MODIFIED SCATTERING DECOMPOSITION FOR SOIL MOISTURE ESTIMATION FROM POLARIMETRIC X-BAND DATA

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ABSTRACT

In this paper, the potential of estimating soil moisture from fully polarimetric X-band SAR data is investigated for the first time. Due to the short wavelength, the Physical Optics model [1] has been chosen for the scattering process representation and a model-based decomposition approach has been used to exploit the polarimetric observable space. For appropriate modelling of the strong cross-polarization contribution of X-band waves, which are scattered by even very small objects, corrections of the volume scattering contribution were implemented. In order to improve the retrieval of the moisture content, the developed polarimetric decomposition has been further modified by means of an eigen-analysis of the coherence matrix.

The SAR data were acquired by the German satellite TerraSAR-X over the agricultural area of Wallerfing (Lower Bavaria, Germany) in April 2009. Simultaneously to the overpasses, *in situ* moisture measurements have been collected in collaboration with the Ludwig-Maximilians-Universität (LMU) München. A validation of the proposed approaches for a quality assessment has been performed by comparing the estimated with the measured soil moistures, resulting in a root mean square error of about 8 Vol.% for all bare fields tested.

1. INTRODUCTION

Soil moisture content represents a key observable in order to model, describe and predict many ecological processes. 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. Thus, there exist innovative techniques for the quantitative retrieval of dielectric constant of the soil [2]. However, up to now, there are still no experimental evaluations performed with SAR acquisitions at higher frequencies. Hence, the scope of this research work is to develop a new scattering decomposition in order to assess accuracy and conditions under which soil moisture content can be estimated from fully polarimetric X-band data.

2. EXPERIMENTAL CAMPAIGN

The SAR acquisitions used in this study were made by the German TerraSAR-X satellite on 27th of April over the agricultural area of Wallerfing, characterized by different crop types and bare soil fields. In **Figure 1** an RGB Pauli representation of the area is depicted, where the different land uses and the strong volume scattering contribution (in green shade) are distinguishable. Simultaneously to the satellite overpasses, soil moisture measurements have been performed on the tested area, using FDR probes. In total, 31 measurement points (17 on bare soil and 14 on vegetated fields) have been collected. All the measured moisture values range between 15 Vol.% and 30 Vol.%.

3. MODIFIED DECOMPOSITION

In order to appropriately describe the interaction between soil surface and X-band wave, the Physical Optics (PO) has been used as reference scattering model. The PO model gives an approximated solution of the Stratton-Chu integral equation in its far field approximation by integrating the Kirchhoff scattered field over the entire rough surface and by expanding the scattering integral in a Taylor series of slopes. For a surface with stationary Gaussian height distribution, the validity conditions of the PO model are [3]

$$kl > 4\sqrt{2}k\sigma, \quad kl > 6, \quad l^2 > 2.76\sigma\lambda, \qquad (1.1)$$

where k is the wave number, l is the correlation length, σ is the standard deviation of the vertical roughness and λ is the wavelength. The constraints in Eq.(1.1) are verified, in X-band, for fields with a variety of roughness conditions [4].

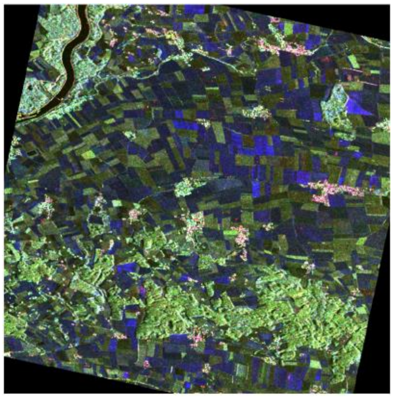

Figure 1. Pauli decomposition of Wallerfing region; blue $\frac{1}{2}\left\langle |HH+VV|^2 \right\rangle$ **; red** $\frac{1}{2}\left\langle |HH-VV|^2 \right\rangle$ **; green** $2\left\langle |XX|^2 \right\rangle$**.**

By considering only the zeroth order field expansion, the backscattering coefficients can be expressed after some algebraic modifications as follows [1]

$$S_{HH}^{(0)} = 2I_0\left(\theta_i, \sigma, l, \rho(\xi)\right) \cdot F_{h00}\left(\varepsilon, \theta_i\right)\cos\theta_i, \qquad (1.2)$$

$$S_{VV}^{(0)} = 2I_0\left(\theta_i, \sigma, l, \rho(\xi)\right) \cdot F_{v00}\left(\varepsilon, \theta_i\right)\cos\theta_i, \qquad (1.3)$$

$$S_{HV}^{(0)} = S_{VH}^{(0)} = 0, \qquad (1.4)$$

where θ_i is the angle of incidence, ε is the dielectric constant, $\rho(\xi)$ is the height correlation function and $F_{h,v00}$ are the Fresnel coefficients for h and v polarization, respectively. The Physical Optics model predicts that the cross polarized contribution is zero, and establishes a separation between the geometrical and dielectric properties of the soil. In fact, geometrical properties like soil roughness are contained entirely in the I_0 term, whereas the dielectric constant appears only in the Fresnel coefficients.

