Dual-Polarization GNSS-R Interference Pattern Technique for Soil Moisture Mapping

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Abstract—The interference pattern technique (IPT) consists of the coherent addition of the direct and reflected global navigation satellite systems (GNSS) signals in the receiving antenna. The detected power oscillates (fading), and the amplitude of these oscillations is very sensitive to the soil reflection coefficient at the specular reflection point. Therefore, variations of the reflection coefficient can be mapped, and thus dielectric constant variations, from which soil moisture can be retrieved. This work extends the use of the IPT technique from vertical polarization (V-Pol) to horizontal polarization (H-Pol). Moreover, the IPT equations are reformulated to facilitate the combination of dual-polarization retrievals. Simulations of the interference patterns at V- and H-Pol are presented for different soil moisture conditions. An upgrade of the SMIGOL GNSS-R instrument for dual-polarization observations is presented. This instrument was deployed in a flat, dry grassland in Yanco, Australia, in order to validate the proposed concepts. Finally, a comparison between the data retrieved from the SMIGOL instrument and the ground-truth soil moisture data is presented showing a good agreement between them and rainfall information.

Index Terms—Brewster angle, global navigation satellite systems (GNSS), GNSS reflectometry (GNSS-R), interference pattern technique (IPT), soil moisture (SM).

NOMENCLATURE

GPS  Global positioning system.

GNSS  Global navigation satellite systems.

GNSS-R  GNSS-reflectometry.

PARIS  Passive Reflectometry and Interferometry System.

DDM  Delay-Doppler map.

EM  Electro-magnetic.

WAF  Woodward ambiguity function.

IPT  Interference pattern technique.

LHCP  Left hand circular polarization.

RHCP  Right hand circular polarization.

SM  Soil moisture.

SMIGOL  SM IPT GNSS Observations at L-Band.

V  Vertical.

H  Horizontal.

SAR  Synthetic aperture radar.

ICF  Interferometric complex field.

RF  Radio frequency.

WP  Waveform peak.

VSWR  Voltage standing wave ratio.

P-SMIGOL  Polarimetric SMIGOL.

ESA  European Space Agency.

I. INTRODUCTION

SM OIL MOISTURE is one of the key parameters in the global water cycle, and is highly related to the global climate [1]. SM monitoring at a global scale is only possible using remote sensing techniques. Optical, thermal infrared or microwave frequencies have been used in the past for its retrieval [2], with each of them having its individual advantages and limitations. Microwave remote sensing at L-band (1–2 GHz) is preferred because the atmosphere is nearly transparent to EM waves, the vegetation layer is semi-opaque up to ~5 kg/m² vegetation water content, and the sensitivity to changes in the dielectric constant of the observed object, and hence in SM, is very large. Active and passive sensors operating in this spectrum band have been successfully used in the past, including GNSS-R in recent years. SAR systems rely on backscattering measurements obtaining very high spatial resolution, but have relatively poor accuracy due to surface roughness effects. Microwave radiometers measure the thermal radiation of the surface [3]. In contrast to SAR, radiometers have higher accuracy, but suffer from poor spatial resolution [2] and potential radio-frequency interference issues. Microwave reflectometers rely on forward scattering measurements of opportunity signals in a bistatic configuration, such as those from GPS satellites. The ground resolution, which is known from bistatic SAR theory [4], [5], is higher than for radiometers, but lower than for SAR due to the shorter coherent integration time. The accuracy, as
for SARs, also suffers from surface roughness, as they are based on similar physical principles.

The concept of GNSS-R started in 1991, when a French military plane testing a GPS receiver got locked to the reflected GPS signals over the ocean, leading to an incorrect navigation solution [6]. In 1993, the PARIS concept was proposed by the ESA, which consisted of using GNSS-reflected signals for multipoint mesoscale altimetry. This is considered to be the beginning of the GNSS-R techniques [7]. Since then, several uses of the GNSS-reflected signals have been proposed for a wide range of applications [8]–[10].

