SOIL MOISTURE ESTIMATION USING DUAL-POLARIMETRIC COHERENT (HH/VV) TERRASAR-X AND TANDEM-X DATA

Thomas Jagdhuber[1], Irena Hajnsek[1,2], Maurizio Caputo[1], Konstantinos P. Papathanassiou[1]

[1]*German Aerospace Center, Microwaves and Radar Insitute, PO BOX 1116, 82234 Wessling, Thomas.jagdhuber@dlr.de, Maurizio.Caputo@dlr.de, Kostas.Papathanassiou@dlr.de*
[2]*ETH Zurich, Institute of Environmental Engineering, HIF D28.1, Schafmattstr. 6, CH-8093 Zurich, Irena.Hajnsek@ifu.baug.ethz.ch*

ABSTRACT

Soil moisture is retrieved under bare and vegetated soil conditions using dual-polarimetric coherent (HH/VV) TerraSAR-X and TanDEM-X data of 2009-2012 from the Wallerfing and DEMMIN test sites in Germany. For the bare soil inversion the dominant alpha scattering angle is calculated from the data and modelled with the IEM scattering model. For the vegetated soils dual polarimetric decomposition techniques are developed and applied together with an innovative synthetized cross-polarization component to remove the vegetation contribution and to invert the remaining ground scattering contribution with the bare soil procedure for soil moisture under vegetation cover. The inversion of soil moisture for bare soils and soils under agricultural vegetation is feasible with reasonable inversion rates (37-50%) using decomposition and inversion techniques on dual-polarimetric (HH/VV) coherent SAR data at X-band. The validation with ground-based sensors (FDR-, TDR-probes) revealed a well agreement with the SAR-based moisture estimates resulting in an RMSE of 7.3-11.4vol.% including large parts of the growth season and a variety of crop types in different phenological stages.

1 Introduction

Due to the outstanding service of the TerraSAR-X and TanDEM-X satellites, more and more dual-polarimetric coherent (HH/VV) X-band data are available over agricultural areas to monitor soil moisture on bare and vegetated soils.
As shown in [1-3], the dual-polarimetric (HH/VV) observation space adds valuable information for geophysical parameter estimation like for instance soil moisture.
However up to now, dual-polarimetric soil moisture inversions at X-band are mostly approached using empirical, semi-empirical and not physical scattering models, whereby the main analyses focus on the estimation of soil moisture on bare soil surfaces, where solely soil roughness influences additionally the scattering signature and needs to be removed.
However, as soon as the vegetation growing cycle starts, the soil moisture retrieval is more and more biased by the emerging vegetation volume scattering. In order to account for the vegetation bias and the soil roughness influence, physically-based scattering models for the vegetation and the ground scattering contributions are incorporated in the retrieval algorithm to account for all occurring scattering mechanisms and to obtain algorithm transferability and test site independence for agricultural regions.

2 Methodology of Soil Moisture Inversion using Dual-Polarimety

Firstly, the dual-polarimetric coherency matrix $[T_2]$ is calculated from the coherent HH/VV-data:

$$[T_2]=\frac{1}{2}\begin{bmatrix}\left\langle\left|S_{HH}+S_{VV}\right|^2\right\rangle & \left\langle\left(S_{HH}+S_{VV}\right)\left(S_{HH}-S_{VV}\right)^*\right\rangle\\ \left\langle\left(S_{HH}+S_{VV}\right)^*\left(S_{HH}-S_{VV}\right)\right\rangle & \left\langle\left|S_{HH}-S_{VV}\right|^2\right\rangle\end{bmatrix} \quad (1)$$

For $[T_2]$, two scattering scenarios are distinguished for dual-polarimetric inversion of soil moisture: The vegetated soil case and the bare soil case.

