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Original
GNSS Reflectometry Systems for soil permittivity determination / Savi, P.; Bertoldo, S.; Milani, A.. - ELETTRONICO. - (2019), pp. 1-4. (Intervento presentato al convegno 13th European Conference on Antennas and Propagation (EuCAP) tenutosi a Krakow, Poland nel 31 March- 5 April).

Availability:
This version is available at: 11583/2730207 since: 2019-09-16T15:33:10Z

Publisher:
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20 September 2024

GNSS Reflectometry Systems for soil permittivity determination

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***Abstract*—Global Navigation Satellite System Reflectometry (GNSS-R) can be successfully used to obtain information about the composition or the properties of ground surfaces, by analyzing GPS signals reflected by the ground. The received power of these signals is proportional to the moduli of the perpendicular and parallel polarization Fresnel coefficients, which in turn depend on the incidence angle and the ground's permittivity, a parameter related to the ground surface's physical properties. The goal is then to obtain the value of permittivity from the known value of the angle of incidence and the values of the Fresnel reflection coefficients, as measured by an automatic GNSS-R system. In general, the permittivity is a complex number: in some cases (e.g. for non-dispersive soils), its imaginary part can be neglected, and the permittivity can be assumed to be a real number. In this case, it is possible to solve the Fresnel reflection coefficients explicitly in terms of the permittivity. The corresponding solution formulas can then be used also to verify the validity of other empirical methods of determination of the permittivity. In this work, we present these formulas, and present a set of their verification, against know values of the permittivity obtained by independent measurements.**

Index Terms— GNSS-R, GNSS ***systems, soil properties, permittivity, Fresnel coefficients, non-dispersive media.***

I. INTRODUCTION

GNSS-R is a technique for remote sensing of the Earth surface, in which GNSS signals reflected off the ground are detected and processed, thereby providing a means to study and monitor the ground's properties remotely. This technique is a particularly relevant in the areas of climate modelling and weather prediction; its implementation uses a passive bi-static radar configuration, which requires no transmitters other than GNSS satellites, thus enabling the system to be light and compact (see e.g. [1]-[11]). The Signal to Noise (SNR) data recorded by GNSS receivers is related to the direct signals, and signals reflected from the ground. Assuming the surface to be flat, and considering a receiving antenna vertically or horizontally polarized, the SNR is related to the Fresnel reflection coefficients for vertical and horizontal polarization, which are functions of the relative permittivity of the soil and of the incidence angle [12]. The relative permittivity of the soil is generally obtained by solving numerically the Fresnel coefficients, from which the soil moisture can be obtained from models as [13], [14].

In this work, we consider a special case of the Fresnel coefficients, in which we measure the horizontal reflection coefficient (or normal coefficient, TE), and the vertical reflection coefficient (or parallel coefficient, TM), for a non-dispersive ground surface. We present the corresponding explicit formulas, which provide the value of permittivity of the surface, as well as some preliminary results to confirm their validity. Thus, these formulas provide a simple and direct way to evaluate the permittivity of a non-dispersive medium by means of the measurements obtained an automatic GNSS-R system.

II. STATE OF THE PROBLEM

A standard GNSS-R system collects the signals coming from the satellites after reflection from the ground [15,16]. More sophisticated systems collect both the direct signal and the reflected signal, thus also allowing the analysis of the ratio of the direct signal versus the reflected signal (polarimetric measurements) [8,17,18] (see Fig. 1). Most GNSS-R systems work with circular polarization, i.e. with the direct signal from the satellite Right Hand Circularly Polarized (RHCP) and the reflected signal mainly Left Hand Circularly Polarized (LHCP). However, measurements have also been performed with linear polarization (vertical and horizontal) [19].

The power scattered by the surface of the ground, close to the reflection point, can be considered as the sum of two contributions: coherent and non-coherent power. If the surface is assumed to be perfectly smooth, the non-coherent power scattered by the glistening zone is negligible.

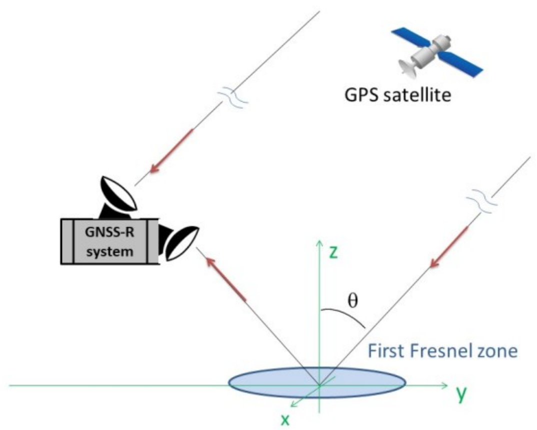

Fig. 1. Measurement setup scheme.