The retrieval of SM using GNSS-R has been widely addressed in the literature. The first technique proposed was based on the polarimetric ratio of the peak of the waveform, which is the cross-correlation of the GNSS direct and reflected signals with a clean replica of the satellite code, or a Doppler cut in the DDM [11] passing through the DDM peak. GNSS signals are transmitted at RHCP, but in the reflection process they become mostly LHCP [11]. The power received at LHCP after reflection in a surface depends on the SM conditions [12]. If the LHCP component is expressed in the two orthogonal polarization components (V- and H-Pol), the SM can be estimated at each polarization. The ratio of the two should theoretically cancel surface roughness effects, but preserve the dielectric constant information [13]. However, due to surface roughness, there is a polarization mixing factor that must be considered. A similar approach is based on sensing the reflected power variations at LHCP from an airborne platform, as was the case of, for instance, the SMEX02 experiment [12], [14], where the received power increased with higher SM. Later, the ICF [15], which is a time series calculated as the ratio between the direct and the reflected waveform peaks, was used for the determination of the surface reflection coefficient [16]. From the estimated average reflection coefficient, the SM can be retrieved [16], [17]. The ICF has also been used with two nadir-looking antennas, one LHCP and another one RHCP, and a zenith-looking RHCP antenna for the direct signal. The polarimetric ratio of both estimated reflection coefficients is highly related to the biomass parameters [17].

Another approach known as the IPT has been followed by different researchers. The feasibility of sensing the complex dielectric constant using the multipath information from GPS SNR was proved in 1998 [18]. Since then, two different techniques using the IPT have been followed. The first one is based on using the multipath information from geodetic zenith-looking GPS antennas. The reflected signal is collected through the sidelobes of the antenna pattern, as it is out of the antenna beamwidth. Following the model presented in [19] and looking to the relative phase variations in the retrieved interference pattern, relative SM variations can be tracked [19]–[21]. The second technique, following [18], is based on measuring the IPT using a linear polarization antenna, particularly V-Pol [22]. With a V-Pol antenna looking at the horizon, which is forcing a 1-ray multipath, the minimum amplitude point or “notch,” corresponds to the Brewster angle position. This can then be linked to the complex dielectric constant determination and thus to the SM content [23].

This work presents the generalization of the IPT using linear dual-polarization measurements instead of only V-Pol. In Section II, the IPT equations are reformulated to account for both V- and H-Pol. In Section III, an upgrade of the SMIGOL [22] instrument from V-Pol to Dual-Pol is presented. In Section IV, a SM retrieval algorithm from dual-polarization acquisitions is presented, discussed, and analyzed. In Section V, the first results from a ground-based experiment conducted in the Yanco area (Australia) are presented. Finally, Section VI presents the conclusion of this work.

II. FORMULATION OF THE IPT EQUATIONS FOR DUAL-POL APPLICATIONS

GNSS signals are circularly polarized (RHCP), but after their reflection on a surface, they become mostly LHCP. A single RHCP antenna is not optimal for acquiring direct and reflected signals as those are orthogonal polarizations. Furthermore, the H-Pol component on the reflected signal masks the information of the Brewster angle position [24]. Consequently, the interference patterns used in this work are acquired using linear polarization. Linerly polarized antennas allow the acquisition of both direct and reflected signals with a single antenna. A linear dual-polarization antenna with a high cross-polar ratio allows the acquisition of the V- and H-Pol interference patterns with a single antenna.

The IPT is based on the coherent addition of direct and reflected GNSS signals. This results in an interference pattern (fading), with high- and low-frequency components. The high-frequency component is due to the phase difference or different path travelled by direct and reflected signals. The low-frequency component is due to the modulation by the antenna pattern and the reflection coefficient amplitude. Previously, the use of V-Pol was preferred due to the presence of the Brewster angle [22]. Using [22] and [24] as a start point, the potential of using H- and V-Pol at the same time to improve the accuracy of the SM retrieval is analyzed in this work.

In order to estimate the interference patterns at both polarizations, a model to compute the reflection coefficients must be used. Different reflection models have been proposed to estimate the reflection coefficients [25], [26]. In [22], a three-layer model was used: the first layer is the air ($\varepsilon_r \sim 1$); the second layer is a thin layer emulating the roughness, with a dielectric constant in between the one from the air layer and the one from the soil layer; the third layer is the soil layer. In this work, a two layer model has been used (Fig. 2), considering the surface roughness as an attenuation in the reflected wave [26]. No significant differences have been found between the two- and three-layer models for relatively smooth terrains, which is the case of the experimental site.