2.1 Bare Soil Inversion

In the case of bare soil scattering a dual-polarimetric eigen-analysis is conducted and the dominant alpha scattering angle (α_1) is calculated [2]:

$$\left[T_2\right]=U_2\Lambda U_2^T \Rightarrow U_2=\begin{bmatrix}u_{11}\\ u_{12}\end{bmatrix},\Lambda=\begin{bmatrix}\lambda_1 & 0\\ 0 & \lambda_2\end{bmatrix} \quad (2)$$
$$\alpha_1=\arccos\left(\left|u_{11}\right|\right)$$

α_1 is also modelled by the IEM scattering model for the high frequency limit of X-band as detailed in [4,p.103],[5]. In this case α_1 should only depend on the dielectric constant (ε) and the local incidence angle (θ), while it should be independent of roughness (no dependency on *ks* and *kl*) as depicted in **Figure 1**.

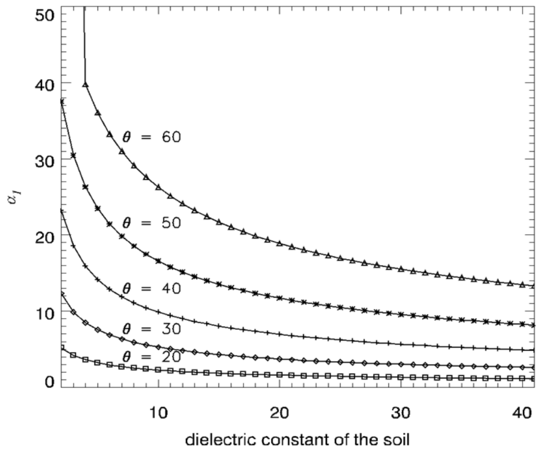

Figure 1 Sensitivity of α_1 regarding the dielectric constant of the soil (ε) (soil moisture) for different local incidence angles (θ) [4].

Figure 1 reveals an increased sensitivity for shallower local incidence, which is known for polarimetric applications. In addition, the sensitivity of α_1 for moister regimes (ε>25) drops significantly.

For inversion, the SAR-derived α_1 is compared with its modelled counterpart for a range of expected ε-values, in order to obtain the best match between data and model for the respective dielectric constant of the soil and via the transfer polynomial of [6] also the soil moisture (see **Figure 2**).

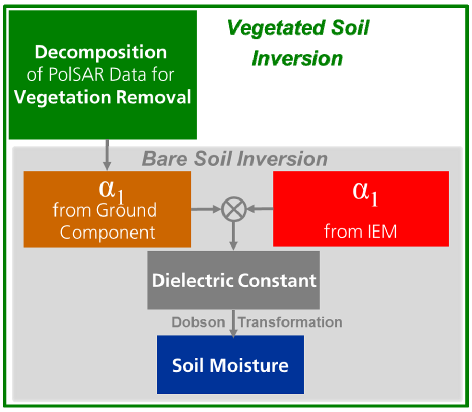

Figure 2 Work flow for soil moisture inversion of bare (gray color) and vegetated (green color) soils.

2.2 Vegetated Soil Inversion

In the case of vegetated soils, **Figure 2** already indicates that the dual-polarimetric signature has to be decomposed by a polarimetric decomposition to separate the vegetation volume scattering (f_V, V_0, V_{11}, V_{12}, V_{22}) from the soil ground scattering (T_{11G}, T_{12G}, T_{22G}):

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{12}^* & T_{22} \end{bmatrix} - \frac{fv}{V_0}\begin{bmatrix} V_{11} & V_{12} \\ V_{12}^* & V_{22} \end{bmatrix} = \begin{bmatrix} T_{11G} & T_{12G} \\ T_{12G}^* & T_{22G} \end{bmatrix}$$

$$\begin{aligned} &V_0 = 1 + A_p^2 && V_{22} = 0.25\left(A_p - 1\right)^2 \times \\ &V_{11} = 0.5\left(A_p + 1\right)^2 && \left(1 + \operatorname{sinc}\left(4\Delta\psi\right)\right) \\ &V_{12} = 0.5\left(A_p^2 - 1\right)\operatorname{sinc}\left(2\Delta\psi\right), \end{aligned} \tag{3}$$

where f_V is the volume scattering intensity. A_p represents the particle anisotropy and therefore a first-order shape of the most dominant plant constituents. In addition, $\Delta\psi$ regulates the orientation distribution width describing the degree of orientation of the plants within the volume structure. Since the observation space is limited in dual-polarimetry, some variables have to be fixed (i.e. $\Delta\psi$, A_p). Hence, a randomly and a horizontally oriented volume matrix are assumed:

Random volume: $\quad$ Horizontal volume:

$$[T_V] = \begin{bmatrix} 1/2 & 0 \\ 0 & 1/4 \end{bmatrix} \qquad [T_V] = \begin{bmatrix} 1/2 & 1/6 \\ 1/6 & 7/30 \end{bmatrix} \tag{4}$$

The dual-polarimetric entropy (H) serves as an indicator to select the fitting volume matrix [T_V] by setting it to random for H>0.5 and to horizontal for H<0.5.

In general, **Equation 3** proposes a hybrid-type of polarimetric decomposition (combining model-based and eigen-based decomposition techniques) as already introduced in [7]. This means, after the model-based volume decomposition the bare soil inversion can be conducted with an eigen-based analysis leading to α_1 and the comparison procedure already introduced for the bare soil case.

2.2.1 Generation of Synthetic Cross-Polarization

Equation 3 includes the volume scattering intensity f_V. In the quad-polarimetric acquisition case, f_V is a function of the cross-polarization component. As this polarization is not available for dual-polarimetric (HH/VV) coherent data, the cross-polarisation can be synthesized and estimated from the dual-polarimetric data under the assumption of azimuthal symmetry [8,4]:

$$\begin{aligned} &fv = 8\left\langle \left|S_{XX}\right|^2 \right\rangle \\ &\left\langle \left|S_{XX}\right|^2 \right\rangle = \frac{1}{4}\left(1-\gamma_{HHVV}\right)\left(\left\langle \left|S_{HH}\right|^2 \right\rangle + \left\langle \left|S_{VV}\right|^2 \right\rangle\right) \\ &\gamma_{HHVV} = \frac{\left\langle S_{HH} S_{VV}^* \right\rangle}{\sqrt{\left\langle \left|S_{HH}\right|^2 \right\rangle \left\langle \left|S_{VV}\right|^2 \right\rangle}} \end{aligned} \tag{5}$$

Figure 3 indicates the quality of the cross-polarization synthesis, when compared with measured quad-polarimetric cross-polarization for L-band (E-SAR) and X-band (TerraSAR-X) data. It is clearly observable that the overestimation of the synthesized cross-polarization is more distinct in L-band with root mean square errors (RMSE) of around 5.0-5.4dB than in X-band with RMSE values of 1.8-2.0dB. Also comparisons with C-band RADARSAT-2 data (not shown), indicate that the assumption of azimuthal symmetry is best met at X-band and can be utilized according to [8] as an estimator for the occurring cross-polarization within agricultural areas (note: high deviation in urban areas due to dihedral scattering).

3 Test Sites and Sensors

The developed algorithm for soil moisture estimation from bare and vegetated soils is tested for the Wallerfing (Lower Bavaria) and the DEMMIN (Mecklenburg-Western Pomerania) test sites in Germany.

