An innovative dielectric method for profiling soil water content

Pascal Xavier[1], Franscisco Antuña Roces[1], Jean Paul Laurent[2], Bernard Mercier[2]
[1] IMEP-LAHC, UMR 5130, CNRS-INPG-UJF-U.Savoie, Minatec, Grenoble, France
[2] LTHE, UMR 5564, CNRS-INPG-IRD-UJF Grenoble, France

ABSTRACT. A prototype of a low cost profilometric probe has been designed and realized using standard PCB hybrid technology and SMC components. It is based on an innovative and patented method of standing waves sampling in a waveguide. It is intended to perform non destructive RF broadband measurements for soil spectroscopic dielectric permittivity profiling, in order to quantify the soil water profile, and also the dispersion and attenuation of the electromagnetic waves occurring in the media. Experimental results in standard media are presented in order to validate the concept.
Keywords: soil water content, profile, dielectric methods, RF measurements

1 Introduction

Profiling soil water content is of major interest in the field of hydrology. Several systems already exist for this purpose: neutron probes, TDR operating in access tube (“TRIME-FM® + T3 tube probe” from Imko Gmbh) [1], multi-sensor or multi-segment capacitance probes (“Enviroscan®” from Sentek Sensor Technologies, “Profile-Probe” from Delta-T Devices, “Moisture•Point®” from Environmental Sensors Inc”…). Some other profiling methods using a single long probe are rather based on inversion techniques somewhat a little bit complex [2].

At the Laboratoire d’étude des Transferts en Hydrologie et l’Environnement (LTHE) in Grenoble, dielectric methods for measuring soil moisture have been developed and tested for many years (capacitive probes, Time Domain Reflectometry TDR [3]). It has been shown then that the operating frequency has to be taken into account for the analysis of the measured permittivity value. In fact, in a moist porous media such as a soil, dispersion and attenuation of the electromagnetic traveling are occurring to variable extends depending on the mineralogy, solute content... To quantify such phenomena, broadband analysis of the complex permittivity has to be performed by impedance spectroscopy. First measurements were done with standard Vector Network Analyzers (VNA) and matched probes, between 10 MHz and 2 GHz, using a simple resonance method [4]. More recently, a low cost portable six-port reflectometer has been realized [5] to perform broadband measurements in outdoor conditions. We now propose an innovative device that measures instantaneously changes of the material’s permittivity along the probe placed in the porous media in a frequency range between 100 MHz and 1 GHz and without any inversion technique.

2 Measurement Principle

The measurement principle proposed here is based on the operation of the patented “RF SWIFTS” [6] developed at the IMEP-LAHC since it is a probe consisting in a transmission line terminated by an open circuit and periodically loaded with sampling power detectors.

When the probe is fed with a sinusoidal RF source, the detectors measure the amplitude of the standing wave which arises in the probe: signal processing is providing the wavelengths and amplitudes that allow to trace permittivity of the medium at each sampled point and this for any frequency provided by the RF generator. This gives the permittivity profile of the medium all along the probe. That’s why we have called our device “SWIP” for Standing Wave Interferometric Profilometer. Time dependence of the permittivity can also be easily measured.

For instance, figure 1 is showing what happens when the medium is homogeneous. Two minima of the standing wave are separated by $\lambda/2$ where λ is the guided wavelength. The formula (1) can be applied, where c is the light velocity, f is the frequency and ε_{eff} is the effective permittivity:

$$\varepsilon_{eff} = \left(\frac{c}{f\lambda}\right)^2 \qquad (1)$$

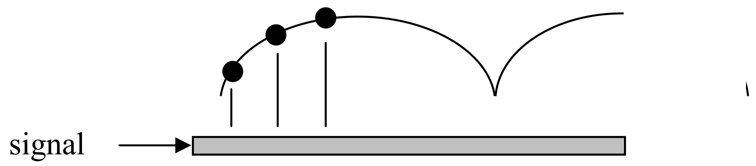

Fig. 1: spatial sampling (points) of the standing wave (in dark) occurring in an open circuited waveguide (in grey)

