measured by the probe and the soil moisture content has to be found. The use of a mixture law allows us to solve a nonlinear inverse problem to obtain the parameters characterizing the constituents of the surrounding medium. In general, soil forms a heterogeneous material made of a mineral-air-water mixture. Thus, its dielectric properties are closely dependent on the dielectric constants of the individual constituents, the volume fractions of the components, the geometric characteristics of the constituents, and the electrochemical interactions between the constituents.

Concerning the dependence of a medium with moisture, several models have been proposed, each with its own characteristics and variables. Fundamental developments have been associated to the empirical formula of Topp et al. [6], to a three-phase model formulated by by de Loor [7], and to a four phase model proposed as a semi-disperse model by Wang and Schmugge [8], a semi-empirical power-law model by Dobson and Ulaby [9], and Peplinski et al. [10], and a generalized refractive dielectric model by Mironov et al. [11]. Recently, Boyarskii et al. [12] have suggested a model of the complex permittivity of bound water versus frequency in wet soils, and Jones et al. [13] have studied the effects of particle size on the bulk dielectric constant. In the present study, the volumetric moisture content (free water) of the soil has been deduced from the real part of the complex permittivity using parametric relations based on the polynomial Topp's formula, and an extended version of the CRIM (Complex refractive Index

Model) formulation [14]. The validation of experimental setup have been performed on experimental measurements associated with different types of sands. This article is focused on the development and the validation of the following novel in-situ device: the capacitive probe HYMENET. The design, the methodology, the data processing, as well as experimental results obtained from laboratory or in-situ experiments are detailed.

THE CAPACITIVE PROBE

Probe geometry and general considerations

The probe HYMENET (Figure. 1) works as an impedance meter working in the range [1; 20] MHz. Its measurement principle is based on the electrokinetic's theory where the scanned soil is considered as a capacitor (C) in parallel with a resistor (R). Because of the device main aim to study porous media filled with some fluids like water, air, or others constrains on its geometry and working frequency f have been imposed upon it. The geometry of the probe allows us to relate the permittivity measurement to a representative volume of the electrical properties of the medium [15]. The geometry must be also simple to derive easily the intrinsic properties of the medium (relative permittivity ε_r and conductivity σ) from R and C. The design consists on two parallel cylindrical electrodes for the probe as shown on Fig. 1. A tension of excitation V_{ex} is applied between the two electrodes plunged inside the medium to be characterized. Both V_{ex} and the resulting current are measured by an electronic board placed inside the ground electrode to deduce the impedance through the generalized Ohm's law. Thus, the impedance meter is able to determine separately the dielectric and conductive properties of the medium (ε_r and σ). This reduces interferences between both variables. One of the electrodes is divided vertically in equal parts of height h, or channels, electrically isolated from each other. This configuration allows to measure the current at different heights and hence to deduce the medium properties at these heights. It is used to study fluid vertical flows. The top and bottom parts assure that the electric field around electrodes is horizontal at the intermediate levels (this has been shown by numerical simulations, e.g. [16]). The two extreme channels constitute these shields while for each intermediate channels, ε_r and σ can be computed. Hence the electrode geometry can be considered as vertically infinite and the following formula can be applied for the impedance determined at each intermediate channel [17]:

$$C = \frac{h\pi\varepsilon_0\varepsilon_r}{\arg ch(\frac{D}{\phi})} \qquad \frac{1}{R} = \frac{h\pi\sigma}{\arg ch(\frac{D}{\phi})} \qquad (1)$$

with ε_0 is the absolute permittivity (8.85 10^{-12} F.m^{-1}) and ε_r the relative permittivity, argch is the inverse of hyperbolic cosine, D is the distance between two electrode axis, Φ is the electrode diameter and h the height of one channel of the ground electrode, and σ is the conductivity. For our current sensor h equals 45 mm, D is 90 mm and Φ is 50 mm. From relation 1, we deduce C(pF) = $1.04\times\varepsilon_r$ and R(Ω) = 9.2/σ. Typical values of ε_r expected for soils range from 3 to 50 [5], giving a capacitance between 3 and 50 pF. For soil bulk conductivity ranging from nearly 0 up to 0.5 S.m^{-1} the associated resistance value varies from infinity down to 20 Ω.

