Relevant polarimetric parameters for surface characterization using SAR data

S. Allain, L. Ferro-Famil, E. Pottier

University of Rennes 1
I.E.T.R, UMR CNRS 6164, Image and Remote Sensing Group
Campus de Beaulieu - Bat 11.C, 263 Avenue Général Leclerc
CS 74205, 35042 Rennes Cedex, France
Email: sophie.allain@univ-rennes1.fr

INTRODUCTION

The aim of this paper is to present a new relevant polarimetric parameter for surface characterization using SAR data. This novel parameter shall be called Eigenvalue Relative Difference (ERD) in the following.

The first part of this work introduces the Integral Equation Model (IEM) in order to characterize the polarimetric behaviour of backscattered signals from rough surfaces. In a second step, from the Cloude/Pottier Eigenvector/value based Polarimetric decomposition theorem, polarimetric descriptors sensitive to surface parameters are presented. The particular case of the parameter called anisotropy is studied in depth. In order to take into account the reflexion symmetry hypothesis considered for natural surfaces, a new polarimetric parameter, the ERD, is presented and compared to anisotropy.

A first validation step of the ERD parameter is led on scatterometric data. Measurements were acquired at EMSL, JRC laboratory (Italy), for a large set of roughness, frequency and incidence angle. Contrary to the anisotropy, the new descriptor, ERD, is strictly monotonous with respect to the surface roughness. In a second validation step, ERD and anisotropy are analysed and compared on a polarimetric SAR dataset acquired by the German Aerospace Center (DLR) E-SAR sensor, at L-band, over the Alling test site in Germany.

POLARIMETRIC SCATTERING MODEL

Soil description

Soil is mainly characterized by its roughness and its moisture. A stochastic surface is defined by its correlation function, $\varphi_{xx}(x,y)$ and correlation length, L_c, its height probability density function and standard deviation, σ. The surface spectrum, which consists the Fourier transform of the n^{th} power of the correlation function, is required by the IEM. By considering the gaussian surface, the n^{th} order surface spectrum takes the form:

$$W^n\left(k_x, k_y\right) = \frac{\sigma^2 \pi L_c^{\ 2}}{n} \exp\left(\frac{-k_x^{\ 2} L_c^{\ 2} - k_y^{\ 2} L_c^{\ 2}}{4n}\right) \qquad (1)$$

The dielectric constant, ε, is directly function of the soil moisture content.

Integral Equation Model

In order to characterize natural surfaces, the IEM is employed in the following to derive backscattering coefficients for co-polarized and cross-polarized channels formulated in [1]. This model is widely used due to its large validity domain and since it has been validated on large sets of experimental data. The cross-polarized information is derived from the multiple scattering formulation taking into account the coherent SAR integration process inside each resolution cell. This model satisfies the reflection symmetry assumption (the correlation between co- and cross-polarized channels is assumed to be zero). The IEM output is a function of the radar angle, the radar frequency, the surface spectrum, the correlation length, L_c, the surface root mean square (rms) height, σ, and the soil dielectric constant, ε. It is important to highlight that the surface rms height is generally considered as the most important surface roughness characteristic [2] [3].
A synoptic of the Integral Equation Model is given in Fig. 1.

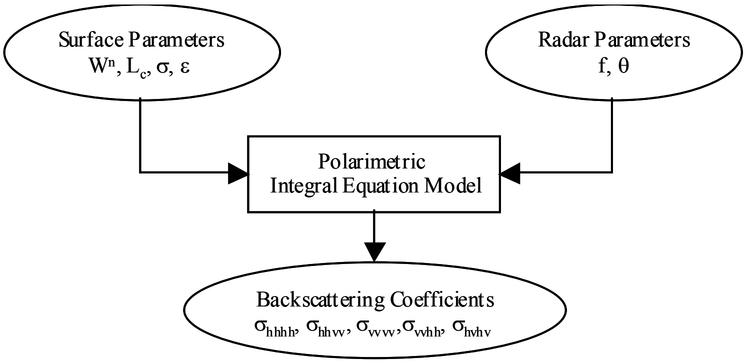


Fig. 1. IEM scattering model

The different backscattering coefficients are gathered into a single matrix representation under the form of a coherency matrix, **T**, defined as follow:

$$\boldsymbol{T} = \frac{1}{2}\begin{bmatrix} A + 2\Re B & A + 2\Im B & 0 \\ A - 2\Im B & A - 2\Re B & 0 \\ 0 & 0 & 4C \end{bmatrix} \tag{2}$$

with

$$\begin{aligned} A &= \sigma_{hhhh} + \sigma_{vvvv} \\ B &= \sigma_{hhvv} \\ C &= \sigma_{hvhv} \end{aligned} \tag{3}$$

Using the IEM model, the coherency matrix has five non-null elements. In what it follows, this model will be employed to analyse the anisotropy and the ERD polarimetric parameters variations and dependences.

EIGENVECTOR/VALUE BASED POLARIMETRIC DECOMPOSITION THEOREM

By transforming the scattering matrix **S**, in the monostatic case, into the complex target vector $\mathbf{k_p}$, the coherency matrix **T** is defined as follows:

$$\boldsymbol{T} = \left\langle \boldsymbol{k_P} \boldsymbol{k_P}^{\dagger} \right\rangle \qquad \text{with} \qquad \boldsymbol{k_P} = \frac{1}{\sqrt{2}}\left[S_{HH} + S_{VV} \quad S_{HH} - S_{VV} \quad 2S_{HV}\right]^T \tag{4}$$

An eigenvector/eigenvalue based decomposition theorem presented in [4] allows to split the distributed matrix, **T**, into a weighted sum of three orthogonal unitary matrices given by:

$$\boldsymbol{T} = \boldsymbol{V}\,\boldsymbol{\Sigma}\,\boldsymbol{V}^{\dagger} = \sum_{i=1}^{3} \lambda_i \boldsymbol{v_i} \boldsymbol{v_i}^{\dagger} = \sum_{i=1}^{3} \lambda_i \boldsymbol{T_i} \tag{5}$$

where **V** and **Σ** represent the distributed target eigenvector and eigenvalue matrices respectively. The unitary eigenvectors are parameterised using four angular variables:

$$\boldsymbol{v_i} = [\cos\alpha_i, \sin\alpha_i \cos\beta_i e^{j\gamma_i}, \sin\alpha_i \sin\beta_i e^{j\delta_i}]^T \tag{6}$$

A statistical analysis of the decomposition is considered then in order to extract the mean scattering mechanism.

The three main parameters of this decomposition are: $\underline{\alpha}$, the indicator of the mean scattering mechanism, entropy, H, which indicates the random behaviour of the global scattering and the anisotropy, A, which represents the relative importance of the secondary mechanisms. The following study concentrates on the analysis of the later parameter.

From the ordered eigenvalues in terms of size, the anisotropy is defined as:

$$A = \frac{\lambda_2 - \lambda_3}{\lambda_2 + \lambda_3} \quad \text{with} \quad 0 < A < 1 \tag{7}$$

This parameter is usually used as a surface roughness descriptor [3].

EIGENVALUE RELATIVE DIFFERENCE

Reflexion Symmetry

As it has been observed with the IEM, in the case of a natural soil, the correlation between co- and cross-polarized channels is often neglected, this phenomenon corresponds to the reflection symmetry case hypothesis. It is then possible to derive, from the coherency matrix **T** presented in (2), the analytical expressions of the eigenvalues.
The literal expressions of the Non-Ordered in Size ("nos") eigenvalues are [5]:

$$\begin{aligned}
\lambda_{1nos} &= \frac{1}{2}\left(\sigma_{hhhh} + \sigma_{vvvv}\right) + \sqrt{f\left(\sigma_{hhhh}, \sigma_{vvvv}\right)} \\
\lambda_{2nos} &= \frac{1}{2}\left(\sigma_{hhhh} + \sigma_{vvvv}\right) - \sqrt{f\left(\sigma_{hhhh}, \sigma_{vvvv}\right)} \\
\lambda_{3nos} &= 4\sigma_{hvhv}
\end{aligned} \tag{8}$$

with

$$f\left(\sigma_{hhhh}, \sigma_{vvvv}\right) = \left(\sigma_{hhhh} + \sigma_{vvvv}\right)^2 + 4\rho_{hhvv}\sigma_{hhhh}\sigma_{vvvv} \tag{9}$$