3 Device Design and Realization

The sampling detectors were chosen to be AD8362 integrated circuits because of their broadband behaviour, high dynamics, low cost and linearity. Taking into account the permittivity range of typical soils (3 to 60), the distance between two adjacent sampling detectors has been fixed to 1 cm. A coplanar waveguide structure (CPW) was also chosen to realize a first prototype of the SWIP (figure 2) with 16 detectors on a FR4 substrate. Although this structure is non-homogeneous, the gap between the ground plane and the main line is set to 3 cm in order to have sufficient electromagnetic fields in the medium and so an effective permittivity close to the one of the medium. The circuitry around the detector was optimized for a good sampling without destroying the standing wave.

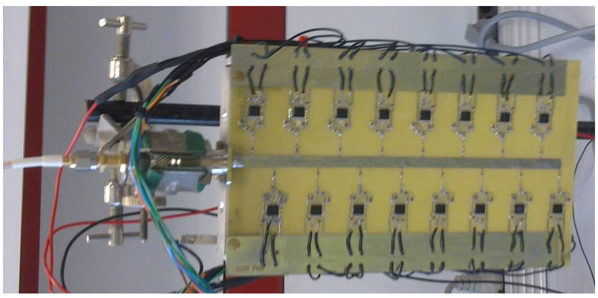

Fig. 2: Photograph of the SWIP prototype

4 Experimental Results

An RF Source Marconi 6202B was used to provide the signal into the probe with a power of 5 dBm and a frequency between 50 MHz and 650 MHz. An Agilent 34970A multimeter with its multiplexer was also used for the voltages measurements of the 16 detectors. The SWIP probe has been put in different standard media: air, distilled water, methanol, 1-butanol.

Figure 3 is showing the obtained voltages at the outputs of the detectors in air for several frequencies. From 50 MHz to 650 MHz, the higher is the frequency, the better we can see the standing wave and its minima or maxima.

Above 650 MHz, a drastic increase in the amount of sampled energy by each detector was observed due to stub effects in the circuitry, which create too much perturbation of the standing wave to obtain relevant measurements. Of course, this cut-off frequency is permittivity dependent so that it decreases when the medium permittivity increases. For example, in distilled water (ε_r = 80) this cut-off frequency is near 250 MHz.

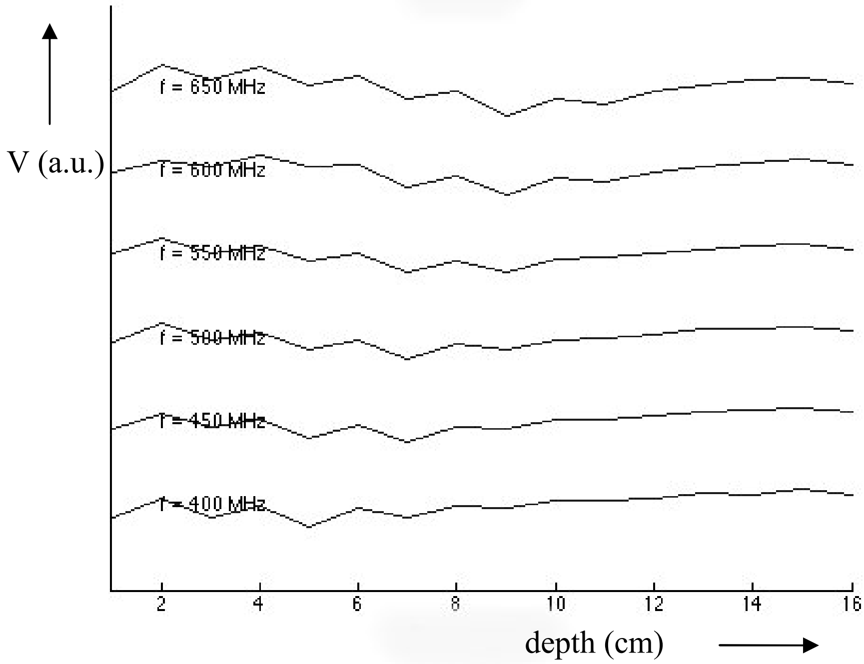

Fig. 3: Voltages in arbitrary units measured in air at the outputs of the detectors in function of the frequency and of the depth (the curves have been shifted on y axis for clarity)