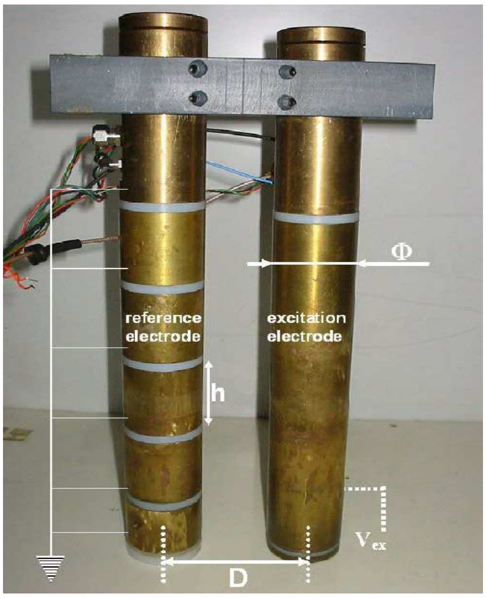

Figure 1: The HYMENET probe. D is the distance between the two electrodes axis, Ɵ the electrode diameter and h the height of one channel of the ground electrode.

Data acquisition and data processing

Different devices are used to power the apparatus (DC power supply HP E3631A), send the exciting voltage (Agilent generator up to 80 MHz HP 33250A), digitalize and record the different signals (Tektronics numerical scope TDS 3012B with analogue filter at 100 MHz, sampling frequency up to 1 GS/s, 8 bit nominal resolution and sensitivity down to 10 mV in full scale). The scope works with a numerical filter at 20 MHz and performs an average over 512 scope recordings to reduce the noise to signal ratio. Data are stored in a computer for further signal analysis (conversion in impedance and electric properties). Thanks to the overall system the medium properties can be monitored over a large period of time (from one hour to more than a month, depending also on the record capabilities of central unit) at different sampling frequencies down to 1 Hz, and the sensor is operating at frequencies up to 20 MHz. The reason is to reduce the sensitivity of εr to other parameters of the porous medium than the fluid permittivity like pore size and shape, or ionic content of fluids. Thus, εr appears as a good indicator of medium water content or fluids showing a strong permittivity contrast as compared with the dried medium. A system of relays and switches remotely operated allows to measure successively voltage and current (via a transimpedance) for each channel. Relays are controlled by a shift register driven by a computer with TTL signals. The same program also controls signals acquisition. The technical details of measurement chains are described in the patent above mentioned. We underline that high frequencies induce major electronic drawbacks like parasitic self inductances of conductors. Moreover, these disturbances grow roughly linearly with the size of the sensor. Consequently capacitors and self inductors will form resonators amplifying high frequency noises that induce voltage drops modifying the signal. A careful circuit design, avoiding some ground loops, plus some low band filters have permitted to control instabilities. The reference change between the different voltages is corrected by analog trim; for each the reference potential is measured and then subtracted to the voltage by on board integrated components placed before sensor output.

Calibration method

Calibration tests consist in connecting standard impedance between electrodes to determine probe systematic errors. Remaining systematic errors of the voltage after analog trim are due to self inductance of conductors (leads are necessary to connect the standard impedances at both electrodes, introducing other parasitic components to be removed), parasitic capacitance between close conductors, probe radiation losses and wire skin effect, and interferences between channels. Such errors are increased by frequency and impedance discrepancy between channels. The numerical program converting voltages into impedance includes parasitic effects corrections. It is based on a physical model (equivalent electric circuit) in which parasitic effects is represented by self-inductances and capacitances. Thus, for instance, coupling two electrodes next to each other corresponds to a capacity up to 10 pF. The model parameter values are determined through standard electronic components (capacitors composed of porcelain multilayer by American Technical Ceramics, accuracy +/- 1%; resistors are 1206 thick film components manufactured by Vishay, accuracy 0.1 %). This calibration is made using resistors values and reference capacitances. The parameters interfering in this model are thus also becoming instrument parameters highly independent of the studied area. This apparatus can then be used for measurements of unknown impedances, be they artificial (e.g., electronics components) or natural (e.g., soils).

