Abstract—In this paper, the Freeman–Durden polarimetric decomposition concept is adapted to polarimetric SAR interferometry (PolInSAR) data. The covariance matrix obtained from PolInSAR observations is decomposed into the three scattering mechanisms matrices proposed by Freeman and Durden for polarimetric SAR (PolSAR) data. The objective is to describe each interferometric cross correlation as the sum of the contributions corresponding to direct, double-bounce, and random volume scattering processes. This procedure enables the retrieval not only of the magnitude associated with each mechanism but also of their location along the vertical dimension of the scene. One of the most important features of this algorithm is the potential to isolate more accurately the direct and volume contributions which usually cannot be correctly separated by means of PolSAR measurements. In addition, it is also possible to distinguish between direct scattering responses originating either at ground or produced by upper layers of vegetation. The proposed algorithm has been tested with simulated data from PolSARProSim software, laboratory data from maize and rice samples, and airborne data from a test site with different scenarios.

Index Terms—Parameter retrieval, polarimetric SAR interferometry (PolInSAR), target decomposition (TD), vegetation.

I. INTRODUCTION

THE ESTIMATION of surface and volume parameters of natural covers by means of polarimetric synthetic aperture radar (PolSAR) observations is one of the most promising applications in the field of active microwave remote sensing [1], [2]. In the case of agricultural crops monitoring, the retrieval of soil roughness and moisture [3]–[5] has become of primarily importance due to the implications that these surface parameters have in water resources management and irrigation practices [6]. Regarding vegetation parameters in agricultural crops, biomass retrieval has been addressed for certain types of crops [7], [8], since it is also a key parameter for crop classification, crop condition assessment, and even yield prediction. On the other hand, parameter estimation procedures for forested areas are also mainly intended to quantify biomass, which is a key indicator for the global carbon cycle [9]–[11]. In both cases, agriculture and forests (particularly for low microwave frequencies), the backscattered signal is always a mixture of responses from the vegetation volume and the underlying ground. Therefore, the applicability and the accuracy of bio/geophysical parameter retrieval approaches, for soil as well as vegetation, depend on the feasibility of effectively identifying and separating different scattering contributions in the SAR data.

Most approaches aimed to overcome this issue are based on using PolSAR data as inputs and rely on target decomposition (TD) techniques [12]. One widely used TD is the Freeman–Durden decomposition [13], [14], which can be classified as a Huynen-type decomposition since it is based on incoherent averaging. This technique assumes that the covariance matrix of the backscattering data can be decomposed into three covariance matrices corresponding to scattering mechanisms of the following types: direct surface (odd-bounce), dihedral-type (double or even-bounce), and a random volume. One of the main advantages of such a decomposition is the clear physical interpretation of the individual scattering mechanisms, which can be easily associated with different physical elements in vegetated scenes.

Nevertheless, this technique presents also two limitations in its definition. In first place, the retrieved direct scattering component, which is supposed to be originated at the ground surface level, can include partially a contribution from the above ground vegetation volume, because the top parts of the plants can also produce scattering with similar polarimetric features. In second place, the Bragg model assumed for the ground surface is not able to simulate the cross-polar backscatter present when the ground is really a rough surface [5]. In fact, the Freeman–Durden decomposition translates always the cross-polar signal into the volume contribution, thus mixing up two different physical contributions.

One general solution to overcome these limitations has been to increase the number of observables, as proposed with the polarimetric SAR interferometry (PolInSAR) technique [15], [16], which is based on merging the polarimetric information with incidence diversity, i.e., interferometric observations. In principle, by using PolInSAR, it is possible to identify not only the scattering mechanisms but also their positions or distributions along the vertical dimension of the land cover structure. This technique has been applied successfully for indirect biomass estimation in forest areas [17], [18] by means of a prior calculation of tree height [19] by using a relatively simple scene model consisting of a homogeneous random volume over a ground surface (RVoG) [20] and the complex interferometric coherences as observables. Note that there are
theoretical evidences [21], obtained by assuming the forest medium as an RVoG model, which state that interferometric measurements can provide more sensitivity to forest structure and biomass than backscattering power, which suffers from saturation at lower values. However, the approach based on the RVoG model and the use of the complex interferometric coherences as observables exhibits limitations when more physical parameters (not only topography and vegetation height) are retrieved. In particular, that approach is not able to distinguish between the two types of ground responses: direct scattering or double-bounce interaction with the trunks. Recently, we have demonstrated that both contributions (when none of them is neglected) are always added (as real numbers) in the final expression of the coherence [22]. Moreover, since both contributions correspond to the same phase center location (at the ground level), they cannot be separated with that approach.

In this context, the central idea of this paper is to explore the possibility of combining the potential of TD approaches for retrieving scattering mechanisms with the capability of interferometric measurements to determine the vertical location of scatterers and, hence, to overcome the mentioned limitations of current approaches. Therefore, this paper addresses the extension of the three-component Freeman–Durden decomposition algorithm to interferometric observations, enabling in first place the estimation not only of power contributions from soil and volume but also their location along the vertical coordinate and, in second place, providing more possibilities for separating and identifying physical components in vegetated scenes.

Note also that this paper is focused on presenting the required formulation for extending this decomposition and on showing a first proof of concept of this extended approach. More mathematical implications and a performance analysis will be addressed in the future.

The organization of this paper is as follows. The description of the extended Freeman–Durden decomposition for interferometric observations is provided in Section II. Then, experimental results of the parametric inversion with simulated, laboratory and airborne data are presented and discussed in Section III. Finally, conclusions and future work are drawn in Section IV.

II. FORMULATION

As stated before, the decomposition proposed in this paper basically relies on the use of the Freeman–Durden decomposition [14], but applied to polarimetric interferometric data instead of just polarimetric ones, i.e., there are two acquisitions with a nonzero baseline between them. The three-component scattering model proposed by Freeman and Durden is assumed in order to decompose the interferometric cross correlation matrix formed in the lexicographic basis. Conceptually, this idea leads to the determination of the three phasors contributing to the total interferometric cross correlation or covariance matrix. As proposed by Freeman and Durden, we assume three scattering mechanisms corresponding to direct surface, dihedral-type, and a random volume, and we consider that these contributions can be located along the vertical dimension of the scene. Fig. 1 shows the contributions to the total $pq$ channel of the cross correlation, named as $C_{pq}$, where $p$ and $q$ are the receive and transmit polarizations, and subscripts 1 and 2 refer to master and slave images, respectively.