A. The Fresnel Reflection Coefficients

The Fresnel reflection coefficients for H- and V-Pol are presented in (1)–(2). To consider the roughness effect, the reflectivity value ($\Gamma_p$) is multiplied by an exponential function [26], [27].

$$R_{h,z} = \frac{\sqrt{1 - \sin^2(\theta_{inc})} - \sqrt{\varepsilon_r - \sin^2(\theta_{inc})}}{\sqrt{1 - \sin^2(\theta_{inc})} + \sqrt{\varepsilon_r - \sin^2(\theta_{inc})}}$$  \hspace{1cm} (1)

$$R_{v,z} = \frac{\varepsilon_r \cdot \sqrt{1 - \sin^2(\theta_{inc})} - \sqrt{\varepsilon_r - \sin^2(\theta_{inc})}}{\varepsilon_r \cdot \sqrt{1 - \sin^2(\theta_{inc})} + \sqrt{\varepsilon_r - \sin^2(\theta_{inc})}}$$  \hspace{1cm} (2)

$$\Gamma_p = |R_{h,z}|^2 \cdot e^{-4k^2\sigma^2_c \cos^2(\theta_{inc})}$$  \hspace{1cm} (3)
where $R_{h,2}$ and $R_{v,2}$ are the Fresnel reflection coefficients for H- and V-Pol, respectively; 1 and 2 are the air and soil layers, respectively; $\varepsilon_r$ is the dielectric constant of the soil layer; $\theta_{inc}$ is the incidence angle; $q$ is the polarization (H-Pol or V-Pol); $k = \frac{2\pi}{\lambda}$, where $\lambda$ is the wavelength ($\sim 19$ cm); and, $\sigma_n$ is the surface $rms$ height.

Fig. 1 shows the reflectivity ($\Gamma$) for a) H- and b) V-Pol as a function of the incidence angle ($\theta_{inc}$), which is the complementary angle of the elevation ($\theta_{elev}$). Note that the H-Pol reflectivity ($\Gamma_H$) is always monotonically increasing. On the contrary, the V-Pol reflectivity ($\Gamma_V$) value is decreasing until it reaches a minimum amplitude point, where it starts increasing. This minimum amplitude point is called “notch,” and corresponds to the Brewster angle position. Note that, as stated in previous works [22], [24], its position mainly depends on the SM content. This means that V-Pol has a high sensitivity to the SM content, and it is the reason why V-Pol was chosen in previous works. For SM contents higher than 5%, the reflectivity value at the Brewster angle position is not equal to 0. This occurs because the real part of the reflection coefficients is almost zero, whereas the imaginary part is not. So, the amplitude does not vanish completely. Moreover, in the scattering area, the SM content is not homogeneous. In real cases, the reflectivity reaches a minimum value, which never becomes 0. Note that at V-Pol, two different SM contents may have the same $\Gamma_V$ value. This leads to an ambiguity in the SM retrieval algorithm when a map is generated. This ambiguity is not seen at H-Pol and for $\theta_{elev} > 5^\circ$. Furthermore, $\Gamma_H$ is always higher than $\Gamma_V$, being advantages of the dual-polarization technique.

The elevation angle region that can be analyzed is $5^\circ < \theta_{elev} < 45^\circ$ due to the antenna pattern half power beamwidth. Also, it is where the Brewster angle is located and $\Gamma_H$ has higher values.

B. The Dual-Polarization Interference Patterns

The interference pattern equation [22] can be rewritten for H- and V-Pol using the reflection coefficients presented in Section II-A and an antenna ($E_a(\theta)$) with an azimuthally symmetric pattern around the boresight (4)

$$P_R \propto |E_i + E_r|^2 = |E_a(\theta_{elev})| \cdot |E_0| \cdot |R_q(\theta_{elev}, \varepsilon_r)| \cdot |e^{j(\Delta \phi + \phi_{R_q}(\theta_{elev}, \varepsilon_r))} |^2$$

where

- $P_R$ Instantaneous received/interference power;
- $E_i$ and $E_r$ Incident and reflected fields, respectively;
- $E_a(\theta_{elev})$ Antenna radiation pattern;
- $E_0$ Incident electric field amplitude;
- $|R_q(\theta_{elev}, \varepsilon_r)|$ Absolute value of the Fresnel reflection coefficient at q polarization;
- $\phi_{R_q}(\theta_{elev}, \varepsilon_r)$ Phase of the Fresnel reflection coefficient at q polarization;
- $\Delta \phi = \frac{4\pi}{\lambda} h \sin(\theta_{elev})$ Phase difference due to the different electrical path between direct and scattered EM waves;
- $\varepsilon_r$ Soil surface dielectric constant.

