Surface Parameter Estimation Using Interferometric Coherences at Different Polarisations


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ABSTRACT: In this work the potential of using the interferometric coherence at different polarisations over surface scatterers in order to extract information about surface parameters is investigated. For the first time the sensitivity of the individual coherence contributions to surface roughness and moisture conditions is discussed and simulated using a novel hybrid polarimetric surface scattering model. The model itself consists of two components, a coherent part obtained from the extended Bragg model and an incoherent part obtained from the integral equation model. Finally, experimental airborne SAR data are used to validate the modeled elements of the Pauli scattering vector.

1 INTRODUCTION

The main problem for the quantitative estimation of soil moisture and/or surface roughness from SAR data lies in the separation of their individual effects on the (coherent) backscattered signal. An independent estimation of roughness conditions is not possible by using a single polarisation and single-frequency SAR data. By increasing the number of observables - using fully polarimetric data - the number of surface parameters and their estimation accuracy increases [1-3]. Indeed, polarimetry plays an important role in the estimation of surface parameters, as it allows a direct or indirect separation of roughness, rms height $s$, and moisture $m_v$ [vol. %] induced effects on the backscattered signal. Several algorithms have been proposed in the literature for the retrieval of surface parameters from polarimetric SAR data. Most of them are based on the evaluation of the backscattering amplitudes. However, the main limitation of using polarimetric backscattering amplitude models is their insufficiency to predict/interpret secondary scattering and depolarisation effects, resulting in a biased surface parameter estimates.

To overcome this problem, the evaluation of second order statistical parameters (correlation coefficients between different polarisations) with respect to surface parameter estimation has been addressed [4-6]. The polarimetric coherences, (e.g. HH-VV, (HH+VV)(HH-VV), LL-RR) and the scattering Anisotropy demonstrated to be dependent/independent to one of the surface parameters and/or to the local incidence angle.

While the problem of soil-moisture/roughness estimation of bare surfaces has been extensively analysed in terms of conventional polarimetric SAR data, the information content of interferometric data regarding these parameters has not been illuminated sufficiently. The link between the polarimetric and the interferometric coherences is given due to the spatial baseline: polarimetric coherences can be regarded as zero baseline interferometric coherences between different polarisations. Introducing a spatial baseline to the polarimetric coherences conventional interferometric coherence are obtained. The interferometric coherence between two images $S_1$ and $S_2$ acquired from slightly different look angles is given by

$$\gamma := \frac{|<S_1 S_2^*>|}{\sqrt{<S_{11} S_{11}^*> <S_{22} S_{22}^*>}}$$

In the following different decorrelation contributions on the interferometric coherence with respect to the estimation of surface parameters are reviewed.

2 INTERFEROMETRIC COHERENCE

The interferometric coherence of a single pass interferometric system (i.e. ignoring temporal decorrelation) can be separated in two main contributions [7]

$$\gamma = \gamma_{Spatial} \gamma_{SNR}$$
Spatial expresses the decorrelation caused by the different projections of the scatterer reflectivity into the two SAR images due to their slightly different acquisition angles. Thus, it is a baseline dependent contribution which can be split into two individual contributions:

\[ \gamma_{\text{Spatial}} = \gamma_{\text{Range}} \gamma_{\text{Volume}} \]  (3)

\( \gamma_{\text{Range}} \) describes the decorrelation due to the different projections of the ground-range scattering reflectivity. On the other side, \( \gamma_{\text{Volume}} \) expresses the decorrelation caused by the different projections of the vertical distribution of the scattering reflectivity. \( \gamma_{\text{Volume}} \) is given by the Fourier transformation of the vertical distribution of the scatterer [8]. Assuming a homogeneous scatterer distribution with an effective height of \( s \), \( \gamma_{\text{Volume}} \) becomes

\[ \gamma_{\text{Volume}} \sim \frac{\sin(\kappa_z s_V)}{\kappa_z s_V} \]  (4)

where \( \kappa_z = (\kappa \Delta \theta) / \sin(\theta_o) \) is the vertical wavenumber, \( \Delta \theta \) the baseline induced difference in the incidence angle and \( \theta_o \) the reference incidence angle.

