Soil Moisture Retrieval under Forest Using Polarimetric Decomposition Techniques at P-Band

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Abstract

Soil moisture estimation was investigated in forested environments by applying long wavelength SAR at P-band together with an innovative polarimetric decomposition technique adjusted for forest vegetation scattering. Oriented volumes, exhibiting no azimuthal symmetry ($T_{22}{\neq}T_{33}$), are incorporated in the scattering model for forest canopies. After extraction of the ground (surface, dihedral) components, applying an innovative surface-dihedral dominance criterion, both components are inverted for soil moisture under forested vegetation cover. Fully polarimetric SAR data of DLR's E-SAR system acquired during the OPAQUE 2007 in Saxony (Germany) and during the BioSAR 2008 campaign in Krycklan (Sweden) were used for algorithm analyses. The results for soil moisture inversion under forest indicates inversion rates between 15vol.% and 21vol.%. A first validation with *in situ* measurements from FDR-probes reveals a RMSE of 12.8vol.% for the OPAQUE test site.

1 Introduction

As most of the areas in higher latitudes (boreal zones) are predominantly covered by forests, the global estimation of soil moisture can only be assessed by a strategy including soil moisture inversion under forested vegetation cover.

Historically, soil moisture retrieval has been a topic in Radar remote sensing for some decades [1]. But the estimation of soil moisture under forested environments was not in the focus of research, which might be caused by the complexity of forest scattering. However, *Moghaddam et al.* published an approach using a dihedral component of a semi-empirical double bounce model for soil moisture inversion under forest [2].

In general two key issues seem to be of major concern for successful sub-canopy information retrieval: 1. Sufficient penetration through the canopy 2. Appropriate decomposition of the different scattering contributions to extract the soil information. Concerning the first issue, **Figure 1** shows an RGB-composite of the Pauli decomposition at L- and P-band for the boreal forest test site of the BioSAR 2008-campaign in Krycklan, Sweden.

Distinctively higher penetration is achieved in P-band than in L-band, which is reflected in the increase of red/blue areas within the forest. This indicates even bounce (dihedral)/ odd bounce (surface) reflection from the ground instead of volume scattering fom the canopy.

The strong ground component points towards a possible polarimetric model-based decomposition and inversion approach utilizing for example the dihedral scattering component after removal of an appropriate volume component for P-band scattering. Hence, this highlights again the second key issue of appropriate data decomposition, which will be detailed in the following section.

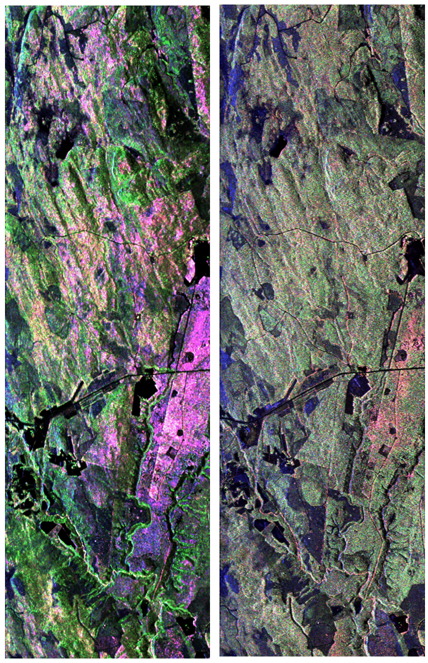

Figure 1 RGB-composites of *Pauli* decomposition at P-band (left) and L-band (right) for the boreal forest test site of the BioSAR 2008 campaign in Krycklan, Sweden (R: Even bounce G: Volume B: Odd bounce).

2 Methodology

2.1 Model-based Polarimetric Decomposition Techniques for P-Band

Figure 1 indicates significant surface and dihedral scattering in forested areas, which emphasizes the implementation of a three component decomposition with a surface $[T_S]$, a dihedral $[T_D]$ and a volume $[T_V]$ contribution. Focusing on the volume contribution, the deep penetration of P-band into foliage and down to the stems should lead to a violation of the azimuthal symmetry assumption of randomly oriented vegetation ($T_{22}=T_{33}$). In order to test this hypothesis, the *Pauli*-based, dihedral ground-to-volume ratio is calculated and shown in **Figure 2** [3]:

$$Pa_D = \frac{T_{22}-T_{33}}{T_{22}+T_{33}} \tag{1}$$

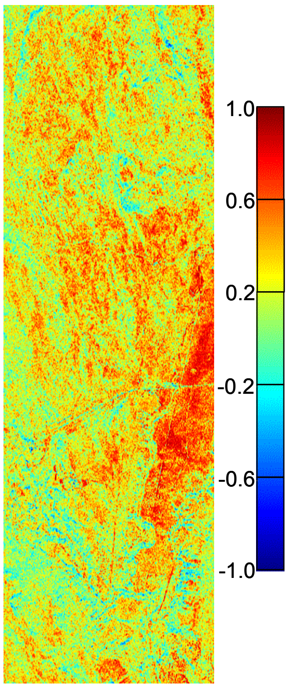

Figure 2 *Pauli*-based, dihedral ground-to-volume ratio Pa_D showing the boreal forest test site of the BioSAR 2008 campaign in Krycklan.

Red color in **Figure 2** indicates the areas, where the azimuthal symmetry assumption does not hold at all (T_{22}>>T_{33}), which includes major parts of the forest! Hence, the volume model has to be adapted to account for oriented volumes with low depolarization. *Cloude* presented ways to enlarge the modeling of volume scattering by small particles in order to account for different particle shapes, orientations and propagation effects [4]. Eq. 2 represents a reflection symmetric volume component with a uniform *pdf* of orientation angles around the line of sight (assuming no tilts in the volume).

$$[T_V] = f_V \begin{bmatrix} \frac{(1+Ap)^2}{2(1+Ap^2)} & \frac{(Ap^2-1)\mathrm{Sinc}2\delta}{2(1+Ap^2)} & 0 \\ \frac{(Ap^2-1)\mathrm{Sinc}2\delta}{2(1+Ap^2)} & \frac{(Ap-1)^2(1+\mathrm{Sinc}4\delta)}{4(1+Ap^2)} & 0 \\ 0 & 0 & \frac{(Ap-1)^2(1-\mathrm{Sinc}4\delta)}{4(1+Ap^2)} \end{bmatrix} \tag{2}$$

In addition, propagation effects are not considered in this volume component due to the low density of boreal forests at P-band.
The adapted volume scattering component $[T_V]$ incorporates a degree of orientation, expressed by the angle δ. Due to the lack of polarimetric observables, the particle anisotropy is set to zero indicating a volume of dipoles ($Ap=0$), which should fit to the trunk domination (long vertical dipoles) in vegetation scattering of P-band leading to the $[T_{VP}]$-component in Eq. 3.

$$[T_{VP}] = f_V \begin{bmatrix} \frac{1}{2} & -\frac{1}{2}\mathrm{Sinc}2\delta & \\ -\frac{1}{2}\mathrm{Sinc}2\delta & \frac{1}{4}(1+\mathrm{Sinc}4\delta) & \\ & & \frac{1}{4}(1-\mathrm{Sinc}4\delta) \end{bmatrix} \tag{3}$$

As there is no variable left in the calculus, the polarimetric entropy H serves as a first estimate for the distribution width δ of the orientation angle: The higher the entropy, the lower the degree of orientation within the vegetation volume. **Figure 3** shows exemplarily the polarimetric entropy of the boreal forest at the Krycklan test site.

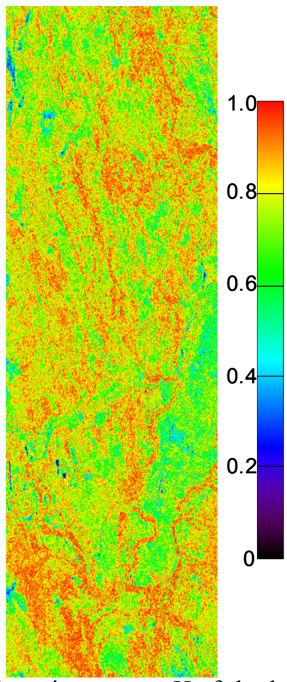

Figure 3 Polarimetric entropy H of the boreal forest test site of the BioSAR 2008 campaign in Krycklan.