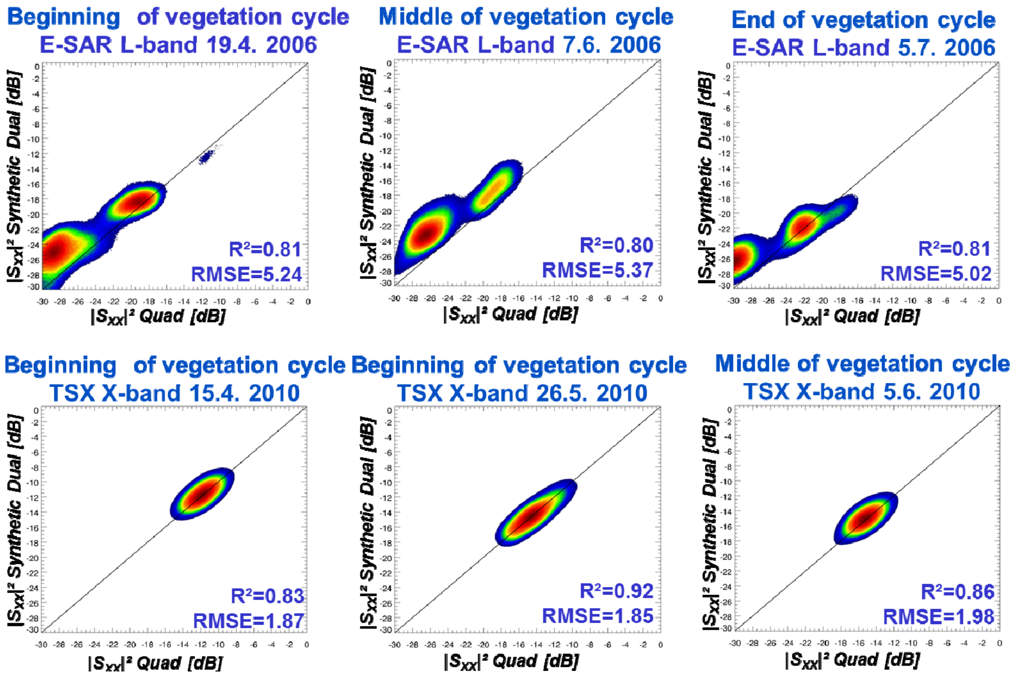

Figure 3 Correlation of cross-polarization from measured quad-polarimetric data (x-axis) and from synthesized dual-polarimetric data (y-axis) for E-SAR L-band (top) and TerraSAR-X X-band (bottom) concerning different dates in the phenological cycle (colors represent a 2D-histogram, where counts rise from blue to red colors).

The *in situ* data were recorded concurrently with the polarimetric acquisitions during field campaigns in 2009-2012. Soil moisture and vegetation parameters were measured on several test fields including a variety of soil and crop types in different phenological stages.

4 Results and Validation of Soil Moisture Inversion using Dual-Polarimety

Soil moisture is estimated for bare and vegetated soils using the algorithms described in Section 2.

4.1 Bare Soil Inversion

Figure 4 presents the soil moisture inversion result scaled from 0 to 50vol.%, while white areas indicate non-invertible pixels (inversion rate: 58%). The variety of moisture levels on the agricultural fields indicates the potential of dual-polarimetry as an observation space for scatterer properties like moisture content. Furthermore, the validation plot reveals a slight overestimation of the estimated soil moisture compared to the measured *in situ* values for five different, bare test fields. However, the RMSE stays below 7vol.% for all roughness and moisture cases.

4.2 Vegetated Soil Inversion

Figure 5 displays the outcome of the soil moisture inversion with growing vegetation cover (vegetated soils), whereby dates after end of June 2011 were discarded due to domination of vegetation volume scattering at X-band indicated by low G-to-V ratios (μ):