Tests and experimental results

Various experiments have been set up to qualify the instrument. One should bear in mind that the moisture measures in probed area are obtained through in-situ calibration curves (like all capacitive methods) by relating relative permittivity to volumetric water content of the medium. The relative permittivity being obtained through probe impedance measurements, the first serial measures have been set up to determine the apparatus capacity to evaluate artificial impedances. To this aim, electronic components (such as resistors and capacitances) have been connected to electrodes using a large value scale ranging from 25 to 5000 Ω as for resistors and from 5 to70 pF as for capacitances. Different configurations have been tested: resistor or capacity alone or combinations of resistors and capacities on a single channel (complex impedance then created), and analyzing the influence of impedance measurements on a single channel when other impedance is present on other one (cross-talk test). Figure. 2 enables us to compare connected impedances and impedances measured by the probe. It reveals that HYMENET probe measurement corresponds precisely to the impedance values obtained through the electrodes whatever the frequency. We can determine the impedance with a resistive part from 0.025 to 5 kΩ and with a capacitive part between 5 to 70 pF. The precision margin arises maximum 5% when dealing with the extreme case of high impedance difference between two neighboring channels (as well as scarce case as for soil measurements). For further details on the calibration processus, the reader is referred to Chavannes 2009 [19].

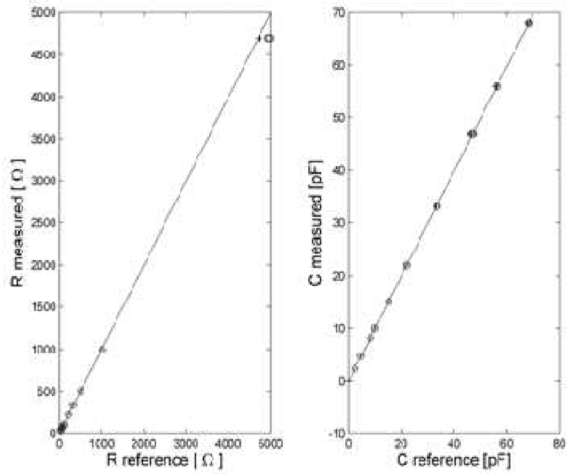

Figure 2: Impedance measurements (resistance on the left, capacitances on the right) for 10 MHz (cross) and 20 MHz (circles) with HYMENET probe.

The next stage consists in comparing the medium characteristics (εr, σ) obtained through those impedance measurements using relations 1. Such comparison entails the use of another apparatus as reference, which is very difficult since no apparatus has up to date been recognised reliable as to its permittivity measurements when electrodes are deported. In the absence of such apparatus, we have chosen the probe developed and commercialised by INRA (HMS9000 probe of SDEC company [20], Figure 3).

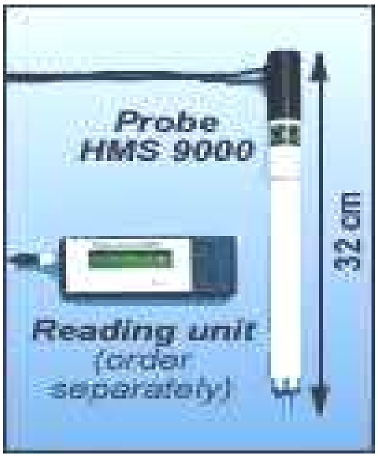

Figure 3: Capacitance probe HMS9000 of SDEC company.

The advantages of this probe are that it has already been studied and that its working frequency is 39 MHz, being then not too far from the frequencies used by HYMENET probes. The studied soil is a Fontainebleau sand (SiO2 > 99.8%, grain size distribution between 150 and 250 µm), which permittivity has been varied by modifying its moisture content. A certain quantity of dry sand has been put into a rectangular tub measuring 560×360×70 mm (to limit skin effect), into which two holes have been pierced for the introduction of the HYMENET probe Figure 4.