Hence, the starting point is the definition of the target vector in the lexicographic basis for both ends of the baseline, $\vec{k}_{L1}$ and $\vec{k}_{L2}$, given by

$$\vec{k}_{L1} = \begin{bmatrix} S_{vv1} \\ \sqrt{2}S_{vh1} \\ S_{hh1} \end{bmatrix}, \quad \vec{k}_{L2} = \begin{bmatrix} S_{vv2} \\ \sqrt{2}S_{vh2} \\ S_{hh2} \end{bmatrix}. \quad (1)$$

The corresponding cross correlation matrix is $C_{\text{int}}$

$$C_{\text{int}} = \begin{bmatrix} \langle S_{vv1}S_{vv1}^* \rangle & \langle \sqrt{2}S_{vv1}S_{vh1}^* \rangle & \langle S_{vv1}S_{hh1}^* \rangle \\ \langle \sqrt{2}S_{vh1}S_{vv1}^* \rangle & \langle 2S_{vh1}S_{vh1}^* \rangle & \langle \sqrt{2}S_{vh1}S_{hh1}^* \rangle \\ \langle S_{hh1}S_{vv1}^* \rangle & \langle \sqrt{2}S_{hh1}S_{vh1}^* \rangle & \langle S_{hh1}S_{hh1}^* \rangle \end{bmatrix}. \quad (2)$$

This matrix will be expressed as the sum of three matrices accounting for the contributions of volume $C_{\text{vol}}$, surface $C_{\text{odd}}$, and dihedral $C_{\text{dbl}}$, as proposed by Freeman and Durden, but added coherently in this case

$$C_{\text{int}} = C_{\text{vol}} + C_{\text{odd}} + C_{\text{dbl}}. \quad (3)$$

Next, the formulation for the three scattering mechanisms and the procedure to retrieve them from the data will be reviewed, pointing out the new issues arising as a consequence of the extension to interferometric observables. Note that, as already demonstrated in [14], a null correlation between copol and crosspol channels will be assumed.

A. Volume Scattering

The scattering matrix for a particle in the random volume is [14]

$$S_{\text{vol}_i} = \begin{bmatrix} S_{vi} & 0 \\ 0 & S_{hi} \end{bmatrix} \quad (4)$$

where $i = 1, 2$, which refers to each end of the baseline.

The random orientation of each particle inside the volume is accounted for by modifying the $S_{\text{vol}_i}$ matrix

$$S'_{\text{vol}_i} = \begin{bmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{bmatrix} \cdot S_{\text{vol}_i} \cdot \begin{bmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{bmatrix}. \quad (5)$$
Hence, the contribution of the particle to both the master and slave images are represented by

\[ S_{\text{VOL}}^{i} = \begin{bmatrix} S_{h_{i}} \sin^{2} \phi + S_{v_{i}} \cos^{2} \phi & (S_{v_{i}} - S_{h_{i}}) \cos \phi \sin \phi \\ (S_{v_{i}} - S_{h_{i}}) \cos \phi \sin \phi & S_{h_{i}} \cos^{2} \phi + S_{v_{i}} \sin^{2} \phi \end{bmatrix}. \]  

(6)

Assuming a volume with a uniform distribution of orientations with probability density function \(1/2\pi\), the expected values of the \(C_{\text{VOL}}\) matrix entries are given by

\[ \langle C_{ij} \rangle = \int_{0}^{2\pi} C_{ij} \cdot \frac{1}{2\pi} d\phi \]  

(7)

where \(C_{ij}\) denotes the \((i, j)\) entry.

The amplitude of the scattering coefficients does not change for both images, being the difference just in the phase term. This phase term will have two contributions: the difference due to the complex scattering coefficient in case of using different polarizations \(\psi_{p_{i}} - \psi_{q_{i}}\); and the interferometric phase related with the position in the vertical coordinate \(\Delta_{v}^{i}\). Note that the phase center of the volume scattering will be assumed the same for all polarizations. For instance, the term \(S_{h_{1}}C_{v2}^{e}\) is given by

\[ S_{h_{1}}C_{v2}^{e} = |S_{h_{1}}||S_{v_{2}}|e^{i(\psi_{v_{2}} - \psi_{h_{1}} + \Delta_{v})} \]  

(8)

where as stated before, it will be assumed that \(|S_{v_{2}}| = |S_{v_{1}}|\) and \(|S_{h_{2}}| = |S_{h_{1}}|\).

Considering a very thin cylinder approximation for the particles [14], which yields \(|S_{h_{h}}| = 0\) and \(|S_{v_{v}}| = 1\), matrix \(C_{\text{VOL}}\) results in

\[ C_{\text{VOL}} = \begin{bmatrix} \frac{3\pi}{4} e^{i\Delta_{p}^{v_{1}}} & 0 & \frac{3\pi}{4} e^{i\Delta_{p}^{v_{2}}} \\ 0 & 2\pi e^{i\Delta_{p}^{v_{1}}} & 0 \\ \frac{3\pi}{4} e^{i\Delta_{p}^{v_{2}}} & 0 & \frac{3\pi}{4} e^{i\Delta_{p}^{v_{1}}} \end{bmatrix}. \]  

(9)

Thus, in (9) the complex term \((3\pi/4)e^{i\Delta_{p}}\) is named \(F\), and therefore

\[ C_{\text{VOL}} = F_{v} \cdot \begin{bmatrix} 1 & 0 & 1/3 \\ 0 & 2/3 & 0 \\ 1/3 & 0 & 1 \end{bmatrix}. \]  

(10)

B. Double-Bounce Contribution

This contribution is modeled by the scattering matrix in (11) for both ends of the baseline [14]

\[ S_{\text{DBL}}^{i} = e^{-j2\gamma_{i}} R_{gy_{i}} R_{ty_{i}} \begin{bmatrix} 0 \\ 0 \end{bmatrix} e^{-j2\gamma_{h_{i}}} R_{gh_{i}} R_{th_{i}} \]  

(11)

where \(i = 1, 2,\) and \(R_{gy_{i}}, R_{ty_{i}}, R_{gh_{i}},\) and \(R_{th_{i}}\) are the Fresnel coefficients for ground, with subscript \(g\), and trunk or stem, with subscript \(t\), for polarizations \(v, h\). These coefficients are assumed to be equal for master and slave images. On the contrary, differences appear on exponential terms accounting for propagation, \(\gamma_{v_{1}}\) and \(\gamma_{h_{1}}\) for master image and \(\gamma_{v_{2}}\) and \(\gamma_{h_{2}}\) for slave image. These terms are divided into two parts considering attenuation \(\sigma\) and phase propagation \(\psi\). Since it will be useful for the subsequent parameter inversion stage, it is recalled that Fresnel coefficients observe that \(|HH| > |VV|\) and \(HV = 0\). Therefore, we can already calculate the cross correlation matrix \(C_{\text{DBL}}\). For instance, the (1, 1) entry, i.e., \(\gamma_{11}\), of that matrix is

\[ C_{11} = e^{-j2(\gamma_{v_{1}} + \gamma_{v_{2}})} |R_{gy_{1}} R_{ty_{1}}|^2 \]  

\[ - e^{-j2(\frac{\omega_{h_{1}}}{\rho} + \frac{\omega_{h_{2}}}{\rho} - \frac{2\pi}{\rho} - \frac{2\pi}{\rho})} |R_{gy_{1}} R_{ty_{1}}|^2. \]  