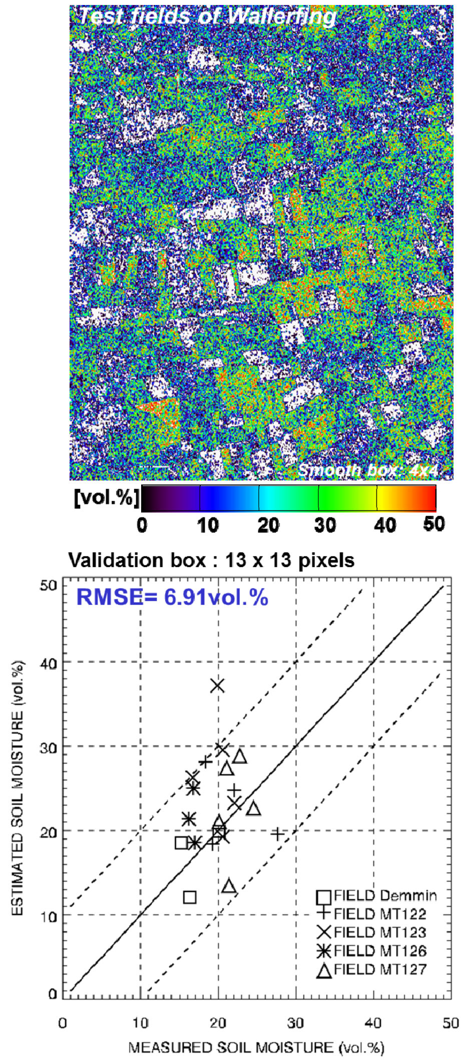

Figure 4 Result (top) and validation (bottom) of soil moisture estimation on bare soil fields for Wallerfing and DEMMIN (only included in scatter plot) test site.

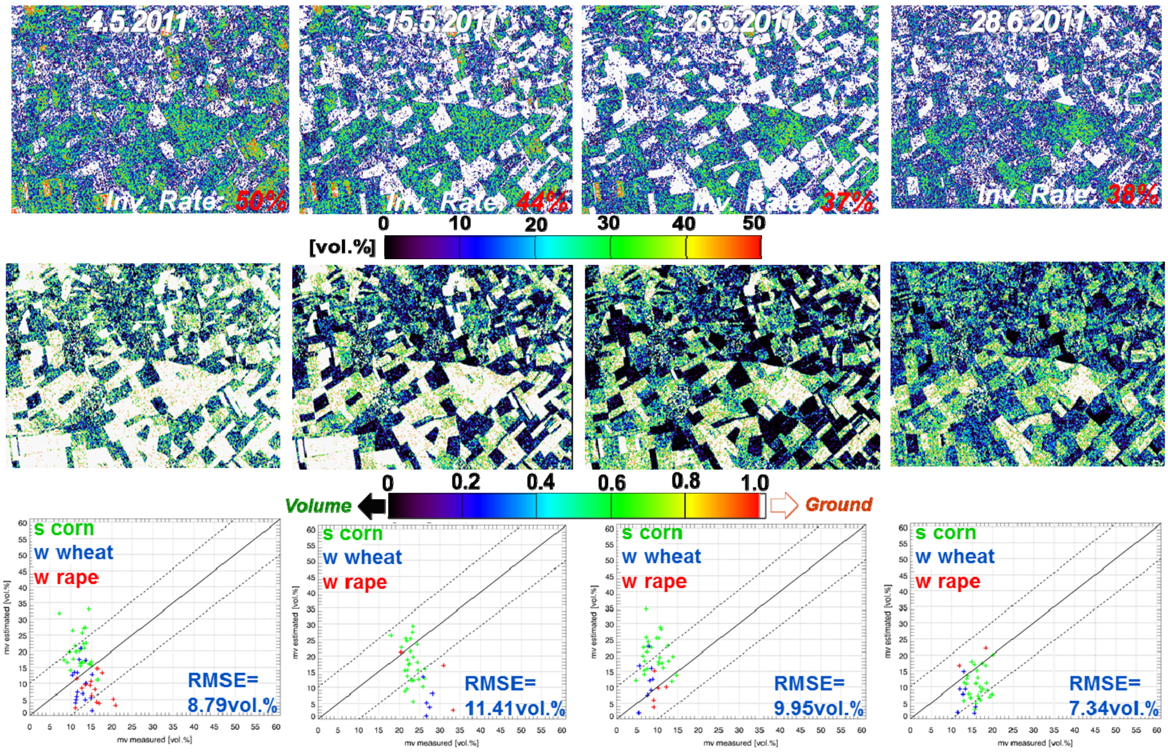

Figure 5 Result (top), Ground-to-Volume (G-to-V) ratios (middle) and validation (bottom) of soil moisture estimation under growing vegetation cover (vegetated soils) for the dual-polarimetric Wallerfing data of 2011; Validation box: 13x13pixels; Moisture image smooth: 4x4.