For a description of the scattering phenomenon up to the second order, a model-based decomposition of the measured coherence matrix $\langle T_{PO} \rangle$ has been followed [5]. According to this, the term describing the scattering from a rough surface is expressed as

$$\langle T_{PO} \rangle_s = f_{s,PO} \begin{bmatrix} 1 & \beta_{PO}^* & 0 \\ \beta_{PO} & |\beta_{PO}|^2 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \qquad (1.5)$$

where $\beta_{PO} = \frac{S_{HH}^{(0)} - S_{VV}^{(0)}}{S_{HH}^{(0)} + S_{VV}^{(0)}}$ and $f_{s,PO} = \frac{I_0}{2}\left|S_{HH}^{(0)} + S_{VV}^{(0)}\right|^2$. Due to the independence of the I_0 from polarization, the roughness contributions cancel out, and the surface descriptor β_{PO} becomes a function only of θ_i and ε. Thus, a simple procedure for inversion can be conducted. Hence, the β_{PO} parameter has been chosen in order to perform the soil moisture estimation (cf. [6]). **Figure 2** shows a plot of β_{PO} as a function of θ_i (only in the range of the acquisition system: 31°-34°), for different values of ε: the β_{PO} is quite sensitive to the soil moisture, and rises with increasing ε.

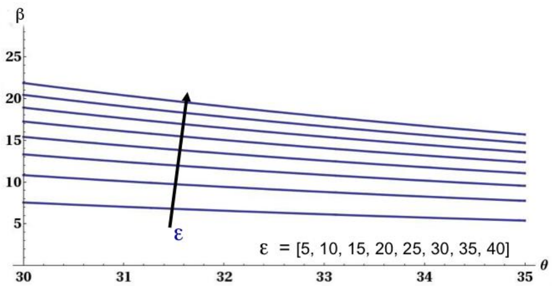

Figure 2. β_{PO} **parameter for** ε **between 5 and 40.**

Due to the low cross-polarization coherence $\gamma_{HV\text{-}VH}$ (around 0.5), the developed polarimetric decomposition has been further modified by means of the eigen-based noise filtering, as described in [2].

Cross-polarized scattering and depolarization effects are not predicted by the PO model but are very strong in X-band. In order to compensate this lack, a roughness term can be introduced by modeling the surface as a reflection symmetric depolarizer, by means of a rotation of the coherence matrix by an angle γ in the plane perpendicular to the scattering plane, and performing an averaging operation over a given *pdf* of γ, of width δ. Such an approach was proposed in [1] in the case of L- and P-band data, and is introduced in this context as *Extended Physical Optics Model* (X-PO). According to this model, the surface coherence matrix can be expressed as

$$\langle T_{X-PO} \rangle_s = f_s \begin{bmatrix} 1 & \beta_{PO}^* \operatorname{sinc}(2\delta) & 0 \\ \beta_{PO} \operatorname{sinc}(2\delta) & \eta_1 & 0 \\ 0 & 0 & \eta_2 \end{bmatrix}, \qquad (1.6)$$

$$\eta_{1,2} = \frac{1}{2}|\beta_{PO}|^2 \left(1 \pm \operatorname{sinc}(4\delta)\right). \qquad (1.7)$$

4. SOIL MOISTURE INVERSION AND VALIDATION

Figure 3 shows the soil moisture inversion m_v (in Vol.%) obtained from the noise-filtered β_{PO} with conversion of the dielectric constant of the dielectric constant into soil moisture with the Topp model [7]. Areas shown in white colour represent non-invertible pixels, which correspond predominantely to vegetated fields. Only a small percentage of invertible pixels (about 5%) has been obtained, and all on bare soil fields. This result is consistent with the very weak penetration capability into vegetation of X-band wave.

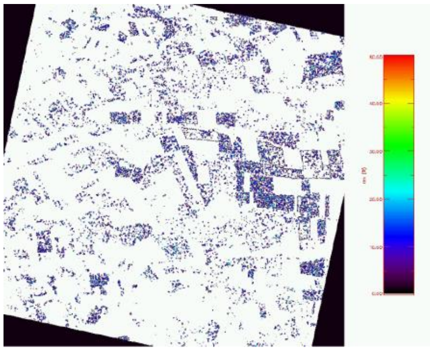

Figure 3. Soil moisture (m_v) in Vol.%. $m_v \in [0,50]$. White areas represent non-physical inversion results.

