Polarimetric Soil Moisture Retrieval at Short Wavelength

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ABSTRACT

Soil moisture was assessed with quad-polarimetric TerraSAR-X and dual-polarimetric (HH/VV) TanDEM-X data from the agricultural region of Wallerfing, Germany. The investigations included a bare soil case in April 2009 (TerraSAR-X) and a time series of 04-07/2011 (TanDEM-X) to estimate soil moisture on bare and vegetated soils including different agricultural crop types at various phenological stages. Therefore polarimetric decomposition methods, incorporating a synthetic cross-polarization, were developed for X-band to separate ground scattering from vegetation scattering. Afterwards the IEM model was used to invert the ground or bare soil scattering components using the dominant scattering alpha angle. For both campaigns, comprising several crop and soil types and different phenological stages along the growth cycle, a root mean square error of <6vol.% (bare soil/TerraSAR-X) and of 5-14vol.% (vegetated soil/TanDEM-X) can be achieved for the soil moisture estimation.

1. INTRODUCTION

In the last five years an enormous amount of polarimetric X-band data got available with the successful establishment of TerraSAR-X and TanDEM-X in space. Especially first investigations on agricultural areas fostered the interest for monitoring of surface soil moisture at X-band. Up to now, soil moisture inversion at this short wavelength is approached with various algorithms using empirical and semi-empirical approaches [1]. In contrast, the physically-based IEM model is used in this case to link the scattering signatures with the moisture content of bare soil areas assuring at the same time test site independence, as no empirical relations are applied. The main focus of most approaches is laid on the estimation of soil moisture on non-vegetated (bare) soil surfaces, where soil roughness additionally influences the scattering signature. However, vegetation covers the soils following the growth cycle and complicates the moisture retrieval. Hence, polarimetric decomposition techniques are a welcome option to assess the separation of scattering contributions from the vegetation volume and from the underlying soil. Afterwards the soil contributions are inverted to retrieve the soil moisture under vegetation at X-band.

2. METHODOLOGY OF SOIL MOISTURE RETRIEVAL AT X-BAND

In [2] the IEM model was investigated for polarimetric bare soil scattering at different frequencies from X- to L-band. In the limit of high frequencies, like X-band, the dominant polarimetric alpha scattering angle α_1, corresponding to the dominant eigenvector and eigenvalue, should only depend on the incidence angle and the dielectric constant of the soil, while the dependency on soil roughness cancels out according to the backscatter modeling in [2]. Therefore a direct link to soil moisture of bare soils can be established [2]:

$$\lim_{f_c \to \text{X-band}} \alpha_1 = \arctan\left(\frac{2 f_{HH} f_{VV}^* - \left(|f_{VV}|^2 - |f_{HH}|^2 + \sqrt{\left(|f_{VV}|^2 - |f_{HH}|^2\right)^2 + 4\left|f_{HH} f_{VV}^*\right|^2}\right)}{2 f_{HH} f_{VV}^* + \left(|f_{VV}|^2 - |f_{HH}|^2 + \sqrt{\left(|f_{VV}|^2 - |f_{HH}|^2\right)^2 + 4\left|f_{HH} f_{VV}^*\right|^2}\right)}\right) \quad (1)$$

with IEM scattering coefficients $f_{VV} = \frac{2F_{VV}}{\cos\theta}, f_{HH} = -\frac{2F_{HH}}{\cos\theta}$

F_{VV} and F_{HH} are the Fresnel coefficients, which are a function of the local incidence angle θ and the dielectric constant of the soil ε_s.
As the dominant scattering alpha angle α_1 calculus for X-band (high frequency limit) depends solely on the co-polarized scattering channels [2], it is feasible to compare the modelled α_1-values with dual-polametric (HH/VV) TanDEM-X-derived as well as quad-polarimetric TerraSAR-X-derived α_1-values to retrieve the dielectric constant of the soil ε_s and the soil moisture using the transfer polynomial of [3] or [4].
In addition, polarimetric decomposition techniques can be used to investigate, until which thickness the vegetation cover can be removed for X-band to enable a soil moisture inversion under growing vegetation cover along the phenological cycle. Thus, in a first step cross-polarization is synthesized for the dual-polarimetric HH/VV data under the assumption of azimuthal symmetry [5].