The contribution of the coherent component of the power is described by the bi-static radar equation, in which the received power is linearly dependent on the radar reflectivity R_{ij} [20]:

$$P_{RX}^{Coh} = \frac{P_{TX} G_{TX} G_{RX}}{4\pi (R_1+R_2)^2} \frac{\lambda}{4\pi} R_{ij} \quad (1)$$

where i, j, represent a generic polarization; P_{RX}^{Coh} is the coherently reflected signal power; P_{TX} is the transmitted power; G_{TX} (G_{RX}) is the transmitter (receiver) antenna gain; λ is the wavelength (19 cm for GPS L1); R_1 is the distance between the transmitter and the specular reflection point; and R_2 is the distance between this point and the receiver.

The radar reflectivity depends on the scattering properties of the ground (soil coverage/moisture and roughness). The roughness of most natural surfaces can be well modelled by a Gaussian height distribution, with zero mean and a given variance. Under this assumption, the reflectivity R_{ij} can be written as:

$$R_{ij} = \left|\Gamma_{ij}(\theta, \varepsilon_r)\right|^2 \exp(-h\cos^2\theta) \quad (2)$$

where Γ_{ij} is the Fresnel reflection coefficient of the equivalent smooth surface, which depends on the incidence angle and on the relative permittivity of the surface ε_r, and h is the roughness parameter. Assuming a perfectly smooth surface, the contribution related to the roughness parameter h is almost zero.

The relative permittivity can be evaluated by solving the Fresnel reflection coefficients

$$\Gamma_n = \frac{\cos\theta - \sqrt{\varepsilon_r - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}} \quad (3)$$

$$\Gamma_p = \frac{\varepsilon_r\cos\theta - \sqrt{\varepsilon_r - \sin^2\theta}}{\varepsilon_r\cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}} \quad (4)$$

This is particularly simple for non-dispersive media, for which the permittivity can be assumed to be a real parameter. In this case, as detailed in [21], starting from the horizontal reflection coefficient, the permittivity is given by the explicit formula

$$\varepsilon_n = 1 + \frac{4|\Gamma_n|\cos^2\theta}{(1-|\Gamma_n|)^2} \quad (5)$$

The permittivity can be obtained also from the vertical polarization reflection coefficient $|\Gamma_p|$. In this case, it is necessary to know Brewster angle θ_B; then,

$$\varepsilon_p = \left(\mu_p + \mathrm{sgn}(\theta_1 - \theta)\sqrt{\left(\mu_p^2 - \sin^2(2\theta)\right)}\right) \quad (6)$$

where θ_1 depends on the Brewster angle:

$$\theta_1 = \begin{cases} \frac{\pi}{2} & \text{if} \quad \tan^2\theta_B \geq 2 \\ \arcsin\left(\frac{1}{\sqrt{2}}\tan\theta_B\right) & \text{if} \quad \theta_B \leq \theta \leq \frac{\pi}{2} \end{cases} \quad (7)$$

and

$$\mu_p = \begin{cases} \frac{1+|\Gamma_p|}{1-|\Gamma_p|} & \text{if} \quad 0 \leq \theta \leq \theta_B \\ \frac{1-|\Gamma_p|}{1+|\Gamma_p|} & \text{if} \quad \theta_B \leq \theta \leq \frac{\pi}{2} \end{cases} \quad (8)$$

The two expressions (5) and (6) coincide if and only if the following compatibility conditions hold in $\left[0, \frac{\pi}{2}\right[$:

$$\lambda_n^2\cos^2\theta + \sin^2\theta = \lambda_p\mu_p \quad (9)$$

$$\begin{aligned} |\Gamma_p| \leq |\Gamma_n|^2 \quad & \text{if} \quad \theta_B \leq \theta \leq \theta_1 \\ |\Gamma_n|^2 \leq |\Gamma_p| \quad & \text{if} \quad \theta_1 \leq \theta \leq \frac{\pi}{2} \end{aligned} \quad (10)$$

In this case, the common value of the permittivity is

$$\varepsilon_c = \lambda_n\,\mu_p \quad (11)$$

On the other hand, if the Brewster angle θ_B is known,

$$\varepsilon_r = \tan^2\theta_B \quad (12)$$

and the values given by (11) and (12) coincide.

The value of the permittivity given by equations (5), (6), (11) and (12) can be easily computed in an automatic GNSS reflectometry system.