Comparing (4) with previous formulation, the envelope of the interference pattern is now dominated by the absolute value of the reflection coefficient. The frequency modulation term is now $\Delta \phi + \phi_{R_q}(\theta, \varepsilon_r)$, which means that it depends on the different electrical path between direct and reflected signals and also on the reflection coefficient phase.

III. DUAL-POLARIZATION SMIGOL INSTRUMENT

The original SMIGOL reflectometer is a ground-based instrument that measures the IPT from GNSS direct and reflected signals. It has a vertically polarized antenna to measure the V-Pol interference pattern [24]. Fig. 2 shows the geometry of the SMIGOL instrument and the IPT.

For the demonstration of the dual-polarization concept, the instrument presented in [24] has been upgraded. The antenna has been modified for dual-polarization measurements and its pattern has been measured at the Universitat Politècnica de Catalunya-BarcelonaTech (UPC) anechoic chamber [28] confirming its
symmetry at both polarizations, and ensuring a cross-polar ratio higher than 20 dB in any direction. The symmetry in the beamwidth is used to avoid antenna pattern compensations. The cross-polar relation is important to avoid receiving power from the undesired polarization, which allows to safely apply dual-polarization algorithms.

After the antenna, there are identical RF amplifiers and receivers for each channel. The controlling system is in charge of internally referencing the data from each channel, and monitoring all the system parameters to keep the full system autonomy.

IV. Dual-Polarization SM Retrievals over Bare Soil

In previous works, in order to obtain a SM map, the amplitude measurements at V-Pol were adapted to the theoretical model as a function of the estimated SM value [24]. However, the aforementioned ambiguity of the reflection coefficient at V-Pol may lead to errors in the SM map. Furthermore, the larger the value of the reflection coefficient, the larger the amplitude oscillations of the IPT and consequently, the higher the amplitude sensitivity to SM variations. This is more noticeable at H-Pol than at V-Pol.

A. The Retrieval Algorithm

The new proposed algorithm uses the position of $\theta_B$ on the V-Pol interference pattern as a first estimation of the SM. Then, for the retrieval of the SM map, the amplitude of the interference pattern at H-Pol is used. Looking at (4), there are points of minima and maxima amplitude of the interference pattern. The minima points occur when the phase term is an odd multiple of $\pi$ or 

\[
(2n + 1)\pi = \Delta \phi + \phi_R(\theta, \varepsilon_r).
\]

The maxima amplitude points occur when the phase term is an even multiple of $\pi$ or 

\[
2n\pi = \Delta \phi + \phi_R(\theta, \varepsilon_r).
\]

So the maxima ($P_{\text{max}}$) and minima ($P_{\text{min}}$) power values are obtained according to (5) and (6), respectively.

\[
P_{\text{max}}(\theta_{\text{elev}}, \varepsilon_r) = F_n(\theta_{\text{elev}}) \cdot |E_0|^2 \cdot |1 + |R_q(\theta_{\text{elev}}, \varepsilon_r)||^2, \quad (5)
\]

\[
P_{\text{min}}(\theta_{\text{elev}}, \varepsilon_r) = F_n(\theta_{\text{elev}}) \cdot |E_0|^2 \cdot |1 - |R_q(\theta_{\text{elev}}, \varepsilon_r)||^2. \quad (6)
\]

If the instrument height is higher than 3 m, the angular separation between consecutive maxima and minima is smaller than 1°. Considering that 1° angular variation in the absolute value of the reflection coefficient is negligible, the overall reflection coefficient at $q$ polarization for a whole interference pattern can be estimated using (7)

\[
|R_q(\theta_{\text{elev}}, \varepsilon_r)| \approx \frac{\sqrt{P_{\text{max}}(\theta_{\text{elev}}, \varepsilon_r)} - 1}{\sqrt{P_{\text{max}}(\theta_{\text{elev}}, \varepsilon_r)} + 1}.
\]