Figure 4 is showing the voltages in function of the depth obtained in air at 600 MHz. The standing wave is clearly seen although there is some residual oscillations due to the dissymmetry of our CPW structure. Despite the poor accuracy of this first uncalibrated prototype, according to equation (1), the effective permittivity seems to be close to 2 since the distance between a minimum and a maximum is between 7 and 8 cm. This is confirmed by TDR measurements of the probe in air on an Agilent 86100A and HFSS simulations of the CPW structure.

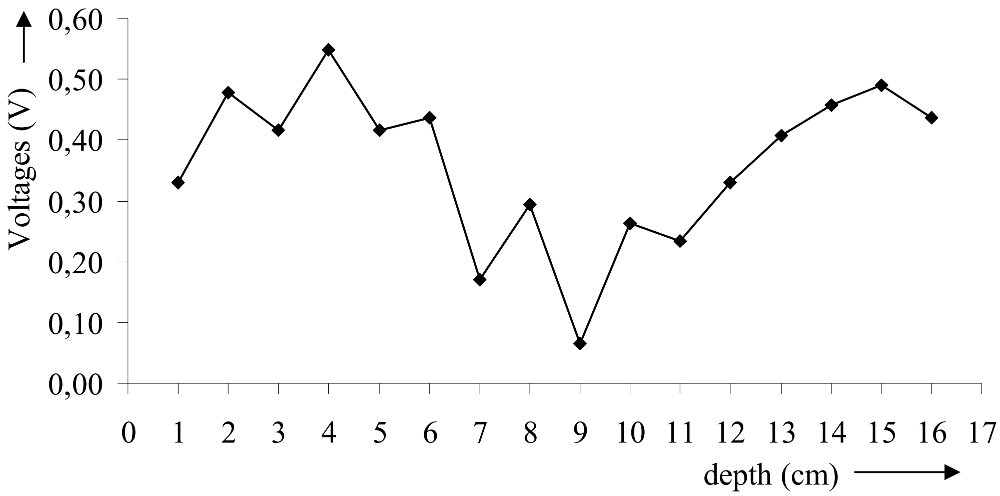

Fig. 4: Standing wave measured at 600 MHz in air

Measurements obtained in distilled water and in methanol at 150 MHz are shown in figure 5 and 6 respectively. The standing waves are also very clear and the variation of the deduced wavelengths seems to be in accordance with the relative permittivity of both media (ε_r = 80 for distilled water and ε_r = 32.6 for methanol).

