

# Inversion of Surface Parameters from Polarimetric SAR Data

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**ABSTRACT** - In this paper we introduce a new model for the inversion of surface roughness and moisture from polarimetric SAR data, based on the eigenvalues and eigenvectors of the coherency matrix. We present how three parameters, namely the polarimetric entropy, the anisotropy and the alpha angle can be used in order to decouple roughness from moisture content offering the possibility of a straightforward inversion of these parameters.

## I. INTRODUCTION

One of the most important applications of scattering polarimetry is in quantitative surface roughness and moisture estimation. In the absence of any simple relationship between scalar reflectivity and surface parameters such as RMS height  $s$ , correlation length  $L$ , and complex permittivity  $\epsilon_r$ , several algorithms have been proposed based on multi-channel polarimetric data. Two main approaches have been employed in the literature based on empirical or semi-empirical relations: scattering amplitude ratio algorithms [1,2] and polarimetric coherence techniques [3,4]. As shown in [5,6] the relationship between surface roughness in scattering polarimetry and the eigenvalues of a coherency matrix have a physical significance in terms of scattering amplitudes and that their ratio represent generalised measures of polarimetric coherence.

A perfectly smooth surface has zero backscatter. However, considering the presence of slight roughness, particularly the case of  $ks \ll 1$  (Bragg scattering), the roughness can be seen as a perturbation of the smooth surface problem. In this case, we obtain the backscatter coefficients for a slightly rough surface using a small perturbation model from Maxwell's equations [3]. According to this model the backscatter from a surface is non-zero and depends on the component of the power spectrum of the surface which matches the incident wavelength and angle of incidence (AOI). The scattering matrix for the surface has the form

$$[S] = \begin{bmatrix} R_s(\theta, \epsilon_r) & 0 \\ 0 & R_p(\theta, \epsilon_r) \end{bmatrix} \quad (1)$$

where the coefficients  $R_s$  and  $R_p$  are functions of the complex permittivity  $\epsilon_r$  and the local incident angle  $\theta$  (2)

$$R_s = \frac{\cos \theta - \sqrt{\epsilon_r - \sin^2 \theta}}{\cos \theta + \sqrt{\epsilon_r - \sin^2 \theta}}$$

$$R_p = \frac{(\epsilon_r - 1)(\sin^2 \theta - \epsilon_r(1 + \sin^2 \theta))}{(\epsilon_r \cos \theta + \sqrt{\epsilon_r - \sin^2 \theta})^2}$$

The scattering vector in its Pauli-basis representation becomes (3)

$$\vec{k}_P = \begin{bmatrix} R_s + R_p \\ R_s - R_p \\ 0 \end{bmatrix} = m \begin{bmatrix} \cos \alpha * \exp i \phi_1 \\ \sin \alpha * \exp i \phi_2 \\ 0 \end{bmatrix}$$

where  $m$  denotes the absolute scattering amplitude. The corresponding coherency matrix results as (4)

$$[T] = \langle \vec{k}_P \vec{k}_P^+ \rangle = \begin{bmatrix} \langle |R_s + R_p|^2 \rangle & \langle (R_s - R_p)(R_s + R_p)^* \rangle & 0 \\ \langle (R_s + R_p)(R_s - R_p)^* \rangle & \langle |R_s - R_p|^2 \rangle & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Note that the angle  $\alpha$ , as defined in (3), is independent of roughness, and can be used to extract the dielectric constant if  $\theta$  is known. The Bragg scattering model, as addressed in (1-4), predicts zero cross-polarisation and zero depolarisation. Real surfaces are characterised by non-zero cross-polarisation backscattering as well as by depolarisation effects.