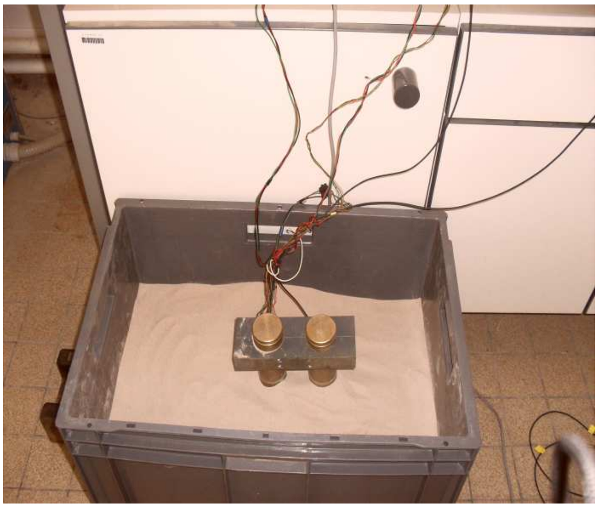

Figure 4: Rectangular tub measuring 560×360×70 mm, containing sand soil and HYMENET.

The height of the sand discharged into the tub corresponds to the height of a measurement channel (i.e. 50 mm). Distilled water has been added successively so as to obtain a volumetric humidity up to de 0.45 cm3.cm-3. Ten measurements have been taken for each water content so as to obtain a medium permittivity value, the probe HMS9000 being highly sensitive to the spatial heterogeneity due to its very low measure volume. Figure 5 shows the results obtained for two frequencies by the HYMENET probe (10 and 20 MHz).

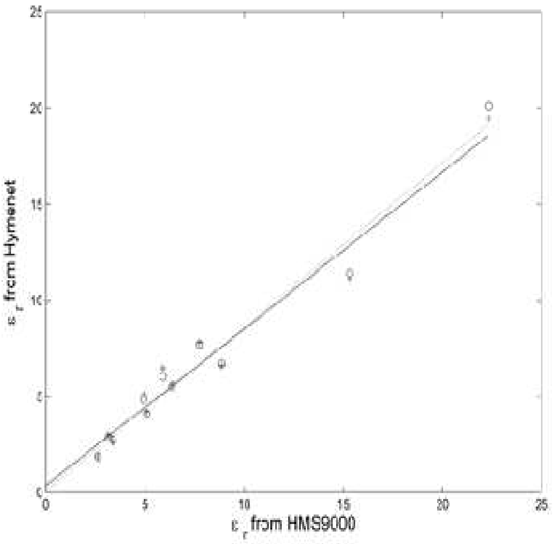

Figure 5: Relationship on the measured permittivity between HMS9000 probe (in abscissa) and HYMENET probe (in ordinate) at the 10 MHz frequency (cross) and 20 MHz (circle). Straight-lines are plotted for both (solid line for 10 MHz and dotted line for 20 MHz).

A very good correlation between the εr values between the two instruments is observed. For the measurements obtained at 10 MHz, the coefficients of the straight-line fit give a slope of 0.833 ± 0.051 and an intercept of -0.174 ± 0.580 with $R^2=0.9906$. For those obtained at 20 MHz, one have a slope of 0.871 ± 0.052, an intercept of -0.413 ± 0.586 with $R^2=0.9912$. The existence of a bias between the HYMENET et HMS9000 probes cannot be argued, even if at this stage determining which one is responsible is impossible. The HMS9000 measurements can be disturbed by the proximity of the electric field created by the HYMENET probe. Similarly, the latter can be disturbed by the current injection of the HMS9000 probe. This could be minor since moisture measurements entail calibration relation with in situ permittivity. However, further experiments using other apparatus (e.g. TDR) will soon be realised to clarify this point. The measurements obtained by the HYMENET probe can be reasonably considered as correct (with a very few percent of error). Experiments as to the medium moisture can then be carried out. This type of experiments are common (e.g. [21, 22]), and, as a first step, the relation between moisture content vs permittivity of Fontainebleau sand has been studied. This experiment has followed an experimental protocol identical to that used for the permittivity. Like permittivity measurements, Fontainebleau sand dried in drying oven has been humidified successively with a certain volume of distilled water and then homogenized. It appears useful to compare HYMENET measurements with the well-known "Topp curve" as a reference. Topp's calibration curve is generally accepted calibration equation for TDR water content measurements which is accurate for sand in general, but represents an average for a number of sandy-loam and clay-loam soils.