(12)

Assuming the same attenuation for both images of the interferometric pair and both polarizations, which is useful for the computation of the rest of elements of the \(C_{\text{DBL}}\) matrix, a simplified expression is

\[ C_{11} = |R_{gy_{1}} R_{ty_{1}}|^2 e^{j(\psi_{v_{1}} - \psi_{v_{2}})} = |R_{gy_{1}} R_{ty_{1}}|^2 e^{j\Delta_{p}^{d}} \]  

(13)

where \(\Delta_{p}^{d}\) represents the phase center of the double-bounce contribution, whose actual value in a vegetated scene is located just at the interface between the ground and the stems or trunks arising from that surface [23].

Operating in the same way, the phase differences in the form \(\psi_{p_{2}} - \psi_{q_{1}}\), when \(p \neq q\) and \(p, q = h, v\), can be expressed as

\[ \psi_{p_{2}} - \psi_{q_{1}} = (\psi_{p_{1}} + \Delta_{p}^{d} - \psi_{q_{1}} = \Delta_{p}^{v_{h}} + \Delta_{p}^{d} \]  

(14)

when \(p = h\) and \(q = v\), or alternatively as

\[ \psi_{p_{2}} - \psi_{q_{1}} = (\psi_{p_{1}} + \Delta_{p}^{d} - \psi_{q_{1}} = -\Delta_{p}^{v_{h}} + \Delta_{p}^{d} \]  

(15)

when \(p = v\) and \(q = h\).

Finally, the elements of the \(C_{\text{DBL}}\) matrix are obtained as follows:

\[ C_{12} = 0 = C_{21} \]

\[ C_{13} = R_{gy_{1}} R_{ty_{1}} R_{gh_{1}} R_{th_{1}} e^{j\Delta_{p}^{d}} \]

\[ C_{22} = 0 \]

\[ C_{23} = 0 = C_{32} \]

\[ C_{31} = R_{gy_{2}} R_{ty_{1}} R_{gh_{1}} R_{th_{1}} e^{-j\Delta_{p}^{d}} \]

\[ C_{33} = |R_{gh_{1}} R_{th_{1}}|^2 e^{j\Delta_{p}^{d}} \]  

(16)

where it is assumed the same phase center for both copolar channels.

Similarly to the volume case, the \(C_{\text{DBL}}\) matrix is normalized by factor \(C_{11}\), which is renamed as \(F_{d} = |R_{gy_{1}} R_{ty_{1}}|^2 e^{j\Delta_{p}^{d}}\). Hence

\[ C_{\text{DBL}} = F_{d} \cdot \begin{bmatrix} 1 & 0 & \alpha \\ 0 & 0 & 0 \\ \alpha^{*} & 0 & |\alpha|^{2} \end{bmatrix}. \]  

(17)

where \(\alpha\) is defined as

\[ \alpha = \frac{R_{gh_{1}} R_{th_{1}}}{R_{gy_{1}} R_{ty_{1}}} e^{j\Delta_{p}^{v_{h}}}. \]  

(18)
C. Direct Scattering

The direct scattering contribution is modeled under the Bragg condition or small perturbation method (SPM) [24], which assumes a relatively smooth surface with \( k \cdot s < 0.3 \) and \( k \cdot l < 0.3 \), where \( k \) is the wavenumber, \( s \) is the rms surface height and \( l \) is the correlation length. The validity range of this model is generally limited up to S-band, and it considers a null crosspolar contribution, \( HV = 0 \). Additionally, it must be recalled that the Bragg model states that \(|VV| > |HH|\). Hence, Bragg scattering parameters for master and slave images, which actually depend on surface complex permittivity and incidence angle, can be expressed in a simplified form as

\[
S_{pp1} = |S_{pp1}| e^{i\psi_{p1}} \quad \text{for master image} \tag{19}
\]
\[
S_{pp2} = |S_{pp2}| e^{i\psi_{p2}} e^{-j\Delta_\rho^s} \quad \text{for slave image} \tag{20}
\]

where \( \Delta_\rho^s \) is defined as the interferometric phase for the direct scattering, which will result not necessarily located at ground level.

Aside from the interferometric phase \( \Delta_\rho^s \), an additional phase difference (ideally with a zero value) is considered resulting from the use of different polarizations for master and slave images. In case of the \( C_{13} \) entry of the \( C_{\text{ODD}} \) matrix, we obtain

\[
C_{13} = |S_{vv1}| e^{i\psi_{v1}} \cdot |S_{hh2}| e^{-i\psi_{h1}} e^{-j\Delta_\rho^s}^* = |S_{vv1}| |S_{hh2}| e^{i(\psi_{v1}-\psi_{h1})} e^{-j\Delta_\rho^s} = |S_{vv1}| |S_{hh1}| e^{j\Delta_\rho^v} e^{j\Delta_\rho^h} \tag{21}
\]

where the equivalence \( |S_{hh2}| = |S_{hh1}| \) is assumed.

Therefore, the rest of the \( C_{\text{ODD}} \) matrix entries are

\[
C_{11} = |S_{vv1}|^2 e^{j\Delta_\rho^s} \\
C_{12} = 0 = C_{21} \\
C_{22} = 0 \\
C_{32} = 0 = C_{31} \\
C_{33} = |S_{hh1}| |S_{vv1}| e^{-j\Delta_\rho^v} e^{j\Delta_\rho^h} \\
C_{33} = |S_{hh1}|^2 e^{2j\Delta_\rho^s} \tag{22}
\]

In this case, the normalization factor is again the term \( C_{11} \), so that we define \( F_s = |S_{vv1}|^2 e^{j\Delta_\rho^s} \), and

\[
C_{\text{ODD}} = F_s \cdot \begin{bmatrix} 1 & \beta \\ 0 & 0 \\ \beta^* & 0 \end{bmatrix} \tag{23}
\]

where \( \beta \) is defined as

\[
\beta = \frac{|S_{hh1}|}{|S_{vv1}|} e^{j\Delta_\rho^v} \tag{24}
\]

D. Decomposition of the Cross-Correlation Matrix \( C_{\text{int}} \)

Taking into account the previous considerations, the elements of the \( C_{\text{int}} \) matrix, which are interferometric observables, can be decomposed as

\[
C_{11} = F_v + F_d + F_s \\
C_{12} = 0 = C_{21} \\
C_{13} = \alpha F_d + \beta F_s + \frac{F_v}{3} \\
C_{22} = \frac{2}{3} F_v \\
C_{23} = 0 = C_{32} \\
C_{31} = \alpha^* F_d + \beta^* F_s + \frac{F_v}{3} \\
C_{32} = 0 \\
C_{33} = |\alpha|^2 F_d + |\beta|^2 F_s + F_v \tag{25}
\]

where there are five complex unknowns, namely, \( F_v, F_d, F_s, \alpha, \) and \( \beta \).

