Investigation of fully polarimetric TerraSAR-X data for soil parameters estimation

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Abstract

The potential of estimating soil moisture from fully polarimetric satellite X-band SAR data is analysed for the first time. The Physical Optics model has been combined with an azimuthally rotation distribution, forming a so-called Extend-PO-model (X-PO), for the scattering process representation which includes a cross-polarized component. In addition, the eigen-based decomposition approach has been used to interpret the scattering mechanisms and to estimate the soil parameters. The developed inversion approach has been applied to data acquired by the German satellite TerraSAR-X over the Wallerfing region in April 2009. Simultaneously to the overpasses, soil moisture and vegetation measurements have been collected on agricultural fields. Finally the estimated soil moistures from the proposed algorithm have been compared with the measured soil moistures collected over bare soil fields resulting in a root mean square error of ~10 Vol.%.

1 Introduction

In the last decades, theoretical and empirical inversion algorithms for soil moisture estimation using PolSAR data at L- and P-band have been intensively investigated. As shown in [1], polarimetry plays an important role as it allows a separation of roughness and moisture induced effects. However, up to now there are no experimental evaluations available using space-borne SAR data at higher frequencies. Hence, the scope of this work is to examine fully polarimetric TerraSAR-X data and evaluate the polarimetric capabilities of this sensor in estimating the soil surface parameters for nearly bare soils at X-band. The potential of using the polarimetric eigen-decomposition technique is still under investigation. In particular the study is focusing on understanding how the scattering entropy ($H$) and the alpha angle ($\alpha$) may be used for the estimation of soil moisture and surface roughness [2].

The model for the inversion proposed in this work is a two component model including the Physical Optics formulation and a mathematical rotation term modelling non-zero cross-polarised backscattering and depolarization effects. The performance of the inversion algorithm will be validated using fully polarimetric TerraSAR-X data together with ground measurements.

2 The experimental campaign

On 27th of April 2009 the TerraSAR-X satellite has acquired data over a large area in the region of Wallerfing (Lower Bavaria, Germany). The test sites were selected on an agricultural area including different crop types (winter wheat, winter barley, winter rape, potatoes). Simultaneously to the satellite overpass, a set of measurements of soil moisture content and vegetation parameters have been collected on the respectively test fields together with the Ludwig-Maximilians-University Munich. By utilizing a FDR probes, 31 measurement points for soil moisture - 17 on bare soil fields and 14 on vegetated areas have been collected. For this study only the sparse and non vegetated fields were used for validation.

The following fields with the following averaged soil moisture and field condition were selected:
- MT122: 21.87 Vol.% - seedbed rough
- MT123: 19.97 Vol.% - seedbed smooth
- MT126: 16.70 Vol.% - seedbed rough with maize seedlings
- MT127: 21.99 Vol.% - seedbed with furrow structure

3 Modelling approach

Several theoretical models for high frequencies have been developed in order to understand the interaction between the electromagnetic waves and the soil surface. The common starting point for these models is
the Stratton-Chu integral equation in its far field approximation, which is an exact relation that expresses the scattered field at any point within a region of space in terms of the tangential component fields on the surface that encloses the region [3]. In this work the soil surface has been considered as a stationary Gaussian distributed random surface with surface heights, \(s\), and correlation length, \(l\) describing the surface roughness. The Kirchhoff approach, which approximates the surface field using the tangential plane approximation, has been considered in its scalar approximation, also known as Physical Optics (PO) approximation. In this approximation, the scattering field has been determined by expanding the Stratton-Chu equation in a Taylor series of slopes. Denoting \(\hat{\rho}\) and \(\hat{\rho}\) the transmitted and received polarisation respectively, its expression can be written as [3]:

\[
E_{sp}^s = KE_0 \left[ \bar{U}_{qp} \exp \left[ jk (\hat{k}_s - \hat{k}_i) \cdot \hat{r} \right] \right] ds, \tag{1}
\]

where \(K = -jk e^{-j\rho_0}/(4\pi R_0)\); \(\hat{k}_s\) is the unit vector in the scattered direction; \(\hat{k}_i\) is the unit vector in the incident direction; \(k\) is the wave number of the medium in which \(E^s\) is evaluated; \(R_0\) is the range from the centre of the illuminated area to the point of observation; \(E_0\) is the amplitude of the electric field; \(\hat{r}\) is the position vector of a generic point on the surface. The field amplitudes are given by [3]:

\[
\bar{U}_{qp} = \frac{1}{E_0} \hat{q} \cdot \hat{k}_s \times \left[ \hat{n} \times \hat{E}_p \right] - \eta \hat{k}_s \times \left[ \hat{n} \times \hat{H}_p \right], \tag{2}
\]

where \(\hat{n}\) is the unit vector normal to interface inside the medium in which scattering is considered, \(\eta\) is the intrinsic impedance of the medium in which \(E^s\) is evaluated and \(\hat{n} \times \hat{E}_p\), \(\hat{n} \times \hat{H}_p\) are the total tangential fields corresponding to an incident field with \(\hat{p}\) unit polarisation vector. These amplitudes have been developed in a Taylor series of slope as [3]:

\[
\bar{U}_{qp} = a_{0qp} + a_{1qp}Z_x + a_{2qp}Z_y \tag{3}
\]

where \(a_i\) are polarisation-dependent coefficients and \(Z_x, Z_y\) represent the surface slopes in the \(x\)- and \(y\)-directions. The incoherent elements of the covariance matrix are given by:

\[
\langle S_{qp}S^*_{qp} \rangle = a_{0qp}a^*_{0qp}I_0 \tag{5}
\]

where \(I_0\) is given by:

\[
I_0 = \int \int \left( \left( \bar{U}_{qp} e^{jak(\hat{k}_s - \hat{k}_i)} \right)^* - \left( \bar{U}_{qp} e^{jak(\hat{k}_s - \hat{k}_i)} \right) \right)^2 ds ds', \tag{6}
\]

It is important to note that this term includes the height standard deviation, \(s\). In the backscattering configuration, the coefficients \(a_{0qp}\) assume the following expressions [3]:

\[
a_{0pp} = 2R_{pp} \cos \gamma, \tag{7}
a_{0pp} = 0 \tag{8}
\]

where \(R_{pp}\) represents the vertical (\(\hat{p} = \hat{v}\)) and horizontal (\(\hat{p} = \hat{h}\)) Fresnel reflection coefficient.

From the covariance matrix it is possible to obtain the coherence matrix \([T^{PO}]\), which assumes the following expression [2]:

\[
T^{PO} = \frac{1}{2} \left( \begin{array}{ccc}
|a_0|^2 + |b_0|^2 + a_0 \bar{b}_0 + b_0 \bar{a}_0 & a_0 \bar{a}_0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{array} \right) \tag{9}
\]

where \(a_0 = 2R_{hh} \cos \gamma\) and \(b_0 = 2R_{hv} \cos \gamma\).

However, since the \(a_{0pp}\) coefficient is zero, the PO model is not able to describe the cross polarised backscattering and the depolarisation in the polarimetric space. In order to introduce these two effects, which are distinct at X-band, the procedure described in [1] for the Bragg model has been adopted on the PO model to form the coherency matrix of the Extended Physical Optics (X-PO) model \([T^{X-PO}]\) [4]:

\[
T^{X-PO} = \frac{1}{2} \left( \begin{array}{ccc}
\alpha_{\gamma} & \beta_{\gamma} & 0 \\
\beta_{\gamma} & \alpha_{\gamma} & 0 \\
0 & 0 & 0 \\
\end{array} \right) \tag{10}
\]

In this way, the surface has been modelled as a reflection symmetric depolariser by a rotation on the PO coherency matrix about an angle \(\gamma\) in the plane perpendicular to the scattering plane and performing an averaging operation over a given uniform distribution \(P(\gamma)\) of the rotation angle \(\gamma\) [1]. The width of the chosen distribution \(\gamma_a\) is related to the roughness disturbance of the modelled surface.

### 4 Polarimetric analysis

The eigen-based decomposition has been applied to the modelled X-PO coherence matrix. From the diagonalisation, the scattering entropy \(H\) and the alpha angle \(\alpha\) of the model have been determined [3].
entropy can be interpreted as a measure of the randomness of the scattering process, whereas the alpha angle $\alpha$ indicates the type of the scattering process [5]. The eigen-based decomposition has also been applied on the TerraSAR-X data, after the application of an eigen-based noise filtering as described in [1]. Figure 1a shows the entropy $H$ and b) the dominant alpha angle $\alpha_1$. The polarimetric entropy $H$ exhibits a high level over the whole scene ($H_{\text{average}} = 0.7$). This indicates a high scattering disorder due to several simultaneously occurring scattering mechanisms. One reason is the effect of the short wavelength at X-band which is even scattered by very small objects within agricultural media. However, lower entropy values on bare soil fields are visible, but the level of entropy is still very high (blue areas in Figure 2a). Also the dominant alpha angle $\alpha_1$ shows high values. Especially on bare and sparsely vegetated fields the values are bigger than 70 degrees (red areas in Figure 2b). In contrary the green areas in Figure 2b with an alpha angle around 45° representing dipole-like scattering of a volume can be allocated to the fields with a compact and distinct vegetation layer, which will be not invertible as shown later in Figure 3.