\( \gamma_{\text{SNR}} \) expresses the decorrelation caused by the uncorrelated additive noise contributions in the two interferometric images

\[ \gamma_{\text{SNR}} = \frac{1}{1 + (\text{SNR})^{-1}} \]  (5)

It depends on the backscattering intensity of the scatterer and is independent of the interferometric baseline. In Fig.1 \( \gamma_{\text{SNR}} \) is plotted against SNR. For \( \text{SNR} = 0 \) [dB] \( \gamma_{\text{SNR}} \approx 0.5 \), for \( \text{SNR} \) values below –10 [dB] \( \gamma_{\text{SNR}} \) drops below 0.1 while for \( \text{SNR} \) values above 15 [dB] \( \gamma_{\text{SNR}} \approx 1 \).

Concerning now the information content of the individual coherence contributions with respect to geometrical and dielectric surface parameters the following conclusions can be stated:

- \( \gamma_{\text{Range}} \) depends (in the first order) on the correlation properties of the ground range reflectivity spectrum. The variation of the statistical parameters of the surface (i.e. roughness and correlation length) effects mainly the amplitude distribution of the ground range reflectivity spectrum but not its correlation properties. Thus, the amount of \( \gamma_{\text{Range}} \) does not provide directly information about the surface characteristics.

- \( \gamma_{\text{Volume}} \) is sensitive to height variations in the order of tenths of \( 2\pi \kappa_Z \). Regarding the fact that most natural surfaces are characterised by a rms height \( s \) on the order of tenths of centimeters the vertical wavenumber has to be on the order of \( ~1 \) cm to provide sensitivity of \( \gamma_{\text{Volume}} \) to \( s \). Such \( \kappa_Z \) values exceed the critical baseline for most realistic system configurations.

- \( \gamma_{\text{SNR}} \) contains information of the surface characteristics, as the backscattered intensity depends on both, geometric and dielectric properties of the surface.

Recapitulating, the baseline dependent contributions of the interferometric coherence do not contain practical useful information about the underlying surface properties. After spectral filtering of both images to a common ground-range bandwidth \( \gamma_{\text{Range}} = 1 \), so that \( \gamma_{\text{Spatial}} = 1 \). Thus, the only remaining contribution sensitive to roughness and dielectric constant conditions of a surface scatterer is \( \gamma_{\text{SNR}} \). Its information content, for a given system noise level, is in principle nothing more than the information about the backscattered intensity. Yet, the sensible difference between \( \gamma_{\text{SNR}} \) and intensity lies in the speckle: while conventional SAR images are affected by speckle, the two interferometric images - after spectral filtering - contain the same speckle contributions which cancel each other out by forming the interferogram (for high interferometric coherences). In the following the extraction of surface parameters from \( \gamma_{\text{SNR}} \) is investigated.
3 HYBRID MODEL SIMULATIONS

Roughness and dielectric constant information are coupled in the measured backscattering intensity, so that a scattering model has to be introduced in order to decouple their contributions. Furthermore, an extension of the observation vector is required for an estimation of both: roughness and dielectric properties. The most promising (and mostly used) way for this, is the introduction of polarisation diversity. As SNR has a coherent and incoherent contribution a hybrid model has been developed to provide some qualitative insights on the influence of surface roughness and dielectric constant. The coherent part is modeled with the recently developed extended Bragg model and the incoherent part using the integral equation model.

3.1 Coherent Scattering Model

The first order extended Bragg model is an extension of the small perturbation model and assumes reflection symmetry surfaces, where the mean normal to the surface vector defines the axis of symmetry. It accounts for cross-polarised backscattering as well as depolarisation effects [3].

\[
\begin{bmatrix}
  t_{11} & t_{12} & t_{13} \\
  t_{21} & t_{22} & t_{23} \\
  t_{31} & t_{32} & t_{33}
\end{bmatrix}
= \begin{bmatrix}
  C_1 & C_2 \sin c(2\beta_1) & 0 \\
  C_2 \sin c(2\beta_1) & C_3(1 + \sin c(4\beta_1)) & 0 \\
  0 & 0 & C_3(1 - \sin c(4\beta_1))
\end{bmatrix}
\]

(6)

The coefficients \(C_1, C_2, C_3\) describing the Bragg component of the surface, and are given by

\[
C_1 = \left[ R_S + R_P \right]^{\frac{1}{2}} \quad C_2 = \left[ R_S^{*} - R_P^{*} \right] \quad C_3 = \frac{1}{2} \left[ R_S - R_P \right]^{\frac{1}{2}}
\]

It is a coherent surface scattering model based on the coherency matrix \([T]\) with three input model parameters, the dielectric constant, the local incidence angle and the surface roughness induced parameter \(\beta_1\).