## II. POLARIMETRIC SURFACE SCATTERING MODEL

In order to include a non-zero HV backscattering coefficient and depolarisation effects in the Bragg scattering model, we propose a configurational average of the above solution, to obtain a coherence less than one at the same time as generating cross polarised energy. The configurational averaging is taken over a uniform distribution about zero of the surface slope in the plane perpendicular to the scattering

plane. If this slope is  $\beta$ , then we propose a uniform distribution of half-width  $\beta_1$  as shown in Fig. 1 (5)

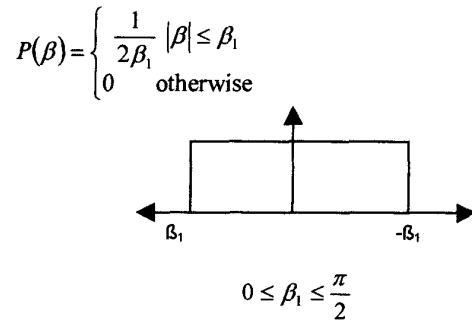


Figure 1: Uniform Distribution of Surface Slope

Assuming now a non-coherent summation of energy across the distribution of  $\beta_1$ , then the coherency matrix for the surface becomes (6)

$$[T] = \begin{bmatrix} C_1 & C_2 \sin c(2\beta_1) & 0 \\ C_2 \sin c(2\beta_1) & C_3(1 + \sin c(4\beta_1)) & 0 \\ 0 & 0 & C_3(1 - \sin c(4\beta_1)) \end{bmatrix}$$

with  $\text{sinc}(x) = \sin(x)/x$ . The coefficients  $C_1$ ,  $C_2$  and  $C_3$  expressed in terms of the smooth surface solution are given by (7)

$$\begin{aligned} C_1 &= |R_s + R_p|^2 \\ C_2 &= (R_s + R_p)(R_s^* - R_p^*) \\ C_3 &= \frac{1}{2} |R_s - R_p|^2 \end{aligned}$$

According to (6) both the polarimetric coherence and the level of cross-polarised power is controlled by a single parameter ( $\beta_1$ ).

Using the polarimetric surface scattering model and estimating the three parameters, the entropy  $H$ , the anisotropy  $A$  and the alpha angle  $\alpha$ , we obtain a separation of roughness from surface dielectric constant. The roughness estimation comes from the anisotropy  $A$  and the dielectric constant estimation from combined  $H/\alpha$  values [6].

### III. EXPERIMENTAL DATA ANALYSIS

For the validation of the proposed model fully polarimetric L-band data from the Elbe river test site in Germany, acquired by the experimental airborne E-SAR system of DLR in August 1997, are used. During the data acquisition campaign, ground data have been collected over test fields with heterogeneous surfaces. Soil roughness was estimated with a needleboard. Soil moisture values were measured in depths of 0-4 cm and 4-8 cm using traditional gravimetric sampling and time domain reflectometry (TDR). Due to the presence of vegetation, only four bare agricultural fields were available

for validation. Nevertheless, as the four fields are located at different ranges (covering an incident angle range from 47 up to 52 degrees) with different roughness and moisture values they are valuable for the validation of inversion results.

After SAR processing and polarimetric calibration, the scattering matrix data are transformed into a covariance matrix form and polarimetrically filtered [8]. Then the eigenvector decomposition is performed, followed by the computation of entropy, anisotropy, and alpha angle [7]. Surface scattering is characterised by a strong dominant scattering mechanism, represented by the first eigenvalue. The amplitudes of the secondary scattering effects, expressed by the second and third eigenvalues, are in comparison very small and therefore, more affected by noise. Thus, in contrast to the entropy, the anisotropy is a more "noisy" parameter especially in low entropy areas and its accurate estimation requires averaging over a large number of samples.

In a pre-selection step, areas where  $H > 0.45$  and  $\alpha > 45$  degrees have been masked out in order to select only surface scatterers [7]. For the remaining areas the  $k_s$  values are evaluated directly from their anisotropy values. The correlation between the estimated and measured  $k_s$  values is shown in Figure 2. To reduce the estimation variation (mainly caused by the noisy character of  $A$ ) the anisotropy  $A$  and the alpha angle  $\alpha$  have been estimated by averaging a minimum number of 1500 independent samples over each field. The high correlation of about 0.95, and the low RMS error of about 1.5 % underline the performance of the proposed method for roughness estimation.

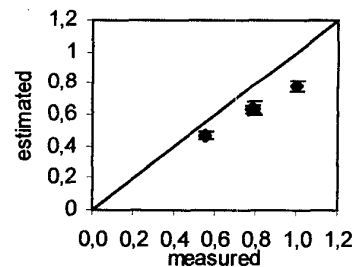


Figure 2: Estimated versus measured surface roughness values.