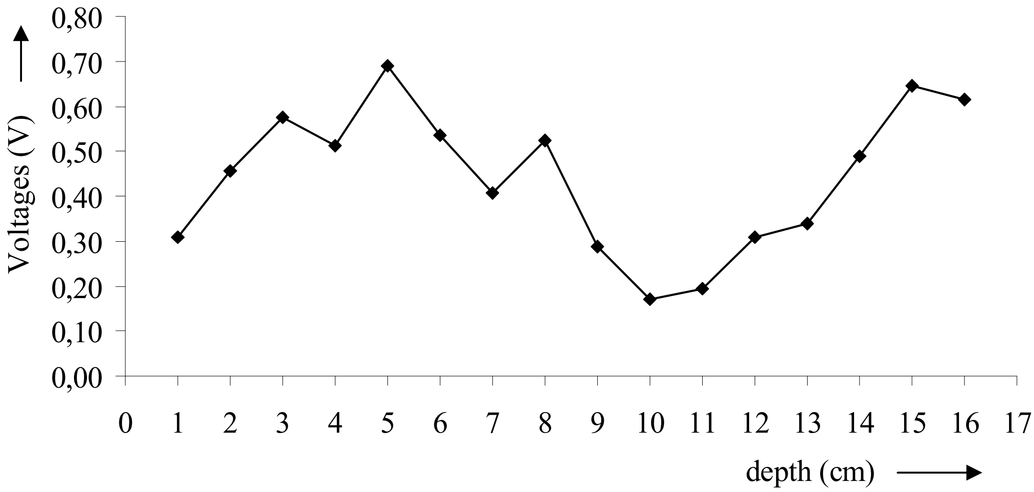

Fig. 5: Standing wave measured at 150 MHz in distilled water

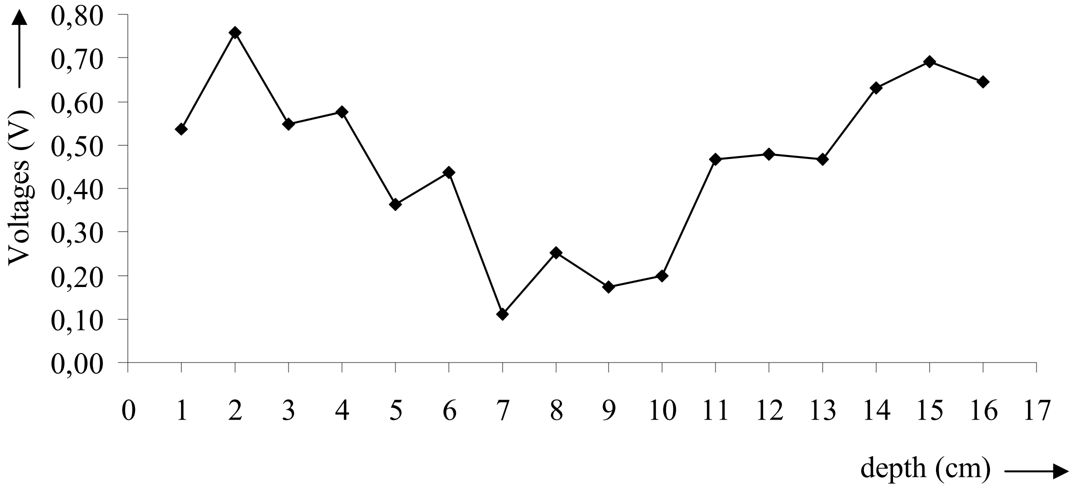

Fig. 6: Standing wave measured at 150 MHz in methanol

The probe has been put in 1-butanol too, a solvent which has some relaxation and losses. In that case, the standing wave is still detected for instance at 100 MHz as shown in figure 7.