Equation (7) is an estimator of the reflection coefficient modulus, and consequently, by definition it will range between 0 and 1. Furthermore, there is a high similarity between (7) and the VSWR definition [29]. The VSWR in a microwave transmission line is the ratio between the maximum and the minimum voltages ($V_{\text{max}}/V_{\text{min}}$). If the transmission line is perfectly matched (ended with a matched load), there is no reflected wave and the VSWR value is 1, since $V_{\text{max}} = V_{\text{min}}$, which occurs at the $\theta_B$ position. However, if it is not loaded, there is a reflected wave and the VSWR value is larger than 1. The load reflection coefficient absolute value and the VSWR are thus intrinsically related [29]. A similarity between the IPT and the VSWR concept can be directly established. In the IPT, the observable are the power fluctuations of the incoming wave (direct) due to a mismatch of the reflecting medium (reflected wave). This happens because the transmission line/medium, in this case the air, is not perfectly matched (i.e., the soil layer is not a matched load for the air). Using this similarity, the VSWR concept is applied to extract an estimation of the reflection coefficient. A difference between the VSWR and the IPT is that, while the VSWR is a constant value for the whole transmission line, in the IPT case, as the reflection point changes due to the GNSS satellite movement, the soil properties may change, and consequently the reflection coefficient itself. This is why the reflection coefficient estimator depends on the elevation angle ($\theta_{\text{elev}}$), and the soil dielectric properties ($\varepsilon_r$).

Summarizing, $|R_q(\theta_{\text{elev}}, \varepsilon_r)|$ is an amplitude estimator of the Fresnel Reflection coefficient at different elevation angles at $q$ polarization. From this estimation, it is straightforward to simulate different reflection coefficients for different $\varepsilon_r$ and $\theta_{\text{elev}}$. Consequently, $\varepsilon_r$ estimates are linked to SM content at the different $\theta_{\text{elev}}$ values. This leads to spatial variability and the SM map.

B. System Limitations and SM Uncertainty Margins

Due to natural effects, such as surface roughness, or induced effects, such as quantization, there is an uncertainty in the estimation of the SM value.

First, quantization errors and noise lead to an uncertainty in the reflection coefficient amplitude estimation. The instrument measures the total received power ($P_{\text{R,signal + noise}}$). As the noise level is nearly constant, measuring the fluctuations of the received interference power is equal to measuring the fluctuations of the signal power. $P_{\text{R}}$ is quantized in the instrument’s receivers at steps of 1 dB. In the quantization, there is an intrinsic uncertainty of $\pm 0.5$ dB. This leads to an uncertainty in the
reflection coefficient estimated. If the reflection coefficient estimator is given by (7), and considering the definition shown in (8), the uncertainty in the reflection coefficient estimation is given by (9)

\[
\begin{align*}
    u(\theta, \varepsilon_r) &= \frac{\gamma_{\text{max}}[\theta, \varepsilon_r] - \gamma_{\text{min}}[\theta, \varepsilon_r]}{10} \\
    \Delta[\hat{R}_q(\theta, \varepsilon_r)] &= \frac{\ln 10 \sqrt{u}}{10(\sqrt{u} + 1)^2} \quad (9)
\end{align*}
\]

where \(dRa_u\) is the measured total received power in arbitrary logarithmic units.

The uncertainty in the reflection coefficient estimation at H-Pol is translated into an uncertainty in the \(\varepsilon_r\) estimation. At H-pol, the dielectric constant (\(\varepsilon_r\)) uncertainty is given by

\[
\Delta[\hat{\varepsilon}_r(\theta, \varepsilon_r)] = 4 \cdot \frac{1 + |\hat{R}_q(\theta, \varepsilon_r)|}{(1 - |\hat{R}_q(\theta, \varepsilon_r)|)^3} \cdot \Delta[\hat{R}_q(\theta, \varepsilon_r)] \quad (10)
\]