Figure. 6 shows the first results of this experiment and comparison with the Topp relation [23] valid for an average soil. $\varepsilon_r = 3.03 + 9.3\theta + 194\theta^2 - 76.6\theta^3$

It reveals that HYMENET measures do not depend on the frequency (corrections brought to the signal appearing as coherent), and that experimental curve trend follows that of Topp modelisation. The differences found between the calibration curve of Topp and the HYMENET data may be attributed to the dielectric behaviour of soils as a function of frequency due to Maxwell-Wagner effect, counterion polarisation and the impact of air bubbles, as highlight by Hilhorst [24].

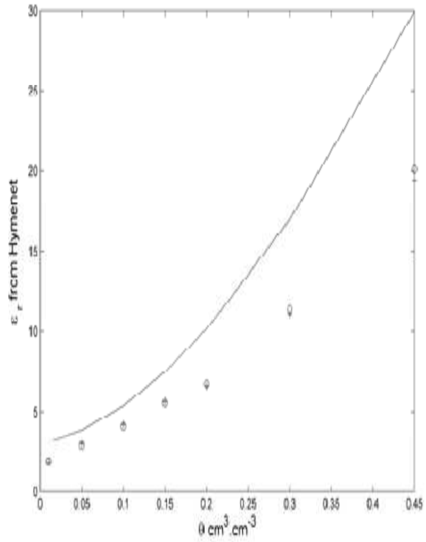

Figure 6: Volumetric water content relationship with measured permittivity by HYMENET probe at 10 MHz (cross) and 20 MHz (circle). The Topp (1980) relation is plotted (solid line).

CONCLUSION

This paper presents new instruments to characterize the moisture content of soft soils using two types of probes in a large frequency range 1-20 MHz and 0.1-4 GHz respectively. As far as the HYMENET probe is concerned, parasitic effects on the impedance measurements by the probe due to the frequency domain used imposed a sophisticated design of the electronics. However, an analog trim coupled with a physical model to take into account self-inductances and parasitic impedances enables the probe to measure the capacitance and the resistance of a medium at different frequencies. The model parameters have been estimated through a calibration process with standard capacitors and resistors. The model allows a determination of the impedance over its operating range of less than 5 % and mainly less than 1 %. An impedance profile can be traced since the conductors are separated along their length in different sections electrically insulated. It must be emphasized that the device determine the effective permittivity and conductivity (computed from the capacitance and the resistance) of the medium surrounding the electrodes, for a large area around the electrodes unlike others devices. This medium can be any porous medium filled with fluids, like a soil or a fresh concrete. Contrary to the TDR regarding which many studies have shown that relative permittivity is influenced by the conductivity (e.g., [2]), the measurement of the complex permittivity of soil with our device is not affected by the conductivity of the soil. Nevertheless, other experiments will be carried out to test the probe more precisely. Calibration tests with standard electronic components will be completed by using standard liquids (ethanol C_2H_5OH $\varepsilon r=24.3$ at 25°C, methanol CH_3OH $\varepsilon r=32.63$ at 25°C, and acetic acid CH_3COOH $\varepsilon r=6.18$ at 24°C). To insure the independency of the permittivity measurements to the conductivity, dedicated experiments will soon be realised by using distilled water with different ionic conductivities. The present system is intended for laboratory works. A more compact and rugged system with self-balanced bridge will substitute the present one and will be more convenient and cheaper for field studies. It will also allow a faster sampling frequency.

REFERENCES

[1] J., Behari, Microwave dielectric behavior of wet soils. Springer, 2005.

[2] J. E Campbell, Dielectrics properties and influence of conductivity in soils at one to fifty Meghertz, Soil Sc. Soc. Am. J. 54 (1990) 332-341.

[3] M.A. Hilhorst, Dielectric characterisation of soil, PhD Thesis, Wageningen, Holland, 1998, 141 p.

[4] J.A. Huisman, S.S. Hubbard, J.D. Redman, A.P. Annan, Measuring soil water content with ground penetrating radar: A review, Vadose Zone J. 2, Nov. 2003, pp. 476-491

[5] D.A. Robinson, S.B. Jones, J.M. Wraith, D. Or, S.P. Friedman, A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry, Vadose Zone J. 2, Nov. 2003, pp. 444-475

[6] G.C. Topp, J.L. Davis, A.P. Annan, Electromagnetic determination of soil water content: Measurements in coaxial transmission lines, Water Resour. Res. 16 (1980) 574-582.