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

Afterwards the data is decomposed in a vegetation volume and a soil ground component, which is then inverted for soil moisture with the bare soil procedure (see Fig. 1).

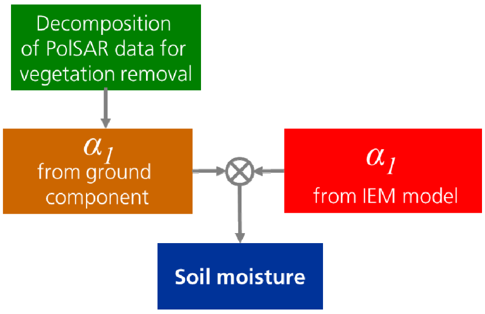

Figure 1: Scheme for decomposition and inversion of soil moisture under vegetation at X-band

The decomposition step using the synthesized cross-pol scattering of Eq. 2 is described in Eq. 3, where a general volume scattering component (V_{11}, V_{12}, V_{22}) is assumed. However, we added a random and a horizontal vegetation volume type as applicable alternatives.

$$\langle [T_{Data}] \rangle - fv[T_{Volume}] = [T_{Ground}] \tag{3}$$

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

Random volume: $T_V = \begin{bmatrix} 1/2 & 0 \\ 0 & 1/4 \end{bmatrix}$

Horizontal volume: $T_V = \begin{bmatrix} 1/2 & 1/6 \\ 1/6 & 7/30 \end{bmatrix}$

Hence, in the following chapter the developed decomposition and inversion algorithms for bare and vegetated soils (applying a synthesized cross-polarization signature) are tested with the acquired X-band SAR data.

3. EXPERIMENTAL RESULTS

The developed algorithm is applied on fully-polarimetric X-band data (TerraSAR-X 2009 campaign) and on a time series of dual-polarimetric (HH/VV) data (TanDEM-X 2011 campaign, 04-07/2011) of an agricultural region near Wallerfing, Germany (see Fig. 2).

In situ field measurements, including soil moisture (with FDR-sensors) and vegetation height, were conducted in collaboration with the LMU Munich for the two campaigns enabling a later comparison with the SAR-based soil moisture estimates. Fig. 3 indicates the increase in the vegetation layer for three test fields onsite in 2011.

Figure 2: Agricultural test site Wallerfing in Lower Bavaria, Germany.

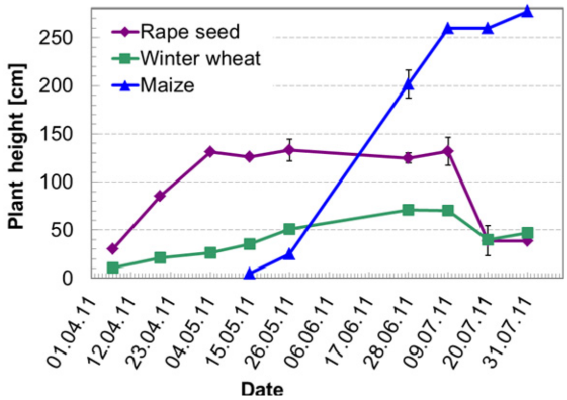

Figure 3: Vegetation height for the three test fields at Wallerfing.

Firstly, the soil moisture estimation algorithm is applied on bare soils. Fig. 7 depicts the dominant alpha scattering angle as input observable and the soil moisture estimates in vol.% as inversion output, where white areas within the scene indicate non-invertible regions. The polarimetric scattering entropy shows that with increasing entropy the inversion rate drops significantly. Hence, areas with distinct scattering entropy (H>0.4) are mostly covered with vegetation and need a different inversion approach.

Thus, in a next step soil moisture estimation under vegetation is investigated at short wavelength (X-band) using polarimetric decomposition techniques. Therefore the validity of the synthetic cross-polarization generation was tested to approve the azimuthal symmetry assumption for X-band.