3.2 Incoherent Scattering Model

A corrected version of the integral equation originally developed by Fung et al. has been used to calculate backscattering intensities [9]. The mathematical formulation of this modified IEM at first order is a straightforward derivation of Eq. (35) to (37) in [9]

\[
\sigma_{pp}^{0} = \frac{1}{4} k^2 L^2 \exp(-4 \sigma^2 k_z^2) \sum_{n=0}^{\infty} \frac{\sigma_{0}^{2 n}}{n!} \left| f_{pp}^{(n)} \right|^2 \exp\left(-k \sin \theta L^2 / n \right)
\]

\[
I_{hh} = -(2k_z k_p^2 f_{hh} + \frac{1}{4} \left( \sigma_{hh}^{(n)} + \sum_{r=1}^{\infty} \sigma_{hh}^{(n,r)} \right))
\]

\[
f_{hh} = -2 R_h(\theta) \quad \sigma_{hh}^{(n)} = -8 k \sin^2 \theta R_h(\theta) \delta_{n0}
\]

\[
\alpha_{hh}^{(n,r)} = 2 \left( k_z - r k_{z2} \right) f_{hh}^{(n-1)} \exp(\sigma_z^2 \left(k_z - k_{z2}\right) f_{hh}^{(n-1)} \left[(1 - R_h(\theta) \right]^{2} k \sin^2 \theta + k^2 / k_{z2} \cos \theta (1 + \sin^2 \theta) - \cos \theta k_{z2})
\]

\[
k_z = k \cos \theta \quad \text{and} \quad k_{z2} = k \sqrt{1 - \sin^2 \theta}
\]

where \(\sigma\) is the rms height and \(l\) is the correlation length of the surface. The VV backscattering coefficient can be easily calculated by applying duality. The absolute amplitude component \((\sigma_{VV}^{0} H H\) and \(\sigma_{VV}^{0} V V\)) are based on the covariance matrix \([C]\) with four input model parameters, the dielectric constant, the surface roughness, the surface correlation length and the local incidence angle.

3.3 Hybrid Scattering Model

The developed hybrid scattering model contains two components the coherent and the incoherent part. Since the output parameters of the two components are obtained in different matrix systems a unitary matrix transformation has to be applied. The absolute amplitude factor \(m_1\) and \(m_2\) are derived as
The behavior of the absolute amplitude factors is shown in Figure 2: Both, $m_1$ and $m_2$, increase with increasing surface roughness, whereas $m_2$ increases slightly higher than $m_1$, satisfying the experimental observations. For further calculation a mean $m$ is used for the absolute amplitude factor.

Next, the absolute amplitude factor is multiplied by the elements of the extended Bragg model and the interferometric coherences between different polarisations are performed, as given by

$$[T] = m \begin{bmatrix} t_{11} & t_{12}^* & 0 \\ t_{12} & t_{22} & 0 \\ 0 & 0 & t_{33} \end{bmatrix}$$

and

$$\gamma_{SNR} = \begin{bmatrix} 1 & 1 & \frac{1}{I + (N_{T_{11}})} \\ 0 & \frac{1}{I + (N_{T_{22}})} & 0 \\ 0 & 0 & \frac{1}{I + (N_{T_{33}})} \end{bmatrix}$$

Figs. 3-6 shows the modeled $\gamma_{SNR}$ for the diagonal elements of the $[T]$ as a function of roughness $ks$, for four different dielectric constants ($\varepsilon_r = 10, 20, 30$ and 40) and an local incidence angle of $35^\circ$ assuming an effective system noise level of $-30$ [dB].

$$m_1 = 2\sigma_{H}^{n}\left|t_{11} + t_{22} + t_{12}^* + t_{12}\right| \quad m_2 = 2\sigma_{V}^{n}\left|t_{11} + t_{22} - t_{12}^* - t_{12}\right|$$

(9)
For the first element, the high SNR suppresses any trend. However, for higher noise levels (not shown here) it becomes independent on roughness and sensitive to dielectric constant differences. The second element is characterised by lower SNR and its coherence is therefore stronger affected by the influence of the underlying surface parameters. Finally, the coherence corresponding to the third element, (cross-polarised channel), shows the strongest variation with increasing roughness (up to $ks = 0.5$). Its dependency on the dielectric constant decreases with increasing dielectric constant so that between $e_r = 20$ and $40$ the difference on the interferometric coherence is below 10%.