In a second step, the computed entropy and alpha images are used for the estimation of the dielectric constant. The estimation can be performed directly in terms of a lookup table which delivers the dielectric constant as a function of entropy/alpha values for each range line accounting in this way the variation of incident angle across the image. The correlation between the estimated and measured values for the four test fields is shown in Fig. 3.

From Fig. 3 results that the inverted  $\epsilon_r$  values correlate better with the  $\epsilon_r$  measurements in a depth of 4-8 cm than with those measured in 0-4cm.

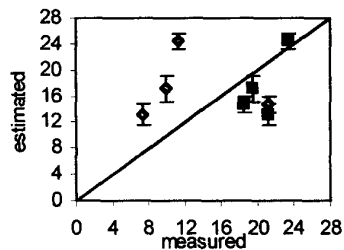


Figure 3: Estimated versus measured dielectric constant. The rhombuses indicate the 0-4 cm depth measurements while the quadrates the 4-8 cm depth measurements.

This is in accordance with the relatively low dielectric constant and the fact of using L-band data. The correlation is about 0.75, and the RMS error lies on the order of 5%. For converting dielectric constant to volumetric moisture a polynomial relationship from [8] is used. After the polynomial conversion to volumetric moisture the results show the same trend with a correlation about 0.72 and a RMS error about 5% as shown in Fig. 4.

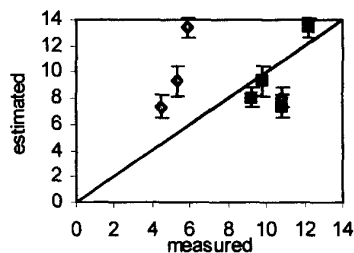


Figure 4: Estimated versus measured volumetric constant. The rhombuses indicate the 0-4 cm depth measurements while the quadrates the 4-8 cm depth measurements.

## V. DISCUSSION AND CONCLUSIONS

In this paper we have developed a new general parametric model which enables the quantitative estimation of roughness and dielectric constant for a wide range of natural bare surfaces up to  $ks = 1$  from polarimetric SAR data. The model assumes reflection symmetric surfaces, since by definition the surface normal imposes an orientation axis on the problem. It allows the HH and VV back-scattering coefficients to be different, and includes non-zero HV cross-polarised power as well as depolarisation. The application of the model to experimental data and the good agreement between the inverted values for  $ks$ ,  $\epsilon_r$  and  $\mu_v$  and the ground truth measurements prove that the structure of the data is in agreement with the predictions of the model over a large range of surface conditions.

The main advantage of the proposed inversion model lies in the separation of roughness and dielectric constant estimation which can be performed straightforwardly without the need for any data regression. Further, as the three key observables, the entropy, the anisotropy and the alpha angle, are invariant under azimuth rotations and the inversion

becomes therefore independent on azimuthal slope variations. This makes the application of the technique possible also for terrains with variable topography without the need of any additional topographic information.

Unknown is the influence of surface correlation length, as it is not appearing explicit in the model. Small correlation lengths lead to dihedral scattering effects which biases the alpha angle  $\alpha$  estimation increasing the Shh/Svv ratio. This bias can not be removed using the model alone. Fields characterised by eminently different correlation lengths in orthogonal directions, as for example ploughed fields, violate the assumption of a rotation-symmetric roughness term and cannot be resolved by the model. The presence of vegetation cover on the one hand increases the entropy and decreases the anisotropy, leading to overestimation of the surface roughness, and on the other hand increases the alpha angle leading to underestimation of the dielectric constant.

Absolute calibration of the scattering matrix data is not strictly required. While for the  $ks$  estimation only cross-talk and relative channel calibration is sufficient, for the estimation of  $\epsilon_r$  copolar-phase calibration is essential. The high dependency of the  $\epsilon_r$  estimation on the alpha-angle values combined with the fact that any copolar-phase imbalance delta phi affects directly the alpha-angle estimation (delta alpha = delta phi / 2) forces the demand on very accurate phase calibration.

## VI. ACKNOWLEDGMENT

This work was performed in the frame of the EC-TMR Radar Polarimetry Network ERB-FMRX CT98-0211.

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