Soil Moisture Retrieval Using GNSS-R Techniques: Experimental Results
Over a Bare Soil Field

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Abstract—This paper presents a new technique to retrieve soil moisture using global navigation satellite signals reflected over the soil surface using the measurement of the power fluctuations of the signal created by the interference between the direct GPS signal and the one reflected over the soil surface. As a function of the elevation angle, power fluctuations at vertical polarization pass through a notch, which is related to the soil moisture content, while horizontal polarization exhibits a very weak dependence. Experimental results of the measurements obtained over a bare soil field are presented and discussed.

Index Terms—Global navigation satellite signal reflectometry, interferometry, soil moisture, soil surface roughness.

I. INTRODUCTION

Knowledge of the surface’s soil moisture content provides useful information for hydrological studies due to its influence in the global water cycle. It is known that soil moisture can be retrieved using L-band microwave radiometry [1]–[3], radar, or synthetic aperture radar (SAR) [4]–[6]. While the spatial resolution of L-band microwave radiometers onboard a satellite is poor (about tens of kilometers), radar systems are more affected by surface roughness effects. Recently, GPS reflectometers [7]–[12] have been used to retrieve soil moisture. In this kind of reflectometers, the reflected signal is correlated with a local replica of the transmitted one, obtaining the so-called waveforms [13] (time-domain correlations, for zero Doppler) or delay-Doppler maps [14] (time-domain correlations for different Doppler shifts). In addition, these global navigation satellite signal (GNSS) reflectometry techniques have been widely used for sea-state retrieval [15]–[18] testing and validating their capability to retrieve surface geophysical parameters. As compared to SAR or radar systems, a GPS reflectometer has the advantage of being a passive instrument, in which the signals emitted by the GPS satellites are taken as sources of opportunity. In addition, as compared to microwave radiometers, thermal stability is not a stringent requirement, and the nature of the GPS signals produces a self-calibrated observable. Furthermore, the GPS working frequency (1.57542 GHz) is in the L-band which is a suitable band to retrieve soil moisture [1], [3], [4].

In this paper, the “Interference Pattern” technique is introduced for soil moisture monitoring. It is based on the simultaneous reception of the direct and the reflected waves, which are coherently added at the antenna where the interference occurs. The received signal level changes as a function of time due to the movements of the GPS satellites. The “Interference Pattern” technique studies the temporal evolution of the interference signal as a function of the angular position.

The interference pattern technique (IPT) is analyzed in Section II. Section III describes the soil moisture retrieval algorithm obtained through theoretical simulations considering bare soils, and Section IV explains the field experiment and the soil moisture maps retrieved with the technique. Finally, the conclusions and future research lines are summarized.

II. INTERFERENCE PATTERN TECHNIQUE

The geometrical configuration of the IPT is shown in Fig. 1. A similar technique was originally devised in [19], [20] to determine the dielectric properties of soil, or a snow-covered metallic plane [21] using a left-hand circularly polarized (LHCP) receiving antenna. In this paper, we have improved this technique by replacing the LHCP antenna by two linearly polarized antennas (vertical and horizontal) [22]. As it will be shown (Fig. 2), the information carried out by the horizontal polarization is very limited and masks the information if an LHCP was used.
Although several models for the incoherent scattering of electromagnetic waves over soil surfaces exist (e.g., [23] among many others), a coherent specular reflection model [24] has been implemented. The link between the main geophysical parameters (surface soil moisture and soil surface roughness) and the GPS-R observables (signal level, angular patterns) is performed through (1)–(8) and the dielectric constant model [25]. The model assumes the GPS working frequency (1.57542 GHz), a rough soil surface, and a multilayered soil, which has different dielectric constant values, as described below.

For a single interface between two layers, the Fresnel reflection coefficients at horizontal and vertical polarizations are

\begin{align}
r_h &= \frac{n_i \cdot \cos(\theta_{inc}) - n_{i+1} \cdot \cos(\theta_i)}{n_i \cdot \cos(\theta_{inc}) + n_{i+1} \cdot \cos(\theta_i)} \tag{1} \\
r_v &= \frac{n_{i+1} \cdot \cos(\theta_{inc}) - n_i \cdot \cos(\theta_i)}{n_{i+1} \cdot \cos(\theta_{inc}) + n_i \cdot \cos(\theta_i)} \tag{2}
\end{align}

where \( \theta_{inc} \) is the incidence angle, \( \theta_i \) is the transmitted angle, \( n_i \) is the refraction index of the incident signal medium, and \( n_{i+1} \) is the refractive index of the transmitted signal medium.