In Figs. 4 and 5 the applicability of the cross-polarization synthesis is supported with a high correlation coefficient of 0.7 between the measured cross-polarization from the quad-polarized configuration and the synthesized cross-polarization from the dual-polarized (HH/VV) configuration. Therefore the cross-polarization signature will be used within the dual-polarimetric decomposition of vegetation volume and ground scattering components within the soil moisture retrieval under vegetation cover with the TanDEM-X (HH/VV) data.

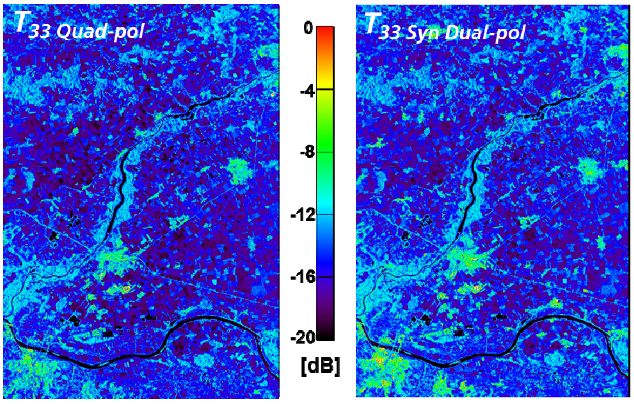

Figure 4: Comparison of cross-polarization (T_{33} $=2\langle|S_{xx}|^2\rangle$) from measured quad-polarimetric TerraSAR-X data (left) and from synthesized dual-polarimetric TerraSAR-X data (right) for the 27th of April 2009.

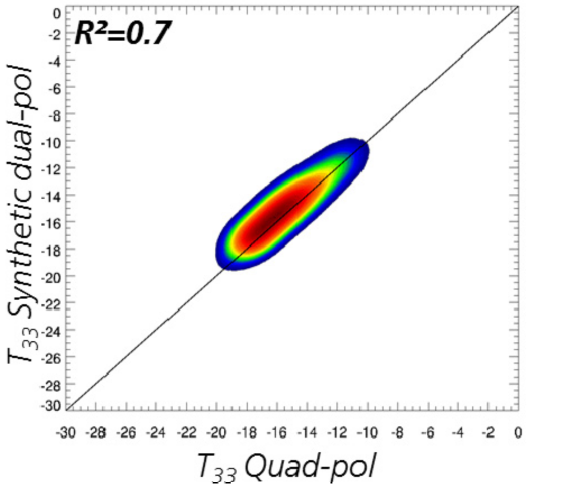

Figure 5: Two-dimensional histogram of (T_{33} $=2\langle|S_{xx}|^2\rangle$) from measured quad-polarimetric TerraSAR-X data (x-axis) and from synthesized dual-polarimetric Terra-SAR-X data (y-axis) for the 27th of April 2009 (counts rise from blue to red colors).

Fig. 8 provides a time series of inversion results for soil moisture using the dual-polarimetric decomposition and inversion technique including a synthesized cross-polarization signature. The entire vegetation growth period from the beginning in April until the end in July 2011 is covered using different vegetation volume cases (horizontal, random). The outcome advocates the potential of this decomposition and inversion approach for dual-polarimetric (HH/VV) X-band data (e.g. from TanDEM-X) to monitor soil moisture under emerging vegetation cover. However, the white regions in the images state the inversion failures, which are increasing along the growing cycle due to the increasing dominance of the vegetation volume hampering a feasible inversion at X-band (cf. Fig. 3). This reflects into the inversion rate, which decreases from about 40% (12/04: 45%, 15/05: 42%) to approximately 20% (26/05: 22%, 09/07: 17%, 31/07: 21%) over the vegetation growing period. Nevertheless, for the first time the soil moisture trend can be tracked along the growing season at X-band using just dual-polarimetric (HH/VV) data.