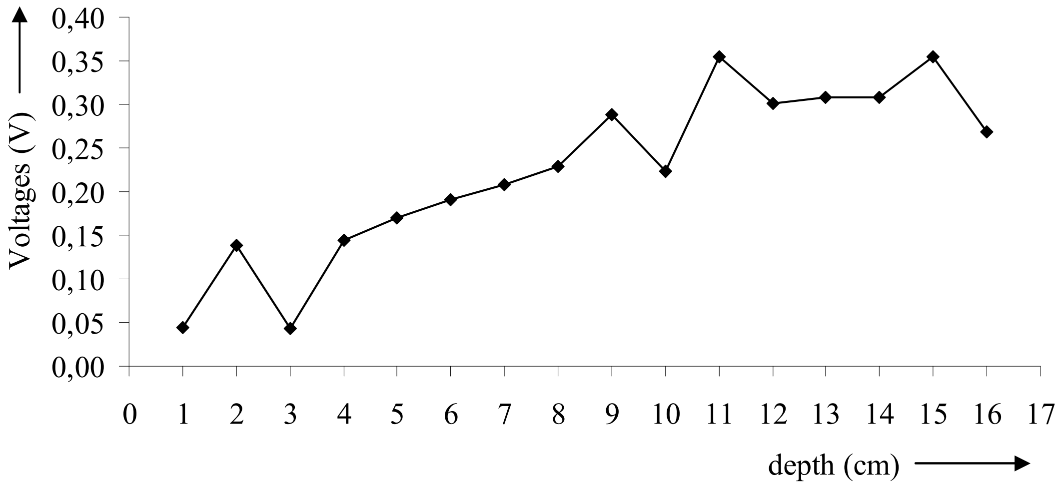

Fig. 7: Standing wave measured at 100 MHz in 1-butanol

Finally, to validate the concept for irrigation control applications, we tested the probe at 200 MHz in a mixing of glass marbles progressively filled with distilled water. The frontier between the dry zone and the wet zone can be easily determined at each height of water h, as it is shown in figure 8. A straight dashed line is added on this figure to simply and easily distinguish between the two observed behaviours of the standing waves.

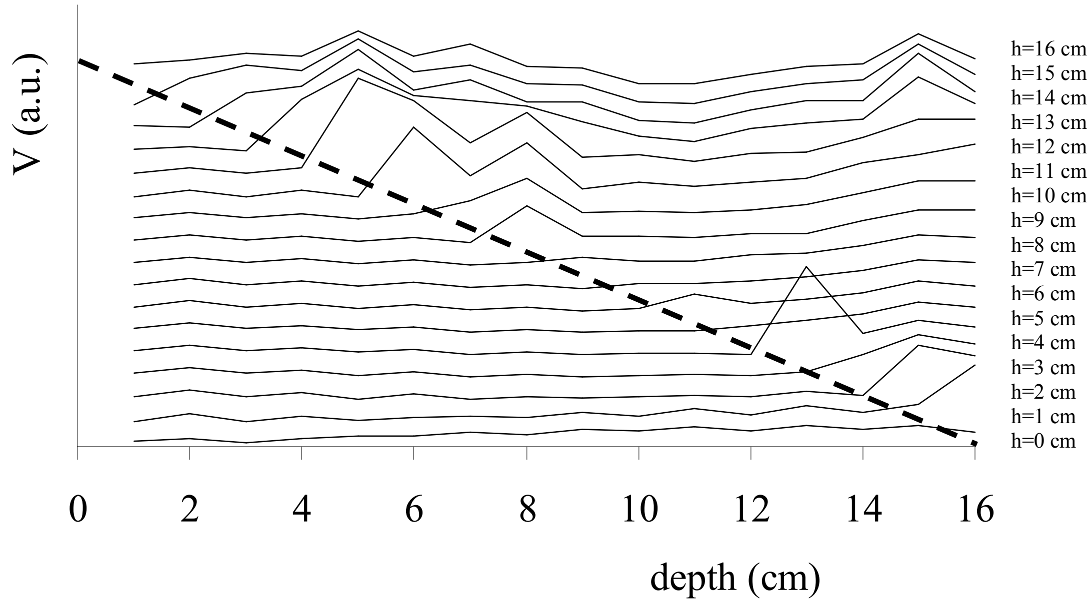

Fig. 8: Voltages (in arbitrary units) measured at 200 MHz in a mixing of glass marbles progressively filled with distilled water (the curves have been shifted on y axis for clarity).

5 Conclusions

A first SWIP probe prototype has been designed and realized. The detection of the standing waves in this probe is very easy and it is shown that it is possible to follow the variation of the medium permittivity with the measurements of the sampling detectors voltages. It is also established that we can estimate the water profile along the probe in the medium. Further experiments and developments are necessary to improve the accuracy of the device and its spatial resolution, in particular concerning calibration aspects.

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Contact point: Pr. Pascal Xavier, IMEP-LAHC, MINATEC Grenoble, 3 Parvis Louis Néel, BP 257, 38016 Grenoble Cedex 1, France ; Phone: + 33-0456-529-569; Fax: + 33-0456-529-501; E-mail: pascal.xavier@ujf-grenoble.fr