Entry \( C_{22} \) corresponds to the cross correlation of the cross-polar terms. As proposed in [14], we assume that the volume contribution comes from the \( C_{22} \) entry. Consequently, we can calculate \( F_v \) from that value

\[
C_{22} = \frac{2}{3} F_v \rightarrow F_v = \frac{3}{2} C_{22} = 3 \langle S_{vh1} S_{vh2}^* \rangle. \tag{26}
\]

As a result, a cross correlation matrix for the volume contribution \( C_{\text{vol}} \) can be obtained. Now, we replicate the Freeman–Durden algorithm and the estimated volume cross-correlation is subtracted from the total \( C_{\text{int}} \) matrix.

At this point, note that as pointed out by Van Zyl [25] for the original Freeman–Durden PolSAR decomposition, the fact of subtracting the estimated volume contribution should be made according to physical criteria, which translates into the condition that the eigenvalues of the remaining PolSAR matrix (i.e., the sum of direct and double-bounce scattering) must be nonnegative. The modification on the original decomposition in order to fulfill this issue was introduced in [25] and consists in modulating the contribution attributed to the volume by means of a factor \( a \). This procedure is expressed as follows for polarimetric data:

\[
C_r = C_{\text{pol}} - a \cdot C_{\text{vol}}. \tag{27}
\]

Once at this point, the characteristic polynomial of \( C_r \) is calculated as a function of \( a \), and hence the eigenvalues of \( C_r \) appear as a function of \( a \). The value of \( a \) to be used is the highest one that ensures all three nonnegative eigenvalues.

Consequently, the final contribution of the volume from PolSAR data is expressed as

\[
F_v = a \cdot \frac{3}{2} C_{22}. \tag{28}
\]

This correction has been introduced in the original Freeman–Durden decomposition for the comparison against the results obtained by the approach proposed in this paper (see Section III). However, it must be pointed out that other approaches have been proposed in order to reduce the occurrence of nonphysical solutions. On the one hand, Yamaguchi et al.
[26] proposed a four-component model (extending the original Freeman–Durden model) where a modification on the probability density function is introduced in order to deal more accurately with the orientation of the dipole scatterers. More recently, Freeman [27] introduced a two-component model (volume and double-bounce or Bragg scattering) where the volume scattering is modeled in a more convenient way by means of an adjusting parameter. Finally, note that there are situations where the presence of nonphysical solutions is due to speckle, so it can be solved only by increasing the size of the multilook windows.

In contrast to the decomposition of PolSAR data, by definition the aforementioned correction cannot be applied to the proposed algorithm for polarimetric interferometric data, since it deals with complex numbers, not power contributions.

Following with the algorithm for polarimetric interferometric data, once the volume contribution has been estimated, the Cr matrix is expressed as

\[
C_r = C_{DBL} + C_{ODD}
\]

\[
= \begin{bmatrix}
F_d + F_s & 0 & \alpha F_d + \beta F_s \\
0 & 0 & 0 \\
\alpha^* F_d + \beta^* F_s & 0 & |\alpha|^2 F_d + |\beta|^2 F_s
\end{bmatrix}
\]

(29)

As can be seen, in matrix Cr, there appear four complex unknowns, i.e., \(F_d, F_s, \alpha, \) and \(\beta,\) and four complex observables, since \(C_r(1,3) \neq C_r(3,1).\) This formulation leads to a determined nonlinear equation system which can be solved numerically.

Finally, it is important to make clear again that it is not possible to establish a one-to-one comparison between the PolSAR-derived parameters (volume, surface, and dihedral) and the parameters extracted with the approach proposed here, because the new approach finds complex contributions at different polarimetric channels (HH and VV), but not a common power contribution as in the PolSAR decomposition. This is a consequence of the coherent definition of the new decomposition. Nonetheless, results provided in next section will show the analogies and differences between both approaches in terms of the retrieved parameters.

III. RESULTS

In this section, the proof of concept of the algorithm proposed in Section II is addressed. For such purpose, we have employed simulated data from PolSARProSim software by Mark L. Williams, wideband indoor data gathered at the European Microwave Signature Laboratory (EML), Joint Research Centre, Ispra, Italy, as well as airborne data acquired by the experimental synthetic aperture radar (E-SAR) system from the German Aerospace Center (DLR).

A. Simulated Data

The proposed approach has been first tested with a simulated RVoG scenario [20], named as hedge in the PolSARProSim software, at 1.3 GHz considering different incidence angles, soil conditions and averaging window sizes. The stand height is 10 m, and it is located on a zero slope terrain. The forest stand occupies a 0.5 Ha area, and the stand density is 360 stem/Ha. Azimuth and ground-range resolutions are 0.69 and 1.38 m, respectively. The interferometer is operated at 1- and 10-m vertical and horizontal baselines, respectively. Fig. 2 shows a red, green, blue (RGB) coding Pauli image of the RVoG scenario considered and the red line indicates the transect analyzed here. The top of the image corresponds to far range, which can be identified due to the shadowing effect at the borders of the forest. As previously mentioned, PolSARProSim allows changing soil roughness and moisture with parameters ranging from zero, i.e., smoothest and driest conditions, to ten, i.e., roughest and wettest soil.

Fig. 3 corresponds to the amplitude of the three scattering mechanisms to the (top) VV and (bottom) HH cross correlations for the whole azimuth interval. Parameters: \(\theta_0 = 45^\circ,\) highest soil roughness, highest soil moisture.
Fig. 4. Height of the three scattering mechanisms contributing to the HH correlation referenced to the ground position for the whole azimuth interval. Parameters: $\theta_0 = 45^\circ$, highest soil roughness, highest soil moisture.