In the proposed technique, linear polarization antennas (\( h \): horizontal and \( v \): vertical) are required instead of circularly polarized (LHCP: left or RHCP: right hand) for two main reasons.

1) \( r_h \) and \( r_v \) have a larger variation with the incidence angle than \( r_{HLCP} \) and \( r_{RHCP} \), and therefore provide more information than a circularly polarized antenna.

2) A single linear polarization antenna can receive the direct and reflected signals simultaneously, while if an RHCP antenna were used, it will collect the direct signal, but not the reflected one, which will mostly be LHCP (except for the cross-polarization of the antenna pattern and the polarization mixing of the reflected signal on the rough surface).

Equation (3) can be used to express \( \theta_i \) as a function of the \( \theta_{inc} \) and the dielectric constant \( n = \sqrt{\varepsilon_r \cdot \mu_r} \), where \( \mu_r \) is the permeability assumed to be equal to one

\begin{equation}
n_i \cdot \sin(\theta_{inc}) = n_{i+1} \cdot \sin(\theta_i) \tag{3}
\end{equation}

resulting in (4) and (5), respectively

\begin{align}
r_{h,i+1,i} &= \frac{\sqrt{\varepsilon_r - \varepsilon_i \cdot \sin^2(\theta_{inc})} - \varepsilon_{r+1} - \varepsilon_i \cdot \sin^2(\theta_{inc})}{\sqrt{\varepsilon_r - \varepsilon_i \cdot \sin^2(\theta_{inc})} + \varepsilon_{r+1} - \varepsilon_i \cdot \sin^2(\theta_{inc})} \tag{4} \\
r_{v,i+1,i} &= \frac{\varepsilon_{r+1} \cdot \sqrt{\varepsilon_r - \varepsilon_i \cdot \sin^2(\theta_{inc})} - \varepsilon_r \cdot \varepsilon_{r+1} \cdot \sin^2(\theta_{inc})}{\varepsilon_{r+1} \cdot \sqrt{\varepsilon_r - \varepsilon_i \cdot \sin^2(\theta_{inc})} + \varepsilon_r \cdot \varepsilon_{r+1} \cdot \sin^2(\theta_{inc})} \tag{5}
\end{align}

Equations (4) and (5) are then computed at the interfaces between soil layers and are combined to obtain the surface’s reflectivity coefficient \( R \). For the sake of simplicity, a three-layer reflectivity model (air + two soil layers) has been used to derive (6). However, it can be readily extended to a \( m \)-layer model in an iterative way

\begin{equation}
R = e^{-\left(\frac{2\pi\sigma}{\lambda}\right)^2} \cdot \frac{r_{i+1,i+2} \cdot e^{\jmath \psi}}{1 + r_{i+1,i+2} \cdot r_{i+1,i+2} \cdot e^{\jmath 2\psi}} \tag{6}
\end{equation}

where \( \sigma \) is the soil surface roughness and the phase term \( \psi \) is given by

\begin{align}
\psi &= \frac{2\pi \cdot n_{i+1}}{\lambda} \cdot t_{i+1} \cdot \cos(\theta_i) \\
\psi &= \frac{2\pi}{\lambda} \cdot t_{i+1} \cdot \sqrt{\varepsilon_{r,i+1} - \varepsilon_r \cdot \sin^2(\theta_{inc})} \tag{7}
\end{align}

being \( t_{i+1} \) the thickness of the \( i + 1 \) layer and \( S \) the surface’s roughness correction factor [24] defined as

\begin{equation}
S = -8 \cdot \left(\frac{\pi \sigma^2}{\lambda} \cdot \sqrt{\varepsilon_{r,i+1} - \varepsilon_r \cdot \sin^2(\theta_{inc})}\right)^2 \tag{8}
\end{equation}

and \( \sigma \) the standard deviation of the roughness of the interface between layers, assumed to be small (< 2 cm) and equal for all layers.