4. VALIDATION OF SOIL MOISTURE ESTIMATION

The extracted SAR-based soil moisture values are validated with the corresponding *in situ* measurements of the agricultural campaigns at Wallerfing for a first quality assessment of soil moisture inversion on bare and vegetated soils. Ground measurements of soil moisture were taken with frequency domain reflectometry (FDR) probes during the campaigns for a quantitative analysis of the inversion. A box of 13x13 pixels was drawn around each measurement location to realize 169 looks for comparison. Fig. 6 compares the *in situ* measurements with the SAR-based estimates for a soil moisture assessment on bare soils with TerraSAR-X data using the bare soil approach.

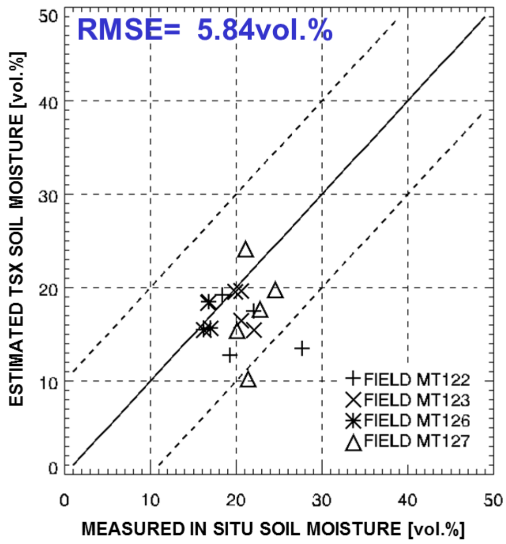

Figure 6: Validation of soil moisture results of the bare soil inversion of the TerraSAR-X data with in situ measurements of FDR probes at the 27th of April 2009; The transfer polynomial of [4] was applied; Validation box: 13x13 pixels.

For all four investigated bare soil fields the inversion is feasible with an overall precision of a root mean square error (RMSE) of 5.84vol.%. Hence, the approach of [2] states its applicability using just the dominant polarimetric alpha scattering angle α_1 in the limit of high frequencies, like X-band.
In Fig. 9 the soil moisture inversion along the vegetation growing from May to July 2011 is validated