Fig. 5. Height of the three scattering mechanisms contributing to the VV correlation referenced to the ground position for the whole azimuth interval. Parameters: $\theta_0 = 45^\circ$, highest soil roughness, highest soil moisture.

direct scattering is dominated by the upper layer scattering elements of the forest stand. Note that the retrieved heights at the bare surfaces are located at the ground, despite some variation for the double-bounce mechanism. It must be noted that the stable values plotted for the double-bounce within the vegetated area do not correspond to output values yielded by the optimization procedure (as happens at the bare surfaces), but to a posteriori corrected values assuming that the double-bounce mechanism is located at the ground level [23]. We have observed that inconsistent parameter values are retrieved when testing the proposed procedure using these particular simulated data sets. This inconsistency is a consequence of finding solutions corresponding to local minima which lead to a nonrealistic retrieval for some parameters. Therefore, this correction is introduced in order to avoid those wrong solutions. Nevertheless, it must be pointed out that 1) this correction is also consistent, as seen by the comparison between actual and reconstructed heights for both channels, and 2) this behavior has not been observed neither in the indoor data nor in the airborne data that we have analyzed (see Sections III-B and III-C). Note also that there are some gaps corresponding to wrong negative height estimates for the odd-bounce scattering which are not shown in Figs. 4 and 5.

Changes in the scene parameters can be noticed by means of the proposed decomposition approach. Fig. 6 shows the magnitude contributions to VV and HH interferometric channels when the lowest value for roughness, i.e., 0, is assumed in the simulation. The rest of parameters remain unchanged. Note that the volume contribution does not vary, as expected. By comparing Figs. 3 and 6, one can observe that for this data set the algorithm accounts for the differences on the roughness by means of the contributions $F_d$ for the odd-bounce and $|\alpha|^2 F_d$ for the double-bounce. On the one hand, the $F_d$ magnitude for the VV channel is significantly lower according to the Fresnel definition for smooth surfaces within the bare surfaces and areas surrounding the transition to/from the volume, despite the response along the volume is quite similar for both roughness conditions. However, the double-bounce mechanism increases
Fig. 7. Amplitude contributions of the three scattering mechanisms to the (top) VV and (bottom) HH cross correlations for the whole azimuth interval. Parameters: $\theta_0 = 30^\circ$, highest soil roughness, highest soil moisture.

Fig. 8. Amplitude contributions of the three scattering mechanisms to the (top) VV and (bottom) HH cross correlations for the whole azimuth interval. Parameters: $\theta_0 = 30^\circ$, lowest soil roughness, highest soil moisture.

and becomes dominant in some areas due to the interaction between smooth surface and trunks.

Next, a 30° incidence angle has been used, and the other parameters have been maintained as in previous simulations. Figs. 7 and 8 show the results for highest and lowest roughness values, respectively. The odd-bounce contribution for both channels is slightly higher when compared with the 45° incidence. The increase is more evident when the roughest soil is assumed in the VV channel, as shown in Fig. 7, which shows some areas where this component is dominant, specially at the bare surfaces. Note also in Fig. 8 that the double-bounce mechanism becomes dominant, and higher than in the 45° case, when the smoothest surface is considered.

Decomposition results obtained from the Freeman–Durden algorithm, including the correction proposed by Van Zyl [25] for avoiding nonphysical solutions, have been also compared with the results shown above. Figs. 9 and 10 correspond to 45° and 30° incidence angles, respectively, and include both extreme roughness conditions.

Fig. 9 shows similar results for direct and volume scattering with respect to the previous plots. However, the PolSAR approach always yields the double-bounce mechanism weaker than the other mechanisms, in contrast with the results provided by the approach proposed here. This feature specially important when the ground is very smooth, since the double-bounce should be high enough and comparable to the other mechanisms. In fact, the approach with polarimetric and interferometric data produces the expected results, as shown in the decomposition of the HH cross correlation in Fig. 6, where the double-bounce interaction dominates the response of that interferometric channel for wide intervals of the azimuth transect. In case of a 30° incidence angle for the PolSAR decomposition, shown in Fig. 10, the most important differences are found within the bare surface response where the direct scattering is higher for the roughest soil, as expected, and also in agreement...
with the qualitative behavior shown in Fig. 7. Nevertheless, note again that the PolSAR decomposition yields double-bounce scattering estimates well below the ones retrieved by using the interferometric HH cross correlation, specially for the smoothest soil, as seen when comparing Figs. 7, 8, and 10.

It must be noted that all results presented in this section have been obtained by using an averaging window size of $13 \times 13$ in case of polarimetric interferometric data and $9 \times 9$ in case of processing of polarimetric data. We have also tested the proposed algorithm with the same data sets using a window size of $9 \times 9$ pixels but the performance becomes seriously degraded because of speckle noise.

**B. Indoor Data**

Next, we have used experimental measurements acquired at the EMSL facility under controlled conditions corresponding to maize and rice samples, which have been widely employed for demonstrating PolSAR and PolInSAR capabilities [29] and validating new algorithms [30]. These data sets consist of fully polarimetric acquisitions ranging from 2 to 9 GHz for incidence angles from 44° to 45° in steps of 0.25°. The height for the maize sample is 1.8 m whereas the rice sample is 75 cm high. More details on the experimental setup can be consulted elsewhere [31].

Fig. 11 shows the magnitude of the contribution of the three scattering mechanisms to the VV and HH cross correlations, provided by the decomposition proposed in this paper, and to the total power, provided by the Freeman–Durden decomposition, as a function of frequency for the maize sample.

The magnitude of the volume component $F_v$ (short dashed line in Fig. 11), which is the same for both copolar channels, is quite stable for the full frequency range and only decreases about 3 dB at high frequencies with respect to its value at 4 GHz. The direct scattering contribution, plotted in long dashed line, represents the $F_s$ parameter for the VV channel and $\beta^2 F_s$ for the HH one, and it is also mostly the same for both channels. Contrarily to the volume component evolution, it presents a slight increase as a function of frequency from 4 GHz. This trend can be interpreted (and will be confirmed when analyzing the height location of scattering mechanisms shown in Fig. 12) as the presence of a stronger direct scattering from vegetation upper layers at higher frequencies. The third scattering mechanism, which is regarded as the double-bounce mechanism and is plotted in solid line, agrees with the expected behavior since the amplitude contribution to HH cross correlation dominates the response for S-band but for higher frequencies exhibits lower values. For C-band, it still remains between direct and volume scattering components, but from 5 GHz, it becomes the lowest in magnitude. The same decreasing trend is observed for the dihedral contribution to the VV cross correlation, but in this case, the magnitude remains always below both direct and volume mechanisms. This difference between the double-bounce contributions derived from the HH and VV channels was expected because the absolute magnitude of VV backscattering is lower than that of HH for such type of scattering mechanism.