A validation of the introduced approaches was carried out. The estimated soil moisture has been calculated as the average value inside a box of 13x13 pixels around the measurement point. By applying the X-PO model, an underestimation of the measured soil moisture is observed. Moreover, the best results are obtained on rape fields with a vegetation height of about 140 cm, which can not be penetrated by X-band wave. Thus, X-PO model seems to be not feasible for soil moisture inversion in the actual configuration. **Figure 4** and **Figure 5** show the scatter plots comparing the estimated and the measured mean soil moistures. In both cases, only bare soil fields can be inverted. Moreover, it can be seen that the inversions performed with including noise filtering lead to a sensitive improvement in terms of rmse (from 10 Vol.% to 8 Vol.%) and correlation coefficient *r* (from 0.17 to 0.39), which has to be further investigated. The best estimations are obtained on the fields MT123 and MT127, which show a very homogeneous seedbed. On the other hand, the fields MT122 and MT126 are characterized by some vegetation seedlings planted and a higher roughness level.

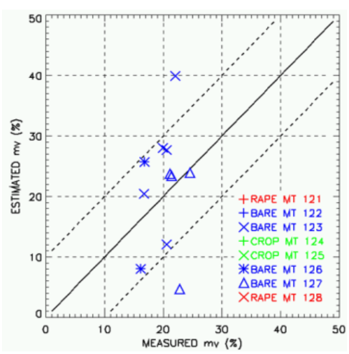

Figure 4. Measured vs estimated soil moisture by using β_{PO}; 11 invertible points, rmse = 10 Vol.%, *r*=0.17.

5. CONCLUSIONS

In this research work a first investigation on fully polarimetric TerraSAR-X data has been performed and a new model-based decomposition approach incorporating the Physical Optics model for soil moisture estimation has been developed. Further modifications in order to model the very strong cross-polarization component and a significant amount of additive noise observed in the data have been also implemented. For the validation of the proposed approaches, *in situ* measurements were collected. The first results show that moisture inversion can be performed only on bare soil fields, with a minimum rmse of 8 Vol.% and a maximum correlation (between estimated and measured moisture) of about 0.4.

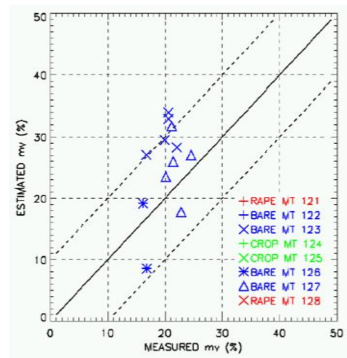

Figure 5. Measured vs estimated soil moisture by using β_{PO} after noise filtering; 12 invertible points, rmse = 8 Vol.%, r=0.39.

6. REFERENCES

[1] R.D. De Roo, *Theory and Measurement of Bistatic Scattering of X-Band Microwaves from Rough Dielectric Surfaces*, PhD dissertation, University of Michigan, 1996.

[2] I. Hajnsek, E. Pottier, and S.R. Cloude, “Inversion of Surface Parameters from Polarimetric SAR,” *IEEE Trans. Geosci. Remote Sensing*, vol.41, pp.727-744, 2003.

[3] Ulaby, F.T., R.K. Moore, and A.K. Fung, *Microwave remote sensing active and passive. Vol.2*, Artech House, 1982.

[4] J. Álvarez-Mozos, N.E.C. Verhoest, A. Larrañaga, J. Casalí, and M. González-Audicana, “Influence of surface roughness spatial variability and temporal dynamics on the retrieval of soil moisture from SAR observations,” *Sensors*, vol.9, pp.463-489, 2009.

[5] A. Freeman, and S.L. Durden, “A Three-Component Scattering Model for Polarimetric SAR Data,” *IEEE Trans. Geosci. Remote Sensing*, vol.36, pp.963-973, 1998.

[6] I. Hajnsek, T. Jagdhuber, H. Schön, and K.P. Papathanassiou, “Potential of Estimating Soil Moisture Under Vegetation Cover by Means of PolSAR,” *IEEE Trans. Geosci. Remote Sensing*, vol.47, pp.442-454, 2009.

[7] G. Topp, J.L. Davis, and A.P. Annan. “Electromagnetic Determination of Soil Water Content: Measurements in Cohaxial Transmission Lines,” *Water Resources Research*, vol.16, pp.574-582, 1980.