The multiple interferences coming from the transmitted and reflected waves that occur between layers are already taken into account applying the boundary conditions of the electric and magnetic fields. The paraxial approximation has been assumed, so that the direct and reflected signals are considered to arrive to the antenna with the same angle.

The total power received \( (P) \) can then be derived from

\begin{equation}
P \propto |E_i + E_r|^2 \equiv F_n(\theta) \cdot |1 + R \cdot e^{\jmath \psi}|^2 \tag{9}
\end{equation}

where \( E_i \) and \( E_r \) are the incident and reflected fields, and the normalized antenna pattern \( F_n(\theta) \) can be approximated by a
parabola around the maximum
\[
F_n[\text{dB}](\theta) = -12 \cdot \left(\frac{90 - \theta_{\text{inc}}}{\Delta \theta_{\text{ant}}}\right)^2
\]  
(10)

being \(\Delta \theta_{\text{ant}}\) the half-power antenna beamwidth and \(\phi\) the phase difference (Fig. 1)
\[
\phi = \frac{4\pi}{\lambda} \cdot h_1 \cdot \cos(\theta_{\text{inc}}).
\]  
(11)

The total received power will vary as a function of the incidence angle due to a fading-type behavior, which is different at \(h\)- and \(v\)-polarizations, and depends on the geophysical parameters that characterize the soil.

The performance of this simplified model is shown in Section IV. Using this simple model, the effect of the soil moisture variations can be analyzed taking into account soil structure and composition, antenna polarization, instrument height, and surface’s roughness.

III. SOIL MOISTURE RETRIEVAL ALGORITHM FOR BARE SOIL SCENARIOS

Soil moisture can be retrieved from the shape of the power of the interference signal (9) versus the elevation angle, defined as \(90^\circ - \theta_{\text{inc}}\). In order to better understand the technique, a simulator has been implemented in which all parameters can be modified.

First studies were focused on bare soil scenarios. In order to consider the effect of the roughness value of the interface between layers, a three-layer model (air + 2 soil layers) has been assumed. The soil moisture content of each layer has been defined from the surface soil moisture. Then, first layer features are the surface soil moisture value and a finite thickness, and the second layer features are an increase on the soil moisture value, which is the stationary behavior for the most of the time, and an infinite thickness.

As shown in Fig. 2, for both polarizations as the surface soil moisture content increases, the amplitude of the fluctuations increases, which is associated to a moderate increase of the average received power. At \(v\)-polarization, there is more sensitivity to the surface soil moisture content of the surface than at \(h\)-polarization. At \(v\)-polarization, the position of the “notch” (elevation angle where the minimum amplitude oscillation occurs) and the “notch amplitude” (amplitude of the oscillation where the notch occurs) are both sensitive to the soil moisture content (Fig. 2).

Fig. 3 shows the main simulation results. The relationship between the notch amplitude and the surface soil moisture of
Fig. 3. Influence of the surface roughness ($\sigma$) and the roughness of the interface between layers ($\sigma_\ell$), (a) and (b) over the notch amplitude, and (c) and (d) over the notch position, as a function of the soil moisture.

Even though the IPT can be used at arbitrary instrument heights, the maximum height is limited by two factors:

1) the coherence of the signal;

2) the valid angular sweep required to determine the soil moisture (an annulus between $14^\circ$ and $30^\circ$ elevation angle).

In order to guarantee the coherence of the signal, the path difference between direct and reflected signals must be less than the coherence distance of the GPS signal. Since the GPS
Fig. 5. SMIGOL reflectometer architecture. (a) Block diagram. (b) v- and h-polarizations passive antenna. (c) GPS receivers connected to the antenna and power supply.

The satellite height is much higher than the GPS receiver height \( h_1 \), the paraxial approximation holds and

\[
\Delta r = r_{\text{reflected}} - r_{\text{direct}} \approx \frac{2h_1}{\sin(90^\circ - \theta_{\text{inc}})} \ll c \cdot \tau_c
\]

\[
= 3 \cdot 10^8 \text{ m/s} \cdot \frac{1 \text{ ms}}{1023} = 293 \text{ m}
\]

where \( \tau_c \) is the coherence time of the GPS signal defined as \( \tau_c = 1 \text{ ms} / 1023 \), being 1023 the number of chips of the pseudorandom noise code [27].