For comparison, we have also applied the Freeman–Durden polarimetric decomposition with and without considering the correction proposed by Van Zyl on the same data set (see bottom picture in Fig. 11). Similar values to the VV cross correlation are obtained, but now the volume contribution dominates the response for the whole frequency range. The interpretation of the information provided by the magnitude of the complex parameters contributing to the VV

**Fig. 11.** Amplitude contributions of the three scattering mechanisms to the VV and HH cross correlations (top and middle plots) and to the total power provided by the Freeman–Durden decomposition (bottom) in its original form (points) and with the Van Zyl correction (lines), as a function of frequency for a maize sample.

**Fig. 12.** Height of the three scattering mechanisms contributing to the VV correlation referenced to the ground position as a function of frequency for a maize sample.
and HH polarizations should be complemented by the phase corresponding to these parameters. This phase is related to the vertical location of the elements originating each scattering mechanism. Figs. 12 and 13 display the estimated phase center height as a function of frequency for each scattering contribution and for both copolar channels, respectively. In addition, we have also plotted the heights for the VV and HH cross correlation measurements (with dots) as well as for the reconstructed values (solid line), which are computed by using the retrieved unknowns from (25). Note that an accurate fit between actual and reconstructed heights is obtained.

The heights of the phase center for each contribution, i.e., direct, volume, and dihedral scattering, are the same for both copolar channels, as expected from the decomposition of elements $C_{11}$ and $C_{33}$ of matrix $C_{\text{int}}$ in (25).

As shown in Figs. 12 and 13, the direct surface component is located somewhere along the vertical extent of the maize sample (1.8 m high) for the whole frequency range. Despite some oscillations appearing from 3 to 5 GHz, its evolution seems to be consistent with the expected behavior: a decreasing trend approaching the volume phase center for higher frequencies, since the volume behaves as a random volume for higher frequencies. Moreover, the retrieved height of the double-bounce is always around its theoretical value at the ground level [23]. It must be noted that these heights for the maize sample do not have the correction required with the simulated data.

It is clear from all plots in Fig. 11 that using only the magnitude could lead to a misinterpretation concerning the actual origin of these mechanisms. For instance, the large direct scattering retrieved for the full frequency range (long dashed line) could be interpreted as a strong response from the ground surface. However, by inspecting the phases or heights (Figs. 12 and 13), it becomes evident that this contribution is actually originated in the above ground vegetation volume. In this example, the large and wide leaves of the maize sample generate this type of scattering, as mentioned previously.

The proposed algorithm has been also tested with a rice sample, which is a much shorter crop and with a quite distinct radar signature as a consequence of the flooded condition of the soil. Fig. 14 shows the decomposition results for magnitudes and heights of the phase centers for each mechanism, in the 5–9 GHz range and with a 0.5° angular baseline. To save space, we only present the heights of the phase centers corresponding to VV channel because the ones corresponding to the HH channel are coincident.

The magnitudes estimated by the proposed algorithm (Fig. 14) reproduce quite well the expected response from the HH correlation for this target with a tenuous vegetation volume, since the dihedral mechanism predominates and the power level of the direct response remains below the volume contribution. Note the fading effect present at about 8 GHz for the $|\beta|^2 F_s$ component, which has no concluding explanation yet. On the other hand, the VV correlation exhibits a higher direct component than HH channel and the same volume contribution as assumed by the model. As in the maize case, the dihedral contribution is lower for the VV channel than for the HH one.

Trends shown by magnitude evolution in Fig. 14 are similar to those obtained by the Freeman–Durden decomposition, shown in Fig. 15. More importantly, we can observe that in this case the interferometric information does not introduce any significant improvement in the estimation of the scattering mechanisms since all phase centers are located at the ground level (see bottom plot in Fig. 14). This is a consequence of the short volume depth as well as the dominant ground-stem and ground-canopy interactions. This result agrees with the
reconstruction of the microwave vertical profile carried out by means of the polarization coherence tomography technique [30], [32] in a single-baseline approach on the same data set [33]. However, the same work also outlined the potential of the PCT with a dual-baseline approach because it was able to retrieve a vertical profile for C- and X-band which mostly agrees with the expected behavior, i.e., a maximum at ground level and a second weaker maximum close to the top of the volume. These results suggest that, when dealing with short crops, more interferometric observables should be added to the proposed decomposition algorithm in order to increase the vertical resolution.

Finally, it is important to make clear the assumptions of the model employed in the decomposition and their possible limitation when applied to this data set. In first place, the morphology of most agricultural crops, regarded by the model as a homogeneous volume over the ground surface, would be better modeled as a heterogeneous volume. Nevertheless, there are some examples in the literature [34], [35] where quantitative information from such crops has been correctly retrieved despite of the homogeneous volume assumption. Additionally, the heterogeneity of maize and rice crops basically arises due to the presence of two different layers, i.e., vertical elements (stalks and stems for maize and rice, respectively) and randomly oriented leaves (for both crops), which indeed correspond with the scattering mechanisms assumed by this decomposition. In second place, it is known that the SPM approach employed for modeling the direct scattering from the ground is valid only up to S-band, whereas we have presented results up to X-band. However, from C-band, the wave extinction through the volume becomes more important so it is expected the direct ground contribution to be negligible (null in case of rice sample because the soil is flooded), which is supported also because of the incidence angle values (45°). In summary, the two limitations do not affect the inversion results produced by the proposed approach and by the Freeman–Durden decomposition, provided that the retrieved parameters are correctly interpreted.

C. Airborne Data

Finally, we have also tested the proposed procedure with airborne data. The test site corresponds to Oberpfaffenhofen, around the DLR, and the measurements were acquired by the E-SAR sensor from DLR. They consist of quad-pol interferometric data at L-band with a 40° average depression angle and 10-m baseline. Fig. 16 shows a composite image of the test site in the Pauli basis, with 1200 pixels in range and 1300 in azimuth, where there can be identified forest areas, buildings corresponding to DLR facilities, the runway of the DLR aerodrome, the surrounding bare surfaces, and some agricultural fields.