Inspired by the independence of scattering anisotropy on the dielectric constant, Fig. 6 shows the difference of the $\gamma_{SNR}$ between the second and the third diagonal element. Indeed, the coherence difference is widely independent on the dielectric constant of the surface and it depends only on the roughness condition.

4 EXPERIMENTAL DATA

The test site Alling is located in Southern Germany and is predominantly covered with agricultural fields. In the frame of the Surface Parameter Retrieval Collaboration (SPARC) project, DLR’s experimental airborne E-SAR system acquired, in March and July 2000, fully polarimetric and interferometric repeat-pass data over the test site at L-band (1.3 GHz) (see Fig. 7).

Simultaneously, ground measurements of volumetric moisture content and surface roughness were collected over different bare and vegetated agricultural fields. The volumetric moisture content measurements were performed using stick cylinders and TDR. Surface roughness $s$ and surface correlation lengths $l$ was measured using scaled boards and a laser profilometer in two directions: perpendicular (PPF) and parallel to the flight direction (PAF). The measurements are summarised in Tab.1. The results presented in the following are obtained from the data collected in March 2000.

<table>
<thead>
<tr>
<th>No.</th>
<th>Field ID</th>
<th>Cultivation</th>
<th>AOI</th>
<th>mv [vol. %]</th>
<th>$ks$ ($\lambda \sim 23$ cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>256</td>
<td>seedbed</td>
<td>46°</td>
<td>26.4</td>
<td>0.23</td>
</tr>
<tr>
<td>2</td>
<td>263</td>
<td>ploughed</td>
<td>45°</td>
<td>29.4</td>
<td>0.39</td>
</tr>
<tr>
<td>3</td>
<td>513</td>
<td>seedbed</td>
<td>47°</td>
<td>35.4</td>
<td>0.21</td>
</tr>
<tr>
<td>4</td>
<td>651</td>
<td>ploughed</td>
<td>51.8°</td>
<td>29.0</td>
<td>0.53</td>
</tr>
<tr>
<td>5</td>
<td>652</td>
<td>seedbed</td>
<td>51.7°</td>
<td>37.9</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Table 1: Ground measurements test site Alling collected in March 2002.

5 EXPERIMENTAL RESULTS

In Figs. 8-11 modeled (solid line) and estimated (stars) coherences (the error bars indicate the variation of the coherence inside the individual fields) as a function of surface roughness for different dielectric constants (see Tab.1) are shown. Overall, the experimental results corresponding very well to the predictions of the modeled SNR coherences. The $T_{11}$ coherence behaves according to the modeled observations: no significant influence of the surface properties is given. A higher sensitivity of the surface properties, different moisture and roughness values is obtained for the $T_{22}$ coherence. For the $T_{33}$ coherence a significant higher sensitivity is obtained in accordance with the model predictions for smaller $ks$ values and saturates for $ks > 0.5$. Note that the ground measurements for soil moisture are between 26 and 40 mv [vol. %] so that the variation of the coherences is mainly due to variation of $ks$. The difference of the interferometric coherences of $T_{22}$ and $T_{33}$ shows the highest sensitivity to $ks$ with the smallest error bars and is therefore suitable for the estimation of $ks$ values up to 0.5.
6 CONCLUSIONS

The potential of using the interferometric coherences at different polarisations for extracting information about surface parameters has been investigated. The dominant decorrelation effect over bare surfaces is SNR. The individual effects of moisture and roughness on the interferometric coherence can be potentially separated by using an appropriate surface scattering model. A new hybrid surface scattering model has been proposed and validated against experimental data. The validation indicates a high sensitivity of the interferometric coherences to moisture and roughness variations especially in the low roughness domain, i.e., 0.2 < ks < 0.5. Due to the absence of speckle effects in high coherence interferograms, the coherence information is more robust than the corresponding amplitude information. The interferometric coherence can be used complementary to amplitude information in order to increase the estimation accuracy of surface parameters.

The new contribution of this work is that the Pauli scattering elements could be for the first time modeled and their correctness validated with experimental data.

7 REFERENCES