Then, using Wang’s model [23] to relate the SM content and the dielectric constant

\[
\varepsilon_r = 3.1 + 17.36 \cdot SM + 63.12 \cdot SM^2 + j \cdot (0.031 + 4.65 \cdot SM + 20.42 \cdot SM^2) \quad (11)
\]

the uncertainty in the SM retrieval is given by

\[
\Delta SM = \frac{1}{\sqrt{(17.36)^2 - 4 \cdot 63.12 \cdot (1 - |\varepsilon_r(\theta, SM)|) \cdot \Delta[\varepsilon_r(\theta, SM)]} \quad (12)
\]

Table I shows a summary of the uncertainty budget propagation at H-Pol due to quantization. It covers the three steps; from the uncertainty in the estimation of the reflection coefficient up to the SM uncertainty. Note that the higher the SM content, the higher the reflection coefficient, the higher amplitude of the interference pattern, and the higher the dynamic range. Consequently, the lower is the quantization uncertainty effect on the reflection coefficient estimation. Different from the reflection coefficient estimation uncertainty, the uncertainty on \(\varepsilon_r\) increases with increasing SM values. Despite the uncertainty on the reflection coefficient decreases with increasing SM, the fact that the higher the SM, the higher the \(\varepsilon_r\) value compensates the decreasing factor and makes it increase. The same behaviour observed in the \(\varepsilon_r\) occurs in the uncertainty of the SM. The higher the uncertainty in the \(\varepsilon_r\), the higher the uncertainty in the SM estimation.

For V-Pol, the uncertainty on the reflection coefficient due to the quantization is also given by (9). As the interference pattern dynamic range at V-Pol is smaller than at H-Pol, the uncertainty obtained will be slightly higher. However, a final expression for the dielectric constant inversion at V-Pol cannot be derived due to the amplitude ambiguity. This expression changes as a function of the Brewster angle position, which is not known a priori.

Another aspect in the error estimation is the fitting between the dielectric constant model used and the real one. If the imaginary part is larger than the one predicted by the model, at the Brewster angle position, the reflection coefficient will have a minimum amplitude point, but not as close to 0. This is seen on the interference pattern as a “notch” with a larger amplitude. This also affects the H-Pol, just by a smaller amplitude uncertainty. In previous works, it has been seen that using the “notch” amplitude value as a SM content estimator with 1 dB quantization resolution, can provide uncertainties higher than 20% of SM value [22]. Therefore, the combination of both polarizations improves the accuracy of the SM retrievals as it will be shown with experimental data in Section V.

C. Theoretical Simulations

IPTs, with and without quantization errors, have been simulated to assess the retrieval algorithm performance. First, the IPT simulated for H- and V-Pol are shown in Fig. 3(a) and (b), respectively. As stated previously, the amplitude of the IPT envelope at H-Pol is larger than at V-Pol due to the difference in the reflection coefficient amplitude. Also, the presence of the Brewster angle is seen in Fig. 3(b) with its position varying as a function of the SM.

By applying the algorithm in (7), an estimation of the reflection coefficient at each polarization is obtained (Fig. 4). Notice that the retrieval has started at \(\theta_{elec} = 5^\circ\), as for lower elevation angles, the dependance of the reflection coefficients on SM is not large enough to get a valuable retrieval. Moreover, an elevation angle mask in the PSMIGOL receivers avoids measuring power for too low elevation angles. In Fig. 4(b), the \(\theta_B\) position is seen, as well as the amplitude ambiguity. At H-Pol, the whole range of elevation angles can be used for the retrieval [Fig. 4(a)].

From the estimated reflection coefficients, the SM at H-Pol has been inferred (Fig. 5), showing the evolution of the estimated SM as a function of the elevation angle. Table II shows the estimated SM value using the Brewster angle position information. As expected, V-Pol gives very precise information. As stated previously, the amplitude of the IPT estimation at H-Pol is larger than at V-Pol due to the difference between the dielectric constant model used and the real one. If the imaginary part is larger than the one predicted by the model, at the Brewster angle position, the reflection coefficient will have a minimum amplitude point, but not as close to 0. This is seen on the interference pattern as a “notch” with a larger amplitude. This also affects the H-Pol, just by a smaller amplitude uncertainty. In previous works, it has been seen that using the “notch” amplitude value as a SM content estimator with 1 dB quantization resolution, can provide uncertainties higher than 20% of SM value [22]. Therefore, the combination of both polarizations improves the accuracy of the SM retrievals as it will be shown with experimental data in Section V.