If the acquisition system works with circular polarizations, the observable parameters Γ_{LR} and Γ_{RR} represent the co-polar and cross-polar reflectivity. The reflection coefficients (LR and RR) can be written as a combination of vertical and horizontal polarizations [12]:

$$\Gamma_{LR} = \frac{1}{2}\left(\Gamma_n - \Gamma_p\right), \qquad \Gamma_{RR} = \frac{1}{2}\left(\Gamma_n + \Gamma_p\right) \quad (13)$$

The magnitude of vertical and horizontal Fresnel coefficients can then be determined from (13):

$$|\Gamma_n| = \frac{1}{2}\left(\left|\Gamma_n - \Gamma_p\right| + \left|\Gamma_n + \Gamma_p\right|\right) \quad (14a)$$

$$\left|\Gamma_p\right| = \frac{1}{2}\left|\left(\left|\Gamma_n - \Gamma_p\right| - \left|\Gamma_n + \Gamma_p\right|\right)\right| \quad (14b)$$

and the permittivity can be evaluated with the same formulas (5,6,11).

TABLE I. MATERIALS AND RELATIVE PERMITTIVIY

Material	ε_r
Sand	3
Snow	4
Soil	6
Common glass (average)	7.5
Melting ice	15
Ethanol	25
Water	80

TABLE II. RELATIVE ERRORS IN THE EVALUATION OF THE FORMULAS (5), (6), (11) FOR REAL VALUES OF PERMITTIVITY

Material	ε_r	$\Delta\varepsilon_n$ ($\cdot 10^{13}$)	$\Delta\varepsilon_p$ ($\cdot 10^{14}$)	$\Delta\varepsilon_c$ ($\cdot 10^{14}$)
Sand	3	0.027	0.281	0.266
Snow	4	0.033	0.089	0.255
Soil	6	0.028	0.089	0.178
Common glass	7.5	0.032	0.059	0.154
Melting ice	15	0.013	0.071	0.083
Ethanol	25	0.084	0.071	0.441
Water	80	0.137	0.195	0.693

III. RESULTS

As a first example, we consider the real permittivity values of some standard materials (see Table I, [22, 23]) and we compute the corresponding linear reflection coefficients Γ_n and Γ_p as a function of the incidence angle θ (see Fig. 2 and Fig. 3 respectively).

The values of the modules of Γ_n and Γ_p were inserted in equations (5), (6) and (11) to evaluate the relative permittivity. Table II reports the relative errors $\Delta\varepsilon_n$, $\Delta\varepsilon_p$, $\Delta\varepsilon_c$ defined as:

$$\Delta\varepsilon_k = \frac{\varepsilon_r - \varepsilon_k}{\varepsilon_r} \tag{15}$$

where *k=n, p, c*.

All the relative errors are of the order of 10^{-14}. The values were computed with a MATLAB© routine with a machine precision of the order of 10^{-16}. Thus, the explicit formulas allow us to obtain exact values of ε_r by simply measuring the Fresnel reflection coefficients; thanks to their simple form, they can be implemented on a GNSS-R measurement system.

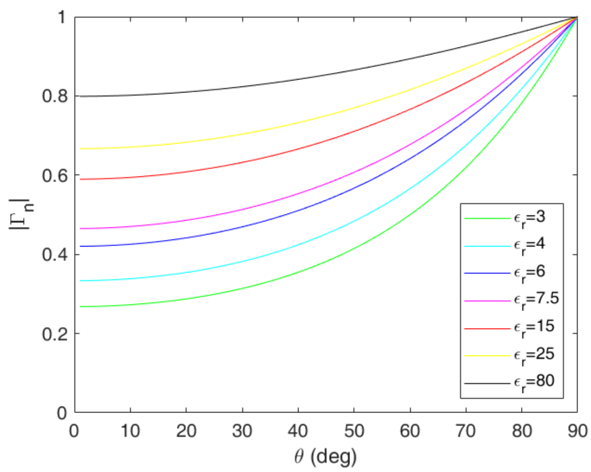

Fig. 2. $|\Gamma_n|$ for different materials with different real ε_r.

As a second example, we considered the values of the linearly polarized reflection coefficients measured in [20] for a medium composed of sand, for which $\varepsilon_r = 3+0.05$ j. Since the imaginary part is comparatively small relative to the real part, it can be neglected, yielding a real value of $\varepsilon_r \sim 3$.

Fig. 4 reports the value $|\Gamma_n|$ and $|\Gamma_p|$ analytically computed from equations (3) and (4) considering $\varepsilon_r = 3$ (solid line), and the measured values (dots) of [20].

