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New *in situ* techniques for the estimation of the dielectric properties and moisture content of soils

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Abstract

Two original *in situ* HF techniques of dielectric characterization in two wide bands have been developed in order to estimate the moisture content of soils by complex impedance measurement. These techniques are based on the capacitive effect (1–20 MHz) and on the propagation of electromagnetic waves at high frequencies (0.1–4 GHz). The two measurement techniques use straight conductors that are inserted into the soil. Specific inversion algorithms were developed to estimate the apparent real permittivity of the soil versus frequency from the complex impedance. The validation of both instruments was made in the laboratory in the presence of dry and wet sands. *In situ* experiments were also made at high frequencies. These complementary devices should enlarge the range of usual soil moisture measurement techniques. ***To cite this article: J.-P. Frangi et al., C. R. Geoscience 341 (2009).***

Résumé

Nouvelles techniques *in situ* pour estimer les propriétés diélectriques et la teneur en eau des sols. Deux techniques d'hyperfréquences originales de caractérisation diélectrique *in situ* dans deux bandes larges de fréquence ont été développées, afin d'estimer la teneur en eau de sols par des mesures d'impédance complexe. Ces techniques sont fondées sur l'effet capacitif (1–20 MHz) et sur la propagation des ondes électromagnétiques en hautes fréquences (0,1–4 GHz). Les deux instruments de mesure sont constitués de conducteurs droits qui sont enfouis dans le sol. Des algorithmes d'inversion spécifiques ont été développés en vue d'estimer la permittivité réelle apparente du sol, en fonction de la fréquence à partir de l'impédance complexe. La validation a été réalisée en laboratoire sur des sables secs et humides et sur le terrain pour l'instrument hautes fréquences. Ces moyens de mesure doivent élargir le choix des techniques de mesure d'humidité dans les sols. ***Pour citer cet article : J.-P. Frangi et al., C. R. Geoscience 341 (2009).***

Keywords: Capacitance; Dielectric characterization; Hyperfrequency; Moisture content; Monopole; Permittivity; Soil

Mots clés : Capacité ; Caractérisation diélectrique ; Hyperfréquence ; Teneur en eau ; Monopôle ; Permittivité ; Sol

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1. Introduction

Various techniques have been developed for measuring moisture content in soils, including microwave radiometry [19], neutron probe [18], nuclear magnetic resonance (NMR) [34], ground penetrating radar (GPR) technology [6], frequency domain or time domain reflectometry [1,6,31], and the dual-probe heat-pulse method [35]. A soil is generally a complex mixture of air, water and soil particles. The potential usefulness of electromagnetic (EM) waves for soil dielectric characterization has long been recognized because of their non-destructive properties [6].

The interaction between an external electric field and a soil–water system can be characterized in terms of polarization and conduction. Polarization represents the ability of a material to store electrical charge, while conduction refers to the mobility of electrical charges through a material. The electrical permittivity is the parameter that reflects the combination of these 2 responses. The apparent (effective) complex permittivity $\tilde{\varepsilon}_{\text{eff}}$ of a soil depends on physical, mechanical and chemical parameters. Water content in a soil appears to be the major changing constituent of the apparent permittivity. As water has the largest real permittivity value (close to 80 [22]) as compared to the real permittivity of dry soils (ranging from 3 to 15), the measurement of the permittivity $\varepsilon'_{\text{eff}}$ of a soil will be highly dependent on its moisture content. Many empirical and semi-empirical relationships between volumetric moisture content θ and the apparent real permittivity $\varepsilon'_{\text{eff}}$ of a soil have been proposed [1]: e.g., the empirical formula of Topp et al. [33], the three-phase model formulated by Polder and Van Santen [27], and by de Loor [8], and the four-phase model proposed as a semi-disperse model by Wang and Schmugge [36], the semi-empirical power-law model by Dobson et al. [10], and Peplinski et al. [26], and the generalized refractive dielectric model by Mironov et al. [23].

This paper presents a broadband (1–20 MHz, and 0.1–4 GHz) characterization of soils using two original *in situ* techniques for measuring dielectric properties as a function of the frequency. They are based on two physical principles: the electrokinetic theory (1–20 MHz), which deals with the capacitive effect (Hygrometric Measurement Network [HYMENET] probe), and the EM propagation theory (0.1–4 GHz), which describes radiation and propagation of waves inside a medium (monopole probe). Both devices could be considered to be new measurement tools able to enlarge the spectrum of usual techniques (TDR, GPR...). In section 2, definitions relative to parameters involved in the working principles of both instruments are given. In sections 3 and 4, details concerning the geometry, the measurement method, and data processing of each measurement tool, the HYMENET and the monopole probes, are presented. The validation of both probes was obtained in the presence of several types of dry and wet sand in the laboratory.

2. Parameter definitions

The fundamental electrical property describing the interactions between the applied electric field and a material (here a soil) is the apparent (effective) complex relative permittivity $\tilde{\varepsilon}_{\text{eff}}$ defined as follows:

$$\tilde{\varepsilon}_{\text{eff}} = \varepsilon'_{\text{eff}} - j\varepsilon''_{\text{eff}} \tag{1}$$

where $\varepsilon'_{\text{eff}}$ is the real part, often called the dielectric constant, and $\varepsilon''_{\text{eff}}$ is the imaginary part of $\tilde{\varepsilon}_{\text{eff}}$.

A dielectric material has an arrangement of electric charge carriers that can be displaced or polarized in an external electric field [1,6]. Water is an example of a substance which shows a strong orientation polarization. As ionic conductivity σ (S.m^{-1}), mainly present at low frequencies, introduces losses into the material, dielectric losses ε''_d due to the dielectric polarization of the particles in an alternating electric field have a dominant effect in the loss component at high frequencies. Thus, the imaginary permittivity can be written as follows:

$$\varepsilon''_{eff} = \varepsilon''_d + \frac{\sigma}{2\pi f \varepsilon_0} \tag{2}$$

where ε_0 is the dielectric permittivity of free space, and f the frequency of the electric field.

Both measurement techniques based on the use of the HYMENET and the monopole probes, suppose that the probes are immersed in the soil, so their complex impedance $\tilde{Z}11$ is modified. While a distributed impedance $\tilde{Z}(h)$ can be measured along the HYMENET probe, an input impedance $\tilde{Z}11$ is measured with the monopole probe. In practice, in the case of the monopole probe, an input reflection coefficient $\tilde{S}11$ is measured using a Vector Network Analyser (VNA). The reflection coefficient $\tilde{S}11(\omega)$ is related to the input impedance $\tilde{Z}11(\omega)$ for electrically thick samples as follows [1]:

$$\tilde{S}11(\omega) = \frac{\tilde{Z}11(\omega) - Z_0}{\tilde{Z}11(\omega) + Z_0} \tag{3}$$

with Z_0 the characteristic impedance of the coaxial transmission line which, in our case, is equal to 50 Ω.