Eigenvalue Relative Difference

From the "nos" eigenvalues presented above, a new parameter called the Eigenvalue Relative Difference and denoted by ERD is defined as:

$$ERD = \frac{\lambda_{2_{nos}} - \lambda_{3_{nos}}}{\lambda_{2_{nos}} + \lambda_{3_{nos}}} \quad \text{with} \quad -1 < ERD < 1 \tag{10}$$

This novel parameter is similar to the anisotropy for small roughness values, but presents a different behaviour in high frequencies. This parameter is very sensitive to roughness and could be compared to the correlation parameter ρ_{RRLL} also developed for roughness retrieval [2][6].

Comparison with Anisotropy

Fig. 2 shows the anisotropy and ERD variations obtained using the IEM model versus kσ for various ε values, where k corresponds to the wave number. In this illustration case, the surface spectrum is considered gaussian, the incident angle presents a value of 40° and the radar frequency is considered to be 1.3 GHz.
As it can be noticed, these two parameters are very sensitive to the surface roughness relative to the frequency, whereas, the dependence on the dielectric constant is less important. On the one hand, for each ε value, one anisotropy value corresponds to two different values of kσ, introducing an ambiguity for surface roughness extraction, whereas, on the other hand, the ERD has a monotonic behaviour. The validity domain of the anisotropy is limited until kσ equals 1.5. The ERD presents the advantage to have a larger validity domain and to be bijective with kσ for each ε value.

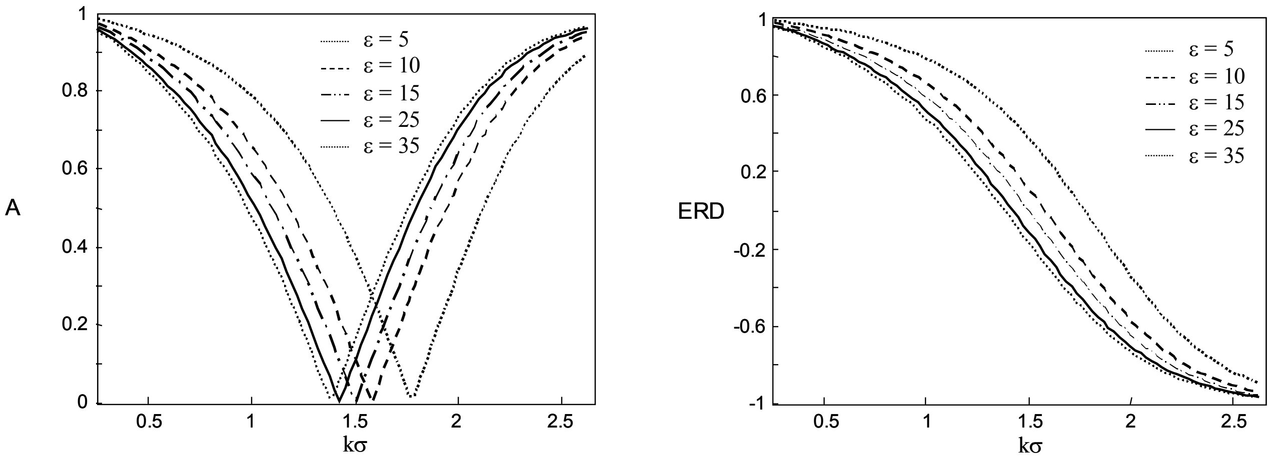


Fig. 2. Anisotropy and ERD values simulated with the IEM model

VALIDATION

In order to validate our theoretical approach, the behaviour of the anisotropy and the ERD are analysed on scatterometric and SAR real datasets.