The analysis has been performed on the azimuth transect at near range shown in Fig. 16. Along this transect, we can identify four different types of scene: bare surfaces, forest areas, buildings, and agricultural fields. Results for the amplitude of the three scattering contributions [see Fig. 17(a) and (b)] reveal that the direct scattering dominates along the whole transect for the VV channel, although in the forest area (which ranges approximately between pixels 200 and 600), the volume contribution exhibits a level very close to the direct scattering. The direct contribution in VV channel also dominates the response for the bare surface within the first 150 pixels, according to the Bragg model. However, in this area, the volume response is clearly lower than in the forest since no vegetation is present. The same behavior occurs for the bare surface from the second half of the transect. Moreover, the direct scattering component, and to a lesser extent the volume scattering, increases its magnitude between pixels 1000 and 1200, which corresponds to a short vegetation zone (agricultural fields), in agreement with the prevailing mixing of direct and double-bounce scattering shown by the Pauli image in Fig. 16. In addition, in agreement with previous results, the double-bounce contribution to the VV correlation is well below the other mechanisms in the presence of vegetation, as can be observed in the forest and agricultural areas of the transect.

The separation of contributions of the HH cross correlation also agrees with the expected behavior. For bare surfaces, the response is similar for odd- and double-bounce mechanisms and stronger than the volume scattering. However, in the agricultural field (from pixel 1000 to 1200), there appears an increase of the dihedral component in agreement with the higher contribution of the double-bounce mechanism shown before.
This is consistent with the definition of Fresnel coefficients, where the HH contribution is higher than the VV one. On the other hand, in forested areas the distribution of the dominant scattering mechanisms is not uniform. The double-bounce and the volume scattering are high and quite similar to each other but, depending on the density of volume scatterers at each position, there appear points where the direct scattering equals the other two contributions, as happens between pixels 320–360 and around pixel 500. This behavior is in agreement with the observations reported in [26], where an odd-bounce in the VV backscatter is justified due to the presence of vertically oriented canopies, which is the characteristic scenario corresponding to fir trees found in the Oberpfaffenhofen area.

For the sake of comparison, results from the Freeman–Durden PolSAR decomposition for both ends of the baseline are shown in Fig. 17(c) and (d). Note that there are no noticeable differences between both cases, as expected, so the following observations apply for any of the polarimetric images of the interferometric pair. As seen, the volume contribution mostly dominates the response in the forested area, whereas the double-bounce contribution is about 6–7 dB below the volume response for wide zones along such area. This is a consequence of the different way in which the distribution of backscattering power among the different contributions is determined by each algorithm. When the interferometric information is considered, a volume contribution is obtained for each copolar channel, and denoted as $F_v$, whereas in the Freeman–Durden algorithm the total volume power is the sum of all the volume contributions to VV, HH, and HV channels, i.e., $8/3 \cdot |F_v|$, and hence a higher absolute level is obtained in this approach.

Differences between both approaches become more evident at the short vegetation area, specially within azimuth intervals 730–880 and 1240–1300. In the Freeman–Durden decomposition results, the magnitude of contributions of volume and odd-bounce (direct) within these areas are nearly equal (indeed, within interval 1240–1300 both contributions are mostly overlapped except for some isolated points). On the other hand, results considering the interferometric information of VV channel [Fig. 17(a)] for the same intervals show that direct scattering magnitude is higher than the volume scattering one (also happens for the double-bounce component for some pixels at the end of the transect), which effectively suggests that this is due to the presence of a Bragg surface and not to a random volume. Note that this differentiation is not so evident in the PolSAR case [Fig. 17(c) and (d)] since two similar values for direct and volume scattering could lead to ambiguities regarding the type of physical mechanism contributing to each magnitude. Additionally, it must be noted that although at interval 1000–1200, the Freeman–Durden decomposition assigns the highest magnitude to the direct scattering, the double-bounce contribution is almost equal to that corresponding to the volume scattering, which disagrees with the dominant direct + dihedral mixed response observed in the Pauli decomposition (see Fig. 16). On the contrary, when the interferometric information is accounted for, the highest contributions effectively retrieved correspond to the direct and double-bounce mechanisms.

Note, however, that at the beginning of the transect (pixels 40–140), there is an agreement between the information retrieved by the VV channel decomposition and results yielded by the Freeman–Durden algorithm, since in both cases direct and volume contributions are assigned to different magnitudes. This suggests that both algorithms can be equivalent for certain types of surfaces, i.e., nonvegetated, since in this case interferometry does not play a role because the mechanisms are not physically separated along the vertical coordinate.

Following the previous argument, the quantitative information provided by the amplitude contributions can be complemented by observing the height estimates for each scattering mechanisms as well as the height differences between direct and volume contributions. In Fig. 18, the retrieved heights for the contributions to the VV correlation are plotted for the whole transect at the top. The bottom plot corresponds to a zoom (indicated with a rectangle in the upper plot) in an area containing bare surface and forest. As shown, heights for bare surfaces are assigned to values around zero, as expected. On the other hand, heights for forested areas present inconsistent values for some pixels, i.e., close to pixels 200 and 400.
These inconsistencies arise from negative values of the volume height, which corresponds to the input HV interferometric cross correlation phase. These unrealistic phase values for the volume component yield a wrong estimation of the rest of parameters, as observed in the corresponding phases for odd- and double-bounce mechanisms. In principle, this result may constitute an indicator of a poor averaging on the data set which suffers from a high speckle noise mainly in the forested areas. Therefore, it is expected that reduced errors can be achieved with more averaging, as happens in the EMSL data that we analyzed in Section III-B.

Note also that double-bounce heights (red squares) are confined to a certain range. This is a consequence of the limitation assumed in the optimization procedure concerning the feasible phases corresponding to the dihedral component (see also the discussion in Section III-A). These values are bounded between $-10^\circ$ and $10^\circ$, i.e., between $-1$ and $1$ m around the ground level, where it is expected to be located the phase center of the dihedral mechanism [23]. This limitation is introduced in order to avoid local minima which lead to inconsistent solutions for the estimated parameters. However, note that this point does not disable the applicability of the proposed algorithm because its occurrence depends on the data set, i.e., the heights for the maize sample (see Figs. 12 and 13) were very accurately estimated without the need of any correction.

Additionally, in Fig. 19, the height differences between direct and volume components are depicted for both copolar channels. Gaps indicate that one of the phase values is not considered since the corresponding magnitude is lower than a fixed threshold. Note that positive values mean that the direct scattering is located at a higher position than the volume scattering and negative values just the opposite. Fig. 19 shows that the largest height differences in the vertical location of odd-bounce and volume scattering mechanisms correspond to the forested areas, mainly located from pixel 200 to pixel 600, whereas the bare surfaces and the agricultural fields exhibit values all around zero. The most noticeable differences result from the VV cross correlation, since the vertical polarization can contribute more than the HH to both the scattering from a rough surface (attending to the Bragg model) and to direct scattering from somewhere along vertical vegetated structure, as mentioned previously and according to the oriented morphology [26] of fir trees within the test site.