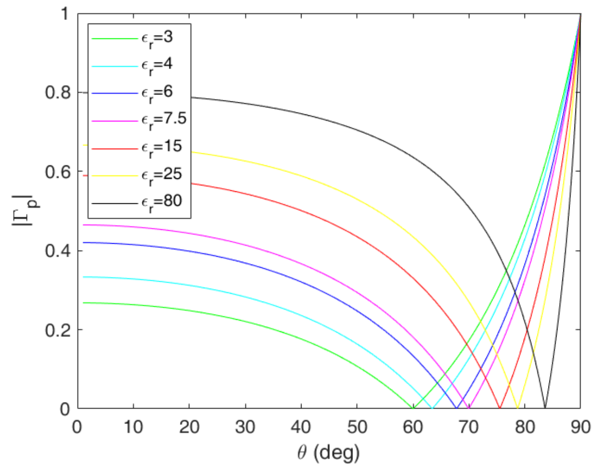

Fig. 3. $|\Gamma_p|$ for different materials with different real ε_r.

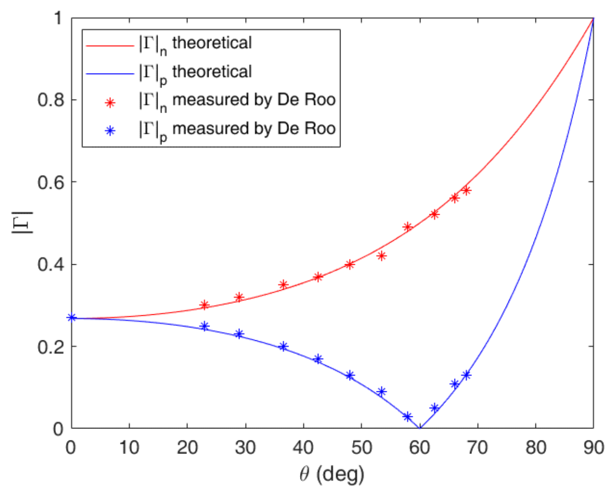

Fig. 4. Comparison of $|\Gamma_n|$ and $|\Gamma_p|$ obtained from the measured values of permittivity and the theoretical curves considering ε_r=3.

Fig. 5 show the comparison between the values of ε_n, ε_p, ε_c with value of ε_r measured by De Roo and Ulaby in [20]. The values of the reflection coefficients are measured. In the first example, of theoretical nature, we considered reference values of the permittivity, which are standard, for different materials (see table II); for this reason, the errors are very small (less than 10^{-14}).

In contrast, in the second example we considered actual, measured values of the reflection coefficients, resulting in larger errors in the evaluation of ε_n, ε_p, ε_c, with respect to the reference ε_r. Since the formulas are exact, this provides a way to assess the validity of the empirical methods employed to evaluate the permittivity, and the accuracy of the measurements; for instance, for the measurements we considered the errors are always lower than 1%, with a maximum of $\Delta\varepsilon_k = 0.03$

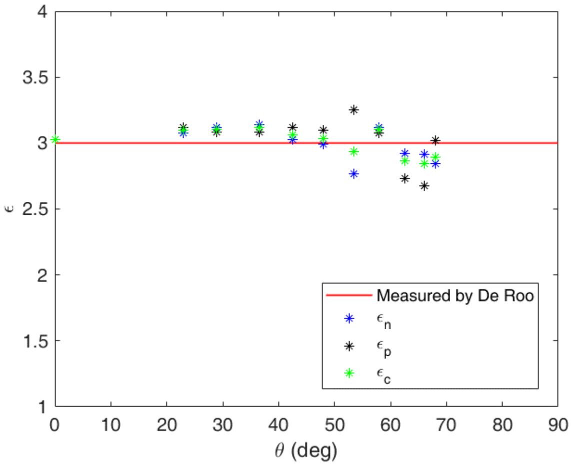

Fig. 5. Comparison of measured value of ε_r and values of permittivity computed with the explicit formulas.

IV. Conclusions

GNSS Reflectometry can be used to determine the characteristics of soil (permittivity and soil moisture). If the ground is flat, the received power can be assumed to be proportional to the moduli of the Fresnel reflection coefficients. Usually, the equipment setup utilizes a Right Circular polarized antenna to measure the direct signal and a Left circular polarized antenna for the signal reflected from the ground. Alternatively, linearly polarized antennas (vertical or horizontal) can be used.

For non-dispersive media, characterized by real values of the relative permittivity, the Fresnel formulas can be solved explicitly and independently. In this paper, we introduced the formulas for the case of linear polarization, and have checked their self-consistency, observing an accuracy of the order of 10^{-14}. We also compared the values obtained with these formulas to the empirical measurements of [17], finding an accuracy up to 0.1 %.

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