Fig. 4 shows the theoretical signal transit time difference between direct and reflected paths \( \tau = \Delta r / c \), as a function of the elevation angle \( 90^\circ - \theta_{\text{inc}} \), for different values of the instrument height. Maximum antenna height is determined by the transit time difference that exceeds the coherence time of the GPS signal (horizontal line in Fig. 4): Direct and reflected signals are uncorrelated, and the shape of the IPT degrades. As shown in Fig. 4, for instrument heights up to 140 m, the technique is valid at any elevation angle, which allows the determination of the soil moisture from 0% to 40% \( i.e., \) \( \Delta r / c \ll \tau_c \) for all \( 90^\circ - \theta_{\text{inc}} \), including the angular sweep necessary for soil moisture determination shown in Fig. 3, being it the elevation angle range from \( 10^\circ \) to \( 33^\circ \). For instrument heights from 140 to 270 m, only the elevation angle range from \( 0^\circ \) to \( 33^\circ \) is valid, which still allows the soil moisture determination. However, above 270-m instrument heights, the elevation angle range is not enough to retrieve soil moisture.

The maximum distance from the instrument’s position that can be measured increases linearly with instrument’s height up to \( \sim 2.2 \text{ km} \) for \( h_1 = 270 \text{ m} \). The spatial resolution (region from which the scattered GPS signal is being collected) can be defined by the half-power width of the so-called glistening zone [28], which is the area over which the GPS signals are scattered, provided that the antenna footprint is much larger than it. The radiation from the glistening zone is incoherent, and modifies the interference pattern between the direct and reflected waves. However, for the geometrical configuration of the experiment this incoherent contribution is low and can be neglected.

IV. EXPERIMENTAL RESULTS

In order to validate the described technique an instrument has been implemented and tested in a field, it has been called Soil Moisture Interference-pattern GNSS Observations at L-band Reflectometer (SMIGOL Reflectometer). The SMIGOL Reflectometer block diagram is shown in Fig. 5(a). Fig. 5(b) shows the patch antenna that is mounted on a mast, pointing at \( 0^\circ \) elevation angle. The angular sweep is automatically achieved during the GPS satellites’ passage. The SMIGOL Reflectometer is mainly composed by two GPS receivers connected to the dual-polarization passive antenna [Fig. 5(c)]. The measurements of the GPS interference signal power at v- and h-polarizations are performed by each receiver.

The field experiment was carried out at Palau d’Anglesola, Lleida, Spain \( (41^\circ 39' 34.53'' \text{ N}, 0^\circ 51' 7.71'' \text{ E}) \), over a wheat field from January to September 2008 covering the different growth stages of the wheat. In this paper, only the soil moisture retrievals over bare soils are considered, therefore the selected measurements correspond to August and September 2008, after the harvest. In August, the soil is mainly dry, but in September, the first seasonal rains occurred and soil became wet. ECH2O soil moisture probes [29] were located in the wheat field at 5, 20, and 40 cm (Fig. 6), in order to measure the volumetric water content at these depths. The soil moisture at 5 cm is systematically higher than at 20 cm. The soil surface roughness has been obtained as a result of 30 points \textit{in situ} measurements in the field and, the averaged value \( (\sim 2 \text{ cm}) \) has been assumed to be constant for the whole field.

Fig. 7 shows representative measurements. The measured signal and the computed theoretical signals have been analyzed...
Fig. 7. Measurements obtained at Palau d’Anglesola, Lleida, Spain compared with the theoretical approximation after applying the algorithm to retrieve soil moisture. In August 22, measurements correspond to (a) GPS satellite 10 with rms error = 0.24 dB, (b) GPS satellite 15 with rms error = 0.27 dB, and (c) GPS satellite 26 with rms error = 0.22 dB; and in September 25, measurements correspond to (d) GPS satellite 10 with rms error = 0.19 dB, (e) GPS satellite 15 with rms error = 0.20 dB, and (f) GPS satellite 26 with rms error = 0.22 dB.

in terms of the rms value of the error between them using

\[ \text{rms}_{\text{error}} = \sqrt{E \left( (P - \hat{P})^2 \right)} \]  

(13)

where \( P \) is the measured power and \( \hat{P} \) is the computed theoretical power.