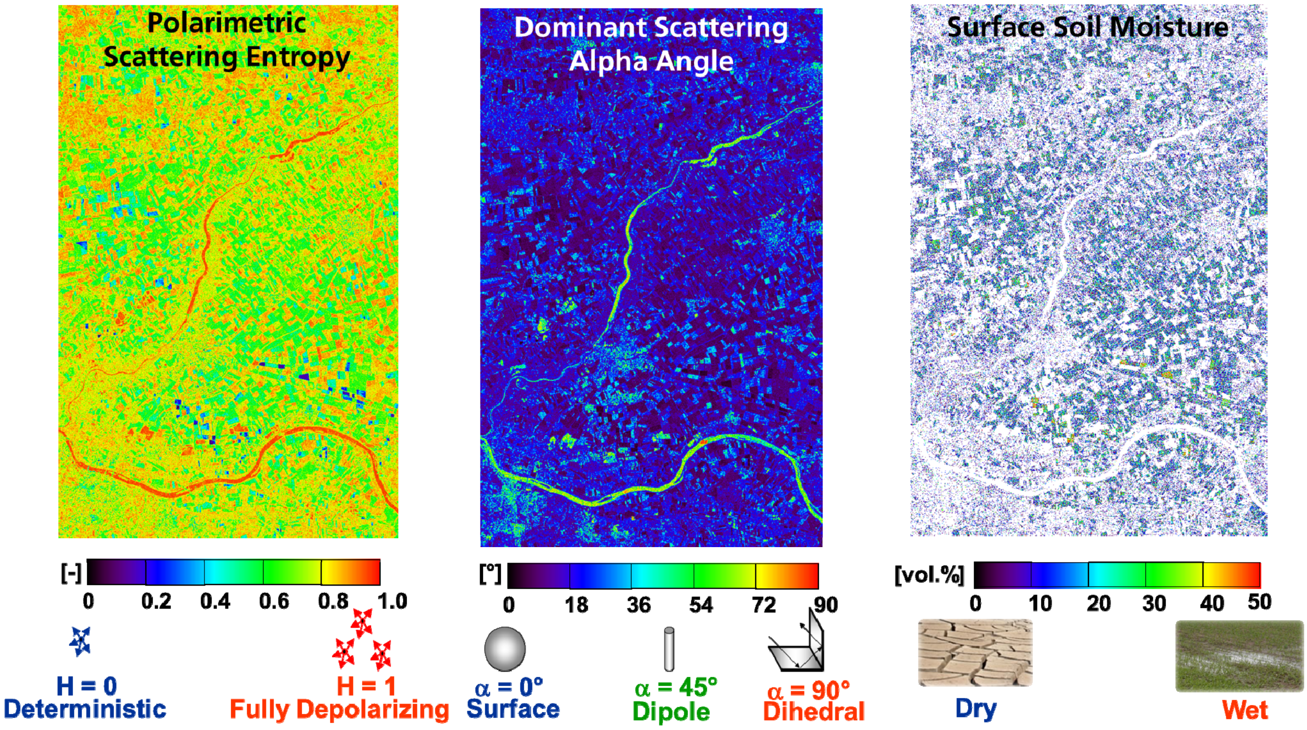

Figure 7: Polarimetric scattering entropy, dominant scattering alpha angle and the result of soil moisture inversion in vol.% for the 27th of April 2009 within the scene of Wallerfing, Lower Bavaria, Germany .Non-invertible pixels are masked white; Moisture image smooth: 4x4.

with *in situ* measurements from FDR probes (for 12/04 and 31/07 no field measurements were available). In May, the validation for the 4th and the 26th exhibit RMSE-values of 8.6 and 5.0vol.% indicating a well performance except for the winter rape field, which already developed a very pronounced vegetation layer of approximately 130cm height. This might be not penetrable for X-band any more, but definitely needs further investigations.

The validation of the 15th of May indicates a higher RMSE of 10.6vol.%, while only the bare summer corn field could be inverted well. The winter crop fields already developed a distinct vegetation layer of more than 30cm vegetation height. In addition, rainfall set in some hours prior to the overflight and wetted the vegetation layer. Hence, also in this case the penetration of the wet vegetation cover at X-band is in the focus of on-going research efforts.

At last, the validation of the 9th of July displays a strong underestimation, which can be understood by comparison with Fig. 3. On this data the maximum vegetation cover with 60-260cm height (incorporating all investigated fields) was present and detoriates strongly a feasible inversion. This leads to a distinct underestimation with a RMSE of 13.8vol.%.

However, the performance of the developed algorithms is in summary encouraging with a RMSE of <6vol.% for bare soils and between 5-14vol.% for vegetated soils.

5. CONCLUSIONS AND FUTURE TASKS

Soil moisture was assessed with quad-polarimetric TerraSAR-X and dual-polarimetric (HH/VV) TanDEM-X data from the agricultural region of Wallerfing, Germany. The investigations included a bare soil case in April 2009 (TerraSAR-X) and a time series from April to July 2011 (TanDEM-X) to estimate soil moisture on bare and vegetated soils including different agricultural crop types at various phenological stages. Therefore polarimetric decomposition methods, incorporating a synthetic cross-polarization, were developed for X-band to separate ground scattering from vegetation scattering. Afterwards the IEM model was used to invert the ground or bare soil scattering components using the dominant scattering alpha angle. For both campaigns, comprising several crop and soil types and different phenological stages along the growth cycle, a root mean square error of <6vol.% (bare soil/TSX) and of 5-14vol.% (vegetated soil/TDX) can be achieved for the soil moisture estimation. For future research, the most prominent tasks will be to find a robust criterion for the selection of the vegetation volume type at X-band and to investigate in detail the influence of the vegetation induced depolarization on the moisture retrieval for vegetated soils [6].