5 Soil moisture estimation

Figure 2 shows the two-dimensional $H/\alpha_1$-classification space with superimposed loci of entropy/alpha derived from the X-PO model. The cross symbols represent different dielectric constant $\varepsilon'$ values and widths of slope distribution $\gamma_w$ for the local incidence angle of 32 degrees matching the TerraSAR-X acquisition geometry. It can be seen in Figure 2 that the data are quite well located inside the look up table and therefore can be represented by the X-PO model. The high alpha angle of the model comes from the Fresnel coefficients inherent in the model formulation, which are located in the dihedral regime. The alpha angle $\alpha$ of the model raises mainly increasing the dielectric constant of the soil. In addition, it can be analysed that the entropy $H$ of the model increases driven by an increase of the distribution width angle $\gamma_w$. Both the entropy $H$ and the alpha angle $\alpha$ of the model have been used for the soil moisture inversion. For a range of dielectric constants, a range of different distribution widths and the local incidence angle of the TerraSAR-X scene, the entropy $H$ and the alpha angle $\alpha$ of the X-PO model have been stored into a look-up table.

Using this look-up table, the dielectric constant values of the soil are obtained directly from the entropy and alpha dominant values of the TerraSAR-X data. Figure 3 shows the soil moisture in Vol.% obtained after transforming the dielectric constant into volumetric soil moisture using the model in [6]. Areas shown in white colour represent non-invertible pixels or densely vegetated areas, which were masked out. In addition, the lowest value of the soil moisture content, 0.2%, has been filtered out as a lower boundary. The
fields which are inverted quite gapless are only sparsely vegetated or bare. For this reason and for the reason of missing penetration capability into the vegetation layer the following validation will be shown only on bare fields.

Figure 3  Soil moisture in Vol.% of the Wallerfing region derived from fully polarimetric TerraSAR-X data. White areas represent non-physical inversion results or dense vegetation which has been masked (image smooth: 4x4).

6 Validation

In order to evaluate the applicability of the X-PO model together with the polarimetric entropy/alpha-dominant decomposition approach for the estimation of soil moisture content, a validation process has been carried out. Soil moisture measurements collected on bare soil fields during the experimental campaign over the agricultural fields in the region of Wallerfing have been used to be compared with the estimated soil moisture values. The latter have been calculated as the average value in a window on 13x13 pixels around the measurement point. Figure 4 shows the results of this comparison. In general there is an apparent underestimation of the soil moisture by the estimated values resulting in an root mean square error (RMSE) of 10.52Vol.% for all investigated fields. The field MT 126 for example has already some maize seedlings planted and has the highest soil roughness, which might lead to the underestimation of more than 10Vol.%. But, on the contrary the field MT123 showed a very homogenous seedbed with a low roughness level. Here, the estimated soil moisture values match the measurements very well. One reason for the quality of match between measured and estimated moistures might be due to the very low roughness on the fields.

Further analysis need to be made for fields with different roughness conditions and vegetation cover. This will be important to answer the question if X-band is a good frequency for soil moisture derivation. In addition also the developed X-PO model needs to be revised with respect to the model performance and the validity range. Finally, the physical behaviour and the applicability of the eigen-based approach at X-band need to be understood.

Figure 4  Estimated compared to measured soil moisture in Vol.% for different bare soil fields within the TerraSAR-X scene (17 invertible points, RMSE = 10.52 Vol.%).

7 Conclusion

In this work the potential of estimating soil moisture from fully polarimetric X-band SAR data has been analysed for the first time. The PO model has been extended in order to take into account the cross polarised backscattering and the depolarisation in the polarimetric space. The new model called X-PO has been used for the inversion technique of soil moisture using the polarimetric entropy/alpha-space and first results on bare soil show a root mean square error of about 10Vol.%. As there were no roughness measurements available the distinct underestimation can not be explained clearly and needs further extensive investigations.

References