As discussed before, the algorithm can retrieve a valid soil moisture value inside the 14° to 30° range of elevation angles, which from now on will be called “internal annulus,” where the notches occur. Rigorously, the retrieved value is only valid at exactly the notch angle, but assuming that the soil moisture relatively remains constant, it can be extrapolated to the rest of the internal annulus. When this assumption does not hold, the shape of the notch elongates [see Fig. 7(f)] and eventually a second notch will appear. To find the soil moisture value outside the internal annulus, an iterative approach is applied: Starting with the soil moisture value retrieved at the internal annulus, the measured amplitude fluctuations are fitted to the predicted ones within an angular window of 2°.

Fig. 8 shows the measurement site main descriptors. The SMIGOL Reflectometer location, the measurement station, the irrigation channel and the observation area, a wheat field, are clearly shown in the different images. Note that there is a negative slope from the location of the SMIGOL Reflectometer to the irrigation channel.

Processing several GPS satellites’ passages a soil moisture map can be obtained (Fig. 9). Note that the wheat field has a slight negative slope from the top to the bottom of the pictures. The map size depends on the instrument height, but as height increases, the resolution decreases (the size of the glistening zone enlarges). In our case, the instrument was located at 2.6 m height and the obtained measurements come from elevation angles in the range 7°–50°. Taking into account that the antenna has a beamwidth of 92° (roughly a quarter of a circle) and the minimum elevation angle is 7° (equivalent to a 21 m radius area), the map size is approximately

\[ A = \frac{A_{\text{circle}}}{4} = \frac{\pi \cdot r^2}{4} = \frac{\pi \cdot 21^2}{4} = 346 \text{ m}^2. \]  

(14)

Larger areas can be covered using antennas with larger horizontal beams and taller antenna masts.

Finally, Fig. 10 shows a scatter plot between the soil moisture measured close to the instrument using the ECH2O soil moisture probes and the SMIGOL Reflectometer retrieved one. As shown in Fig. 10, retrieved measurements and ground data measurements are similar to 5-cm ECH2O data for September measurements after seasonal rain, but they are more similar to 20-cm ECH2O data for all August measurements and for the first measurements of September before the seasonal rain. This occurs because dry soils have a penetration depth larger than wet soils. Note that ECH2O soil moisture probes are located near the SMIGOL Reflectometer. The rms error between the 5-cm probe soil moisture measurement and the SMIGOL Reflectometer retrieved one is just 2.7% for August/September...
Fig. 8. Description of Palau d’Anglesola site. (a) Main points of the site: the measurements station and the SMIGOL Reflectometer location at the top of the picture, the observation area in the middle and the irrigation channel at the bottom. (b) Two photographs taken during the field campaign of the SMIGOL Reflectometer and the observation area.

Fig. 9. Soil moisture map retrieved for the bare soil scenario, fit in Google Earth map at Palau d’Anglesola site, Lleida, Spain (41°39’34.53” N, 0°51’7.71” E), in (a) August and (b) September, after seasonal rains.

observations. The rms error between the 20-cm probe soil moisture measurement and the SMIGOL Reflectometer retrieved one is 3.1% for August/September observations.

V. Conclusion

This paper has presented a new technique to measure surface soil moisture based on the power variations of the interference signal between the direct and reflected GPS signals.

1) A simple soil moisture retrieval algorithm has been devised based on the position of the notch of the interference pattern at $\psi$-polarization.

2) Experimental data over a bare soil field have been presented to validate the technique.

3) This technique can be applied at different instrument heights: up to 140 m without restrictions on the valid elevation angle range needed to determine the soil moisture.

From 140 to 270 m instrument height, with a decreasing valid elevation angle range, but still enough to determine the soil moisture, and above 270 m the valid elevation angle range is not enough to retrieve the soil moisture.

Future research lines will focus on the study of the vegetation effects, and the data processing of the whole field campaign, including the vegetation stages.

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