$$\mu = Tr([T_G]) / Tr([T_V]) \quad (6)$$

The time series of moisture result and the validation show a feasible inversion (inversion rates: 37-50%) for the four dates with varying inversion quality of RMSE 7.3-11.4vol.%, while the highest RMSE for 15.5.2011 occurs due to a strong rain event shortly before the data take suggesting a distinctively limited penetration through the wet canopy.

5 Summary and Outlook

Soil moisture is estimated for bare and vegetated soils using dual-polarimetric coherent (HH/VV) TerraSAR-X and TanDEM-X data from the Wallerfing and DEMMIN test sites in Germany. For the bare soil inversion the dominant alpha scattering angle is calculated from the data and modelled with the IEM scattering model. For the vegetated soils dual polarimetric decomposition techniques are developed and applied together with an innovative synthetized cross-polarization component to remove the vegetation contribution and to invert the remaining ground scattering contribution with the bare soil procedure for soil moisture under vegetation cover. The validation with ground-based sensors (FDR-, TDR-probes) revealed a well agreement with the SAR-based moisture estimates resulting in an RMSE of 7.3-11.4vol.% including large parts of the growth season and a variety of crop types in different phenological stages. In order to further decrease the estimation error, the vegetation volume model will be investigated more broadly and adapted to the specific scattering cases in agriculture. Moreover, the Ground-to-Volume ratios (μ) will be analyzed with the time series of DEMMIN data to understand their capabilities to indicate inversion impossibility due to prevailing scattering of the grown agricultural vegetation cover instead of the soil.

References

[1] Cloude, S.R.: *Polarisation: Applications in Remote Sensing*, Oxford, Oxford University Press, GB, 2010.

[2] Cloude, S.R.: *The Dual Polarisation Entropy/Alpha Decomposition: A PALSAR Case Study.* Proc. of PolInSAR Conference 2007, Frascati, Italy, p.1-6, 2007.

[3] Lopez-Sanchez, J., Ballester-Berman J.D., Hajnsek, I.: *First Results of Rice Monitoring Practices in Spain by Means of Time Series of TerraSAR-X Dual-Pol Images.* IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 4, p.634-646, 2011.

[4] Allain, S.: *Charactérisation d'un sol nu à partir de données SAR polarimétriques Etude multi-fréquentielle et multi-résolutions*.PhD thesis, University of Rennes 1, Rennes, France, 2003.

[5] Jagdhuber, T., Hajnsek, I., Papathanassiou, K.P.: Polarimetric *Soil Moisture Retrieval at Short Wavelength*, Proc. of PolInSAR Conference 2013. Frascati, Italy, p.1-6, 2013.

[6] Dobson, M.C., Ulaby, F.T., Hallikainen, M.T., El-Rayes, M.A.: *Microwaves Dielectric Behavior of Wet Soil-Part II: Dielectric Mixing Models*. IEEE Transactions on Geoscience and Remote Sensing, vol. GE-23, p.35-46, 1985.

[7] Jagdhuber, T.: *Soil Parameter Retrieval under Vegetation Cover Using SAR Polarimetry*, PhD Thesis, University Potsdam, Potsdam, published online under creative commons, 2013.

[8] Souyris, J.-C., Imbo, P., Fjortoft, R., Mingot, S., Lee, J.-S.: *Compact Polarimetry Based on Symmetry Properties of Geophysical Media. The π/4 Mode*. IEEE Transactions on Geoscience and Remote Sensing, vol. 43, p.634-646, 2005.