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values retrieved. The presence of the bias has been reduced for SM > 5%. Conversely, for SM = 0%, the bias has been increased because the estimation of the Brewster angle position is not as accurate due to relatively high uncertainty of the dielectric constant. This can be seen in Fig. 4, where for SM = 0% the minimum amplitude point occupies a wide range of elevation angles. SM values are expected to vary from 5% (dry), 20% (moist), and 35% (wet).

In this section, the surface roughness parameter has been considered to be negligible. In real cases, as will be seen in Section V, it is not negligible. This effect is seen in the “notch” as a higher amplitude minimum not as close to 0.

In order to summarize the simulation analysis section, the theoretical mean and the standard deviation values of the simulated retrievals, in ideal case and with quantization, have been computed and presented in Table III.

V. FIELD EXPERIMENT: REAL DATA ANALYSIS

In order to show the performance of the dual-polarization algorithm and the concepts proposed in this work, a field experiment was conducted at the Yanco, New South Wales, Australia field site of Monash University. The field experiment site is located within the OzNet SM monitoring network [30].

A. Field Experiment Setup

The PSMIGOL was installed on a wooden mast at a height of 3.6 m to avoid undesired reflections and multipath. In addition, the orientation of the antenna is in line (i.e., parallel) to the ground surface. As the surface conditions at this site are almost perfectly flat, both direct and reflected signals will have the same antenna gain. A fence was constructed surrounding the mast in
order to protect it from livestock present in the field. All fencing materials (posts, joints, pins, fence, and wire), as well as the mast itself and its restraints, are of nylon and wood. As those materials are nonreflective in the microwave spectrum, it was possible to avoid undesired reflections within the field of view of PSMIGOL. Fig. 7 shows the masthead with the PSMIGOL installation, along with the nylon wires (orange). Note that the PSMIGOL has the antenna covered by a radome, protecting it from harsh environmental conditions. It also has solar panels in order to give autonomy to the instrument. All the electronics were fitted inside an IP-66 gray box, where the antenna radome is glued.

B. Field Experiment Results

Fig. 8 shows the real data IPTs a) from GNSS PRN 1 on the July 16, 2013, and b) from the GNSS PRN 23 on the July 27, 2013. It is seen that the amplitude of the H-Pol IPT is larger than that from the V-Pol due to the larger reflection coefficient value. Both IPT, H- and V-Pol, are not aligned in none of the IPTs shown. This is due to the effect of having two phase terms in the IPT. One is related to the different path length of the direct and reflected signals, which is the same for both polarizations. The other term comes from the reflection coefficient phase at each polarization, which is different, and so it is the resultant phase of both IPT. The sensitivity to different surface points as the satellite moves is also seen as the envelope of the IPT changes due to different elevation angles and SM conditions.

The absolute value of the reflection coefficient as a function of the elevation angle is extracted for both polarizations, by applying (7). From the reflection coefficient estimation, the SM values are inferred for each of the satellites as a function of the elevation angle. To do so, the $\theta_B$ is taken as a reference value, and then the H-Pol is used for the SM mapping. As seen in Fig. 9, where the $\theta_B$ SM estimation is marked in red and the blue marks are related to the H-Pol retrievals, the $\theta_B$ SM retrieval differs slightly from the mean value (22.1% and 14.1%, respectively) of the H-Pol retrievals.

Several IPTs retrieved between July 16th and July 31st have been analyzed. The data between the SM value retrieved using the Brewster angle information and the mean value of the

<table>
<thead>
<tr>
<th>True SM (%)</th>
<th>Estimated SM (%)</th>
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<tr>
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different point SM values using H-Pol for each satellite in view has been compared. Fig. 10 shows this comparison and a good linear fit ($R^2 = 0.895$ and RMSE = 2.2%) between both methods for estimating SM.

The last part of the data processing is to combine the data from different satellites to show the spatial and temporal diversities of the proposed technique. Fig. 11 shows the SM maps retrieved for a) July 16 and b) July 24, 2013. It shows the different reflection points due to satellite movement. Consequently, the SM values retrieved are different too. In addition, there are very close points corresponding to different satellites, from which SM estimated may differ by 10%. This aspect is related to the accuracy of the technique and the time difference between each sample was taken. This time difference can be up to 4 h with a rainfall occurring in between measurements.