Validation on JRC scatterometric data

Indoor scatterometric measurements obtained in the European Microwave Signature Laboratory (EMSL) anechoic chamber at JRC laboratory [7] are now considered. Data were acquired in a monostatic mode in the frequency range from 1 to 19 GHz at various incidence angles between 10° and 50° and for 72 rotation angles. The target consists of a smooth isotropic surface with a correlation length of 6 cm and a surface rms height of 0.4 cm.
It is important to notice that the correlation between the co- and the cross-polarized channels is non-null. To build our coherency matrix based on the reflexion symmetry hypothesis, these correlations are considered equal to zero.
The anisotropy and the ERD are respectively plotted versus $k\sigma$ on the Figs. 3 and 4. On these two figures, the anisotropy has the same behaviour, independently of the incident angle value, as observed for the ERD descriptor. As it has been obtained with the IEM model, the anisotropy decreases for small $k\sigma$, corresponding to smaller frequencies, and increases as $k\sigma$ increases, whereas, the ERD decreases always with $k\sigma$. These data permit to validate the polarimetric parameter variations with $k\sigma$ derived with the IEM model.

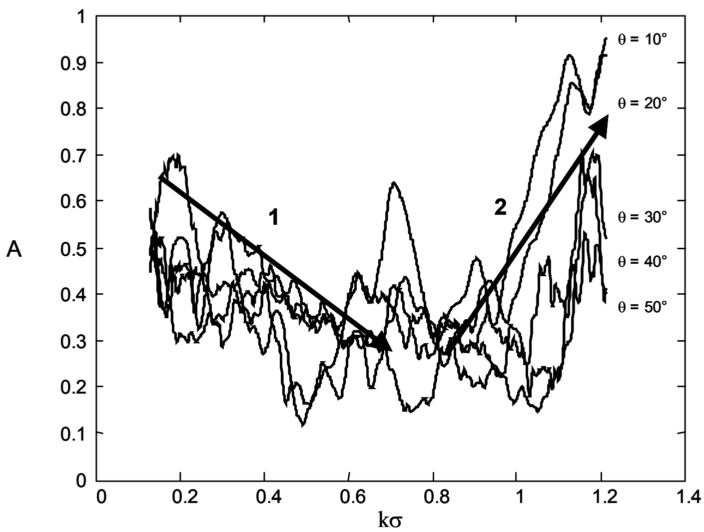


Fig. 3. Anisotropy versus kσ from JRC data

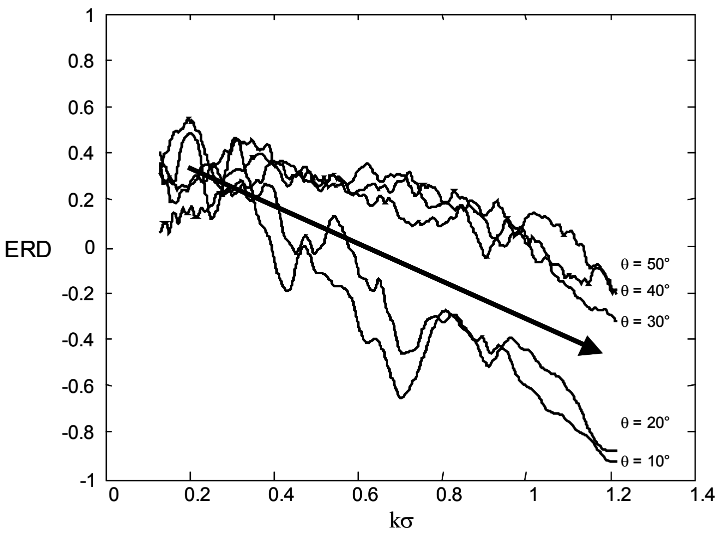


Fig. 4. ERD versus kσ from JRC data

Validation on Alling E-SAR data

The second step of this approach is to study the ERD and anisotropy variations on real SAR data. The polarimetric SAR dataset under analysis was acquired by the German Aerospace Center (DLR) E-SAR sensor, at L-band, over the Alling test site in Germany. The considered scene, represented in Fig. 5 -a-, is mainly composed of agricultural fields and forest. An urban area is located at the bottom left-hand corner of the image, and an isolated building can be observed in the top right-hand part of the scene. On the Figs. 5 -b- and -c-, the ERD and the anisotropy are represented. It is visible that the ERD permits to distinguish various field areas, whereas they are not visible with the anisotropy. This is mainly due to the high correlation between the co- and cross-polarized channels on these dataset, which correspond to “noise information”.

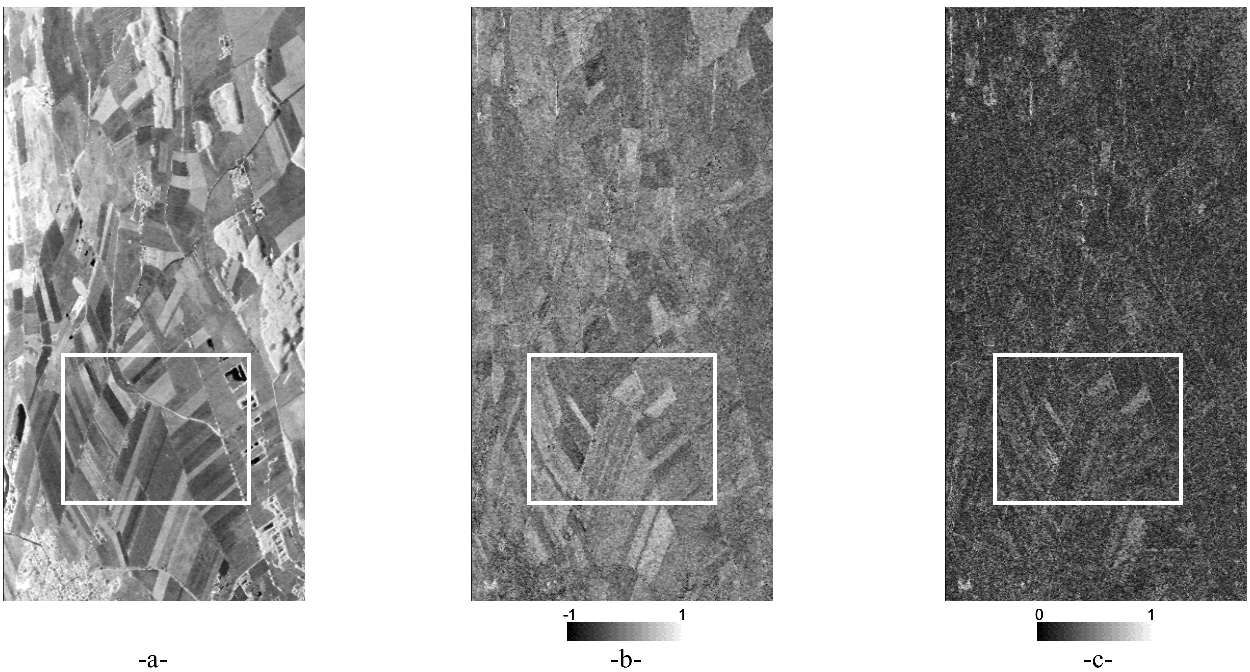
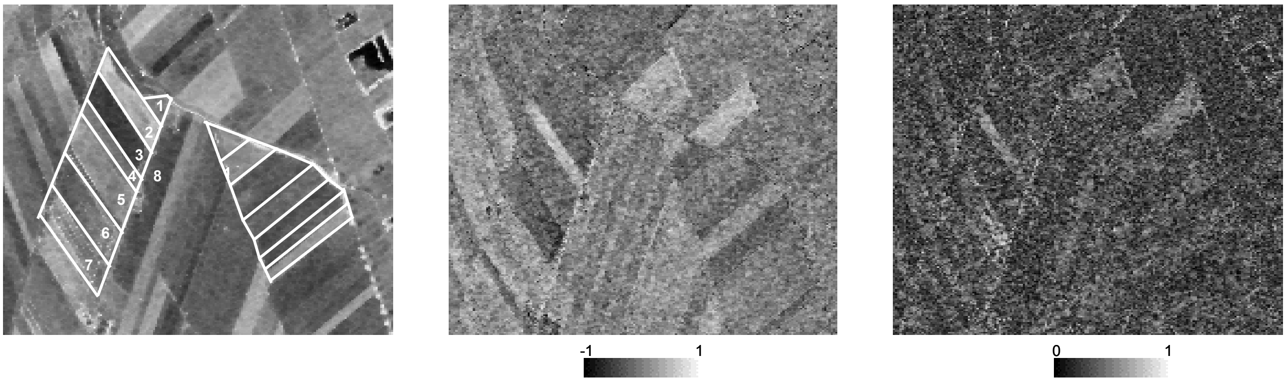