The ground components $[T_S]$ and $[T_D]$ are assumed to be both of rank-1 (no surface roughness disturbance due to long wavelength at P-band) and are modeled according to [5]:

$$[T_S] = f_S \begin{bmatrix} 1 & \beta^* & 0 \\ \beta & |\beta|^2 & 0 \\ 0 & 0 & 0 \end{bmatrix}, [T_D] = f_D \begin{bmatrix} |\alpha|^2 & \alpha & 0 \\ \alpha^* & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{4}$$

Finally the acquired fully polarimetric SAR data $[T]$ can be decomposed as follows:

$$[T] = [T_S] + [T_D] + [T_{VP}] \tag{5}$$

2.2. Soil Moisture Inversion under Forest

After removal of the volume component $[T_{VP}]$ from the acquired SAR data $[T]$, the ground components ($[T_S]$, $[T_D]$) are separated according to an innovative dominance criterion described in Eq. 6.

$$\begin{aligned} &\text{If } \Im\left[\left\langle S_{HH} S_{VV}^{*} \right\rangle\right] > 0 \Rightarrow \text{ surface dominant} \\ &\text{If } \Im\left[\left\langle S_{HH} S_{VV}^{*} \right\rangle\right] < 0 \Rightarrow \text{ dihedral dominant} \end{aligned} \tag{6}$$

In this way only the dominant scattering component is inverted for soil moisture establishing an analytically solvable algorithm of four variables and four observables [5]. In the case of surface dominant scattering under forest canopy, the surface scattering mechanism β is used for soil moisture inversion applying the inversion technique proposed in [5].
In the case of dihedral dominant scattering under forest canopy, the dihedral scattering intensity f_D and the dihedral scattering mechanism α are incorporated into a joint analysis for soil moisture using basically the inversion method introduced in [5].
Finally the non-forested regions exhibit very low surface scattering in P-Band (see black areas in **Figure 1**). An inversion of the surface component in these areas is not appropriate due to the low signal-to-noise (SNR) level (both co-polarized channels $\leq$ -20dB) and these areas will be masked gray in the decomposition and inversion results [6].

3 Experimental Results

The developed polarimetric decomposition and inversion method for soil moisture retrieval under forest is applied on the data of the OPAQUE 2007 and BioSAR 2008 campaign [7,8]. Fully polarimetric data at P-band were acquired by DLR's E-SAR sensor over the forest test sites in Saxony, Germany (OPAQUE) and in Krycklan, Sweden (BioSAR). Due to national restrictions for P-band, the data were received in reduced (OPAQUE, 10MHz) and full (BioSAR, 94MHz) resolution. Simultaneously to the overflights, ground measurements for forest and soil characteristics were conducted for a vegetation characterization and for a first comparison with the inverted soil moisture product.

3.1 Model-based Polarimetric Decomposition at P-Band

In **Figure 4** the result of the model-based polarimetric decomposition, adjusted to the case of forest canopies at P-band, is shown as normalized powers, where low SNR regions are masked gray. The RGB-images are composed by the three scattering components, where dihedral scattering is set to red, volume scattering is set to green and surface scattering is set to blue.

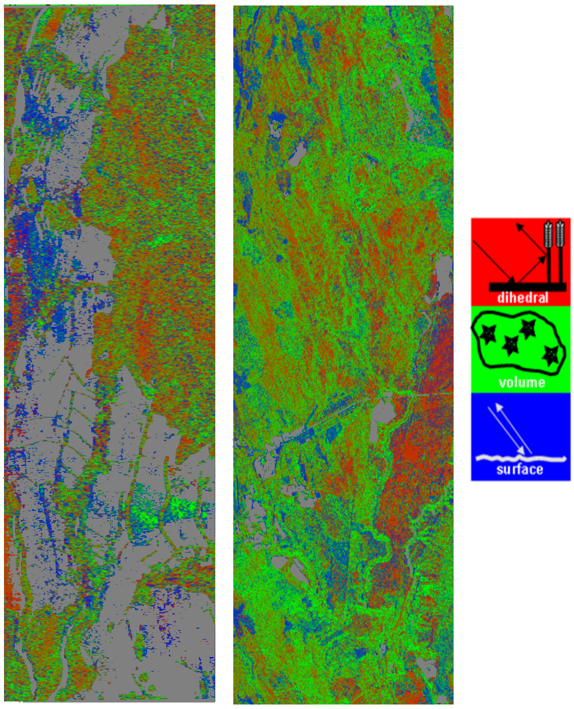

Figure 4 RGB-images of normalized decomposition powers for the forest test sites in Saxony (left) and in Krycklan (right) (R: Dihedral, G: Volume, B: Surface, gray: SNR mask).

The forested regions are dihedral (reddish) and volume (greenish) dominated, while the low and non-forested regions, which are still above the noise level of -20dB, appear bluish due to surface dominance. After comparison of the decomposition results with the local incidence angle and the orientation angle after *Lee et al.*[4] (not shown in the manuscript), the volume domination in some areas can be traced back to the range and azimuth slopes of the hilly terrain.