### C. Comparison Against Ground-Truth Data

The results obtained for different days between July 16 and July 31, 2013, have been compared with in situ SM instruments and rainfall events in that period. Fig. 12 shows a summary of the whole ground-truth information retrieved during the field experiment. The bars represent the rain events (in mm/day) from the closest information stations available: in blue the Yanco Agricultural Institute (YI) and in red the Narrandera Airport (NA). Rainfall information at those points is either collected with the traditional “Manual Rain Gauge,” which is a manual measurement of the total amount of rain, or with the “Tipping Bucket Rain Gauge,” an automatic measurement of the total amount of

<table>
<thead>
<tr>
<th>SM (%)</th>
<th>H-Pol Ideal</th>
<th>Quantized</th>
<th>H-Pol and V-Pol combined Ideal</th>
<th>Quantized</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (%)</td>
<td>STD (%)</td>
<td>Mean (%)</td>
<td>STD (%)</td>
</tr>
<tr>
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<td>0.32</td>
<td>1.01</td>
<td>1.02</td>
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<td>8.77</td>
<td>1.58</td>
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<td>33.49</td>
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<td>40</td>
<td>42.67</td>
<td>1.09</td>
<td>42.08</td>
<td>2.69</td>
</tr>
</tbody>
</table>

![Fig. 7. PSMIGOL on the mast at the Yanco Field Experiment site.](image)

![Fig. 8. Real data IPT retrieved, V-Pol (blue) and H-Pol (red). (a) 16th July 2013 (PRN: 1). (b) 27th July 2013 (PRN: 23).](image)
The SM measurements shown in Fig. 12 have been obtained with two different instruments: the Cosmic Ray Probe (CRP) and a SDI-12 SM probe. The CRP probe counts the number of neutrons emitted spontaneously by the soil to measure an area-average SM. The penetration depth of the CRP probe ranges between 10 and 25 cm, being lower for high SM values, and vice versa. The data shown from the CRP probe is the mean value of the time series data retrieved. The YB7 SM measurement station contains an SDI-12 SM probe, which provides point measurements of the top 5-cm volumetric SM content. The PSMIGOL instrument falls in the coverage area of the CRP sensor (200 m diameter), whereas the SDI-12 probe available is 700 m far away from the PSMIGOL.

The data obtained from the PSMIGOL instrument using either the mean value of the H-Pol information or the Brewster angle information are in between the data retrieved from both SM sensors. This agrees with the principles of the technique, being the penetration depth of the PSMIGOL instrument between 7 and 15 cm depending on the SM conditions. As the penetration depth of the PSMIGOL is higher than the SDI-12 and lower than the CRP sensor, it is expected to obtain SM values in between both sensors. It is also seen that after a rain
event, SM increases and then it starts a decreasing trend as
occurs in both CRP and SDI-12 sensors.

VI. CONCLUSION

This work has formulated the IPT equations for the dual-
polarization case. The use of H-Pol helps to improve the accuracy
of the estimated SM maps over bare soil or with very low
vegetation (grass) scenarios. Although the Brewer angle position
is a more accurate estimator of the average SM content at a
determined position, H-Pol amplitude measurements are a better
estimator away from the Brewer angle position, and eliminate
the amplitude ambiguities of V-Pol.

An alternative method has been proposed for the estimation of
the whole SM map, which is based on using the maxima and
minima amplitude points of the IPT fast oscillations to retrieve a
reflection coefficient image. The accuracy of this method is
assessed including instrumental and modeling errors, showing
that the range of elevation angles to be observed by the interfer-
ence pattern is between 5° and 45°. The lower elevation angle
is determined by the low dynamic range of the reflection coefficient
amplitude, whereas the higher elevation angle is determined by
the antenna pattern beamwidth ($\Delta \phi \approx 45^\circ$). Results from
a field experiment conducted on Yanco, New South Wales,
Australia, are presented showing a good agreement between the
SM retrievals obtained using PSMIGOL and ground-truth.

Finally, to apply this technique, the cross-polar relationship of
the antenna must be larger than 20 dB because, if the cross-polar
relationship is not high enough, the “notch” can be masked due
to the leakage between polarizations.

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