Fig. 5. Images of the Alling site at L band: -a- Span, -b- ERD, -c- Anisotropy

On Fig. 6, the selected area marked in Fig. 5 is analyzed. The fields 1,4 and 7 correspond to vegetated areas. Within them, the ERD is very high, whereas the anisotropy presents different values. The ERD permits to detect vegetation on these areas. Moreover, on fields 1 and 3, the corresponding in-situ rms height measurements are 1.4 cm and 0.92 cm respectively, for the same correlation length. The ERD decreases between these two fields, which corresponds to the results obtained with the IEM model. Finally, the ERD presents homogenous values for the same cultivated fields (harrowed or seedbed). Therefore, a classification of the various surfaces is possible.



-a- -b- -c-

Fig. 6. Images of the selected zone: -a- Span, -b- ERD, -c- Anisotropy

CONCLUSION

In this paper, a new polarimetric descriptor based on the reflexion symmetry hypothesis: the Eigenvalue Relative Difference (ERD) has been presented. Using the IEM surface scattering model, it has been demonstrated that ERD has a larger validity domain than Anisotropy. Moreover it presents a larger dynamic range.

From measured data, the ERD is shown relevant for surface characterization. In fact, the reflexion symmetry hypothesis is assumed. This information is considered as “noise” on surface natural media. In the case of the Alling SAR data, these correlations are very high and so, the anisotropy is shown very noisy. For less noisy datasets the difference between the ERD and the anisotropy will be less remarkable.

REFERENCES

[1] A. K. Fung, Z. Li and K. S. Chen, "Backscattering from a randomly rough dielectric surface", *IEEE Trans. Geosci. Remote Sensing*, vol. 30, no. 2, pp. 356-369, 1992.

[2] S. Allain, L. Ferro-Famil and E. Pottier, "Surface parameters retrieval from polarimetric and multi-frequency SAR data", *Proc. IGARSS*, July 2003.

[3] I. Hajnsek, "Inversion of Surface Parameters using Polarimetric SAR", Doctoral Thesis Universität Jena, DLR - Science Report, ISSN 1434-8454, 2001.

[4] S. R. Cloude and E. Pottier, "A Review of Target Decomposition Theorems in Radar Polarimetry", *IEEE Trans. Geosci. Remote Sensing*, vol. 34, no. 2, pp. 498-518, 1996.

[6] J. J. van Zyl, "Application of Cloude’s target decomposition theorem to polarimetric imaging radar", *SPIE*, vol. 127, pp. 184-212, 1992.

[5] F. Mattia, T. Le Toan, J.-C. Souyris, C. De Carolis, N. Floury, F. Posa and N. G. Pasquariello, " The effect of surface roughness on multifrequency polarimetric SAR data", *IEEE Trans. Geosci. Remote Sensing*, vol. 35, no. 4, pp. 954-966, July 1997.

[7] G. Nesti, “EMSL Experiment Report, Backscattering from Rough Dielectric surfaces”, July 1998.