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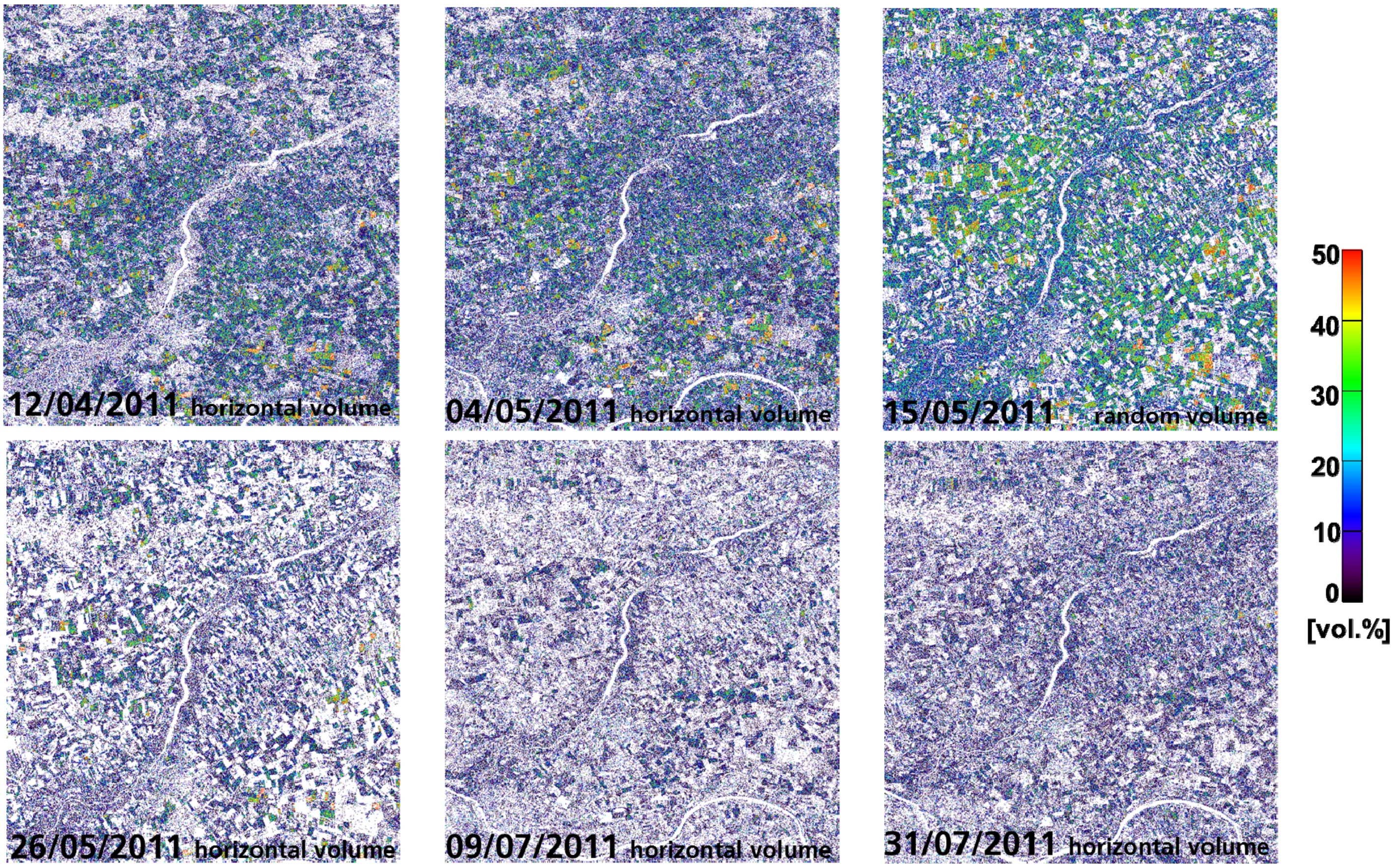

Figure 8: Soil moisture results in vol.% of the dual-polarimetric decomposition and inversion including a synthesized cross-polarization signature from the beginning (12th of April) until the end (31st of July) of the vegetation growth period in 2011 based on dual-polarimetric (HH/VV) TanDEM-X acquisitions. White areas indicate non-invertible regions; Moisture image smooth: 4x4.