3.2. Soil Moisture Inversion under Forest at P-band

As introduced in **Section 2**, both ground components (surface, dihedral) were inverted for soil moisture estimation under forest in order to obtain a most complete inversion. In **Figure 5** the inverted soil moisture under forest for both components is depicted ranging from 0vol.% to 50vol.%, while non-physical results in the inversion are masked white. The results reveal a heterogeneous moisture distribution over the forest area with inversion rates of 15% (Saxony) and 21% (Krycklan) for the whole scene (without low SNR regions). For the Krycklan test site, the dry regions (blue color in **Figure 5**) seem to be allocated in the upper right and in the lower area of the scene, whereas the very moist regions (orange color in **Figure 5**) correspond well with the dihedral dominant regions in the middle of the scene.

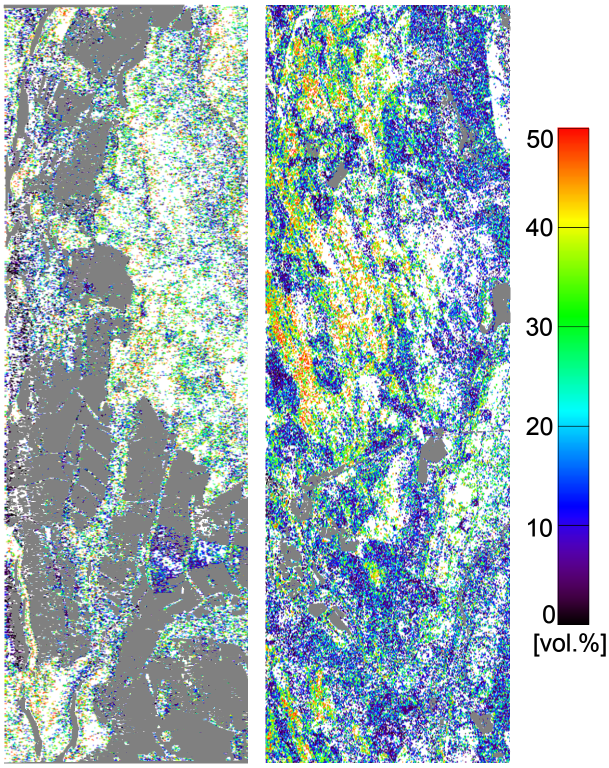

Figure 5 Inverted soil moisture under forest for the test sites in Saxony (left) and in Krycklan (right) (low SNR regions are masked gray; White areas are non-invertible regions; Image smooth: 4x4).

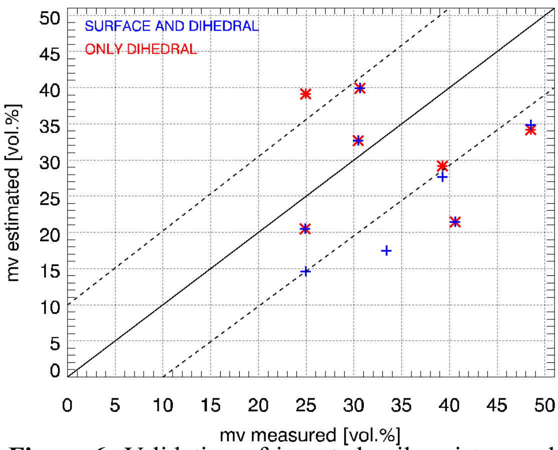

Figure 6 Validation of inverted soil moisture values with *in situ* measurements from FDR-probes for the forest test site in Saxony, Germany.

How far the soil moisture distribution reflects natural conditions in hilly terrain and how much it is affected by remaining artifacts from the inversion algorithm, can not be investigated for the Krycklan data due to the lack of reliable *in situ* measurements. However, a validation with mobile FDR-probes was feasible for the inversion result of the Saxony test site (cf. **Figure 6**), where RMSE-values of 12.90vol.% and 12.81vol.% are obtained for the inversion with both ground components (surface and dihedral) and with only the dihedral component respectively.

4 Conclusion and Outlook

The first results for soil moisture retrieval under forest at P-band using an adapted model-based polarimetric decomposition for orientations in forests turn out promising. But it has to be noted, that entropy represents just a first estimate of the distribution width δ for the degree of orientation within the forest canopy. Further ideas using an iterative technique for retrieval of δ are currently under investigation. For future work, the presence of orientation angle effects still needs to be investigated further in order to understand the impact on soil moisture inversion at P-band. In addition, a campaign focused on P-band fully polarimetric SAR acquisitions together with extensive soil moisture measurements under forest would be highly desirable. Besides, a future investigation of soil moisture retrieval under different types of forest would reveal further potentials and limitations of the presented approach.

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