To complete this proof of concept, a qualitative measure of the accuracy of the proposed decomposition procedure is shown in Fig. 20. The plots represent the distance on the complex plane between the measured and the estimated cross correlations for the whole azimuth interval. Note that the estimated values correspond to the elements of covariance matrix $C_{\text{int}}$ reconstructed from the retrieved parameters, i.e., $C_{11}$, $C_{33}$, $C_{13}$, and $C_{31}$. As observed, the reconstruction error is relatively high in the forested area for all entries of the matrix except for the VV channel. It is also interesting to see that for the VVHH and HHVV correlations (entries $C_{13}$ and $C_{31}$), there are differences also in the 1000–1200 zone (agricultural field), where VV and HH (entries $C_{11}$ and $C_{33}$) are quite well.
estimated. This is also a consequence of the actual magnitude of these correlations, which clearly influences the subsequent decomposition. Nevertheless, as we noted in the previous lines, speckle noise must be considered as another source of error for this decomposition.

Finally, it must be stressed that additional improvements for a higher accuracy in the estimated parameters should be addressed in a future work. On the one hand, one must take into account that the model inversion, i.e., (29), relies on a non-linear system equation whose numerical solution is not always unique since it depends on the algorithm adopted to compute it. Hence, implementation issues may play a key role on the final estimates. As a suggestion of one referee in the reviewing process, one way to overcome such limitations could be to implement the inversion procedure by considering not only the interferometric information but also the polarimetric data corresponding to both ends of the baseline. Although this improvement requires further investigation and should be addressed in a future work, the merging of polarimetric and interferometric information in the inversion procedure could avoid such inconsistent solutions. On the other hand, as stated in Section II-D, a wrong fit among parameters and data may be a consequence of the wrong choice on the volume scattering model. Therefore, the modification of the volume description as proposed in other recent polarimetric approaches such as [26] and [27] will probably lead to an improvement on the estimates consistency.

IV. CONCLUSION

This paper proposes a procedure for exporting the Freeman–Durden PolSAR TD concept to PolInSAR data. The formulation of the Freeman–Durden decomposition has been adapted to PolInSAR in order to jointly retrieve not only the magnitude but also the interferometric phases (related to the vertical locations) of the direct (odd-bounce), double-bounce, and volume scattering mechanisms. The procedure assumes that the interferometric cross correlation for the linear basis can be decomposed into these three mechanisms. Simulated, indoor and airborne data have been used for testing the procedure, and its potential has been analyzed also in comparison with the original Freeman–Durden decomposition for PolSAR corrected by the modification proposed by Van Zyl. It has been shown that current limitations on polarimetric decompositions regarding the inability to determine or separate physical mechanisms present in the scene (e.g., direct scattering from the vegetation volume can be wrongly assigned to the ground) can be overcome when the interferometric information is also considered. In this case, the retrieved parameters are defined with magnitude and phase, and hence the power contribution is estimated jointly with the phase center of the scattering mechanism.

Among the new results provided by this approach, it has been clearly shown in indoor data from a maize sample that the direct scattering phase center of direct scattering (usually associated with the ground) is located higher than the rest of mechanisms. On the other hand, the double-bounce scattering remains always around the ground level, as expected.

When applied to airborne data on a forested area, the proposed algorithm does not retrieve the volume contribution as the dominant one as happens in the Freeman–Durden decomposition. The results are analyzed in terms of the VV cross correlation and HH cross correlation. By doing this, it is shown that the VV correlation is mostly made up of the odd-bounce, which is dominant, and the volume contributions. This occurs for the bare surface, forests, and the agricultural area. On the other hand, the HH correlation is dominated by both the double-bounce and volume mechanisms within forested areas and only by the dihedral scattering along bare surfaces and the agricultural area. In addition, inside this last zone, results of the proposed algorithm agree with the Pauli decomposition image since it retrieves the double-bounce and direct scattering as the dominant ones, which is a characteristic feature of crops. Nevertheless, the Freeman–Durden decomposition assigned the strongest contribution to the direct scattering.

The performance of this type of decomposition, in terms of accuracy of volume scattering description and other numerical issues, is subject of future work. The current inversion of the equations system strongly relies on the optimization technique applied and, hence, final solutions are not unique. A more suitable modeling of the volume scattering must be explored and introduced in order to improve the performance. Moreover, the influence of speckle filtering and multilooking, of prime importance in PolInSAR, should be also assessed in terms of this decomposition. Finally, an alternative and more complete extension of this approach would consist in decomposing a $6 \times 6$ matrix formed by including both the cross correlation information between images (as proposed in this paper) and the correlation information at each baseline end.

ACKNOWLEDGMENT

The authors would like to thank the personnel of the European Microwave Signature Laboratory for providing the indoor data; C. Lopez-Martinez for his helpful comments; and the anonymous reviewers for their constructive suggestions that contributed to improve this paper. The airborne data set, provided by DLR, is available together with the POLSARPro software at http://earth.esa.int/polsarpro/.

REFERENCES


[36] J. David Ballester-Berman was born in Xixona, Spain, in 1975. He received the Ingeniero degree in telecommunications engineering from the Technical University of Valencia, Valencia, Spain, in 2000 and the Doctor Ingeniero degree in telecommunications engineering from the University of Alicante (UA), Alicante, Spain, in 2007.

From 2000 to 2001, he was a Support Engineer in the development of software tools for the planning and design of terrestrial digital television systems. Since 2001, he has been with the Signals, Systems and Telecommunication Group, UA, carrying out educational and research tasks, where he holds a position as an Assistant Professor. His research interests include microwave remote sensing applied to biophysical parameter retrieval, polarimetric synthetic aperture radar interferometry techniques, electromagnetic modeling of vegetation covers, and radar imaging signal processing.

Juan M. Lopez-Sanchez (S’94–M’00–SM’05) was born in Alicante, Spain, in 1972. He received the Ingeniero and Doctor Ingeniero degrees in telecommunications engineering from the Technical University of Valencia, Valencia, Spain, in 1996 and 2000, respectively.

From 1998 to 1999, he worked as a Predoctoral grandholder with the Space Applications Institute, Joint Research Centre of the European Commission, Ispra, Italy. Since 2000, he has led the Signals, Systems and Telecommunication Group, University of Alicante, Alicante, where he is currently an Associate Professor. He has coauthored more than 20 papers in refereed journals and more than 50 papers and presentations in international conferences and symposia. His main research interests include microwave remote sensing for inversion of biophysical parameters, polarimetric and interferometric techniques, synthetic aperture radar imaging algorithms and analytical and numerical models for multiple-scattering problems.

Dr. Lopez-Sanchez received the INDRA award for the best Ph.D. thesis about radar in Spain in 2001.