[7] G.P. de Loor, The dielectric properties of wet soils, IEEE Trans. Geoscience Remote Sensing GE-21 (3), July 1983, 364-369

[8] J.R.Wang, T.J. Schmugge, An empirical model for the complex dielectric permittivity of soils as a function of water content, IEEE Trans. Geos. Remote Sens. 18 (1980) 288-295.

[9] M.C. Dobson, F. Kouyate, F.T. Ulaby, M.T. Hallikainen, M.A. El Rayes, Microwave dielectric behaviour of wet soil - Part II: Dielectric mixing models. IEEE Trans. Geoscience and Remote Sensing, 23 (1985) 51-61.

[10] N.R. Peplinski, F.T. Ulaby, M.C. Dobson, Dielectric properties of soils in the 0.3-1.3 GHz range, IEEE Trans. Geos. Remote Sens. 33 (3) (1995) 803-807.

[11] V.L. Mironov, M.C. Dobson, V.H. Kaupp, S.A. Komarov, V.N. Kleshchenko, Generalized refractive mixing dielectric model for moist soils, IEEE Trans. Geos. Remote Sens. 42 (2004) 773-785.

[12] D.A. Boyarskii, V.V. Tikhonov, N.Y. Komarova, Model of dielectric constant of bound water in soil for applications of microwave remote sensing, PIER 35 (2002) 251-269.

[13] S.B. Jones, S.P. Friedman, Particle shape effects on the effective permittivity of anisotropic or isotropic media consisting of aligned or randomly oriented ellipsoidal particle, Water Resour. Res., 36 (2000) 2821-2833.

[14] JM.C. Dobson, F. Kouyate, F.T. Ulaby, M.T. Hallikainen, M.A. El Rayes, Microwave dielectric behaviour of wet soil - Part II: Dielectric mixing models. IEEE Trans. Geoscience and Remote Sensing, 23 (1985) 51-61. [15] G. de Rosny, A. Chanzy, M. Pardé, J.C. Gaudu, J.-P. Frangi, J.-P. Laurent, Numerical Modeling of a Capacitance Probe Response, Soil Sci. Soc. Am. J. 65 (2001) 13-18.

[15] J.-P. Frangi, G. de Rosny, X. Chavanne, D. Richard, A. Bruère,. Device for measuring electrical properties of a water-containing medium. World Intellectual Property Org. WO/2008/006973, Patent PCT/FR2007/01180, publication date: 17.01.2008.

[16] G. de Rosny, A. Chanzy, M. Pardé, J.C. Gaudu, J.-P. Frangi, J.-P. Laurent, Numerical Modeling of a Capacitance Probe Response, Soil Sci. Soc. Am. J. 65 (2001) 13-18..

[17] E. Durand, Electrostatique, Masson, Paris, 1966, 389 p.
J. E Campbell, Dielectrics properties and influence of conductivity in soils at one to fifty Meghertz, Soil Sc. Soc. Am. J. 54 (1990) 332-341.

[18] A. Chanzy, J. Chadoeuf, J.-C. Gaudu, D. Mohrath, G. Richard, L. Bruckler, Soil moisture monitoring at the field scale using automatic capacitance probes, Eur. J. Soil Sci. 49 (1998) 637–648.

[19] Chavannes X,Frangi, A new device for *in situ* measurement of an impedance profile at 1 to 20 MHz, Instrumentation and Measurement, IEEE Transactions on(2009), 1850 - 1859

[20] A. Chanzy, J. Chadoeuf, J.-C. Gaudu, D. Mohrath, G. Richard, L. Bruckler, Soil moisture monitoring at the field scale using automatic capacitance probes, Eur. J. Soil Sci. 49 (1998) 637–648.

[21] C.M.K. Gardner, T.J. Dean, J.D. Cooper. Soil Water Content Measurement with a High-Frequency Capacitance Sensor, J. agric. Engng Res. 71 (1998) 395-403.

[22] G.C. Topp, J.L. Davis, A.P. Annan, Electromagnetic determination of soil water content: Measurements in coaxial transmission lines, Water Resour. Res. 16 (1980) 574-582.

[23] M.A. Hilhorst, Dielectric characterisation of soil, PhD Thesis, Wageningen, Holland, 1998, 141 p.