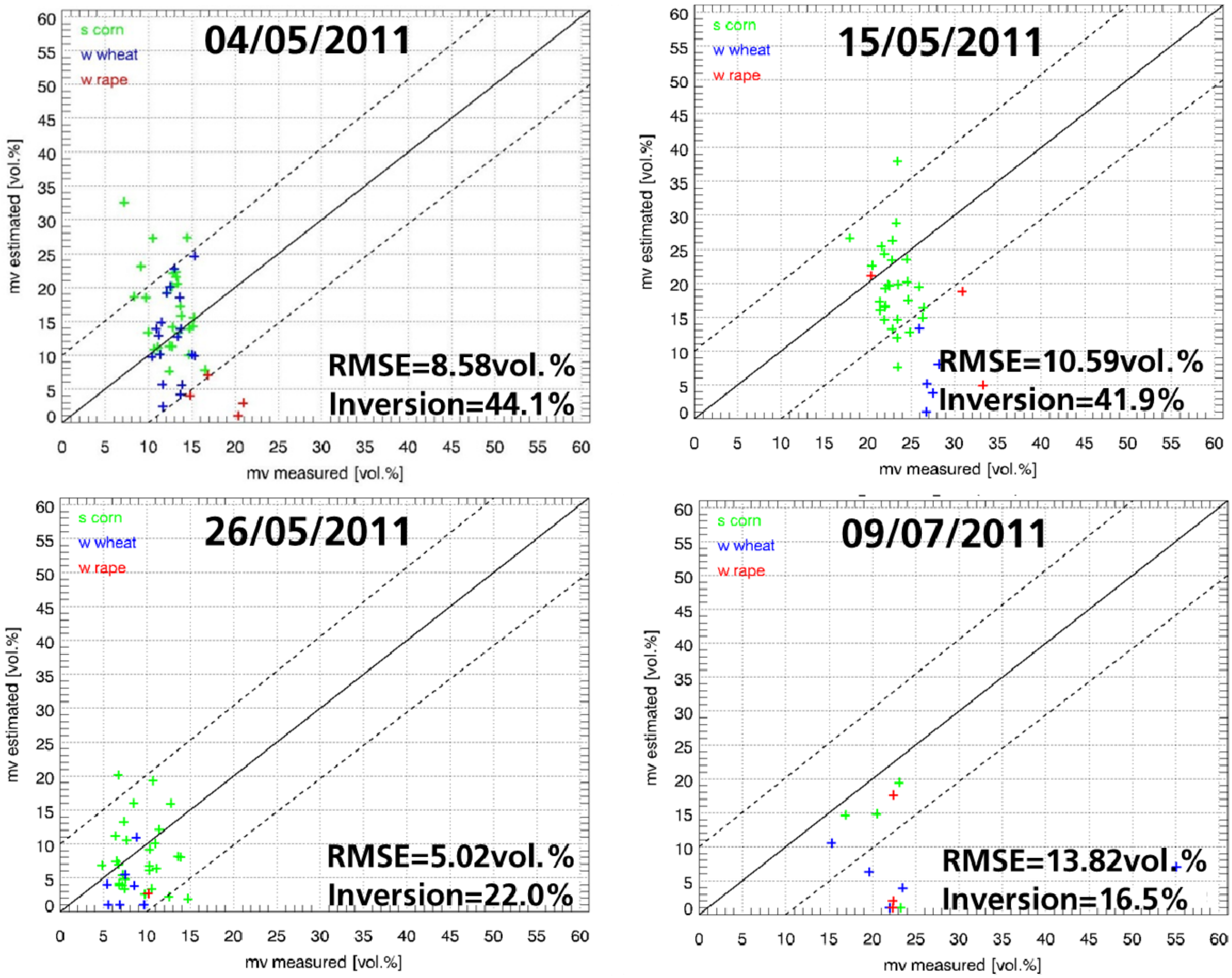

Figure 9: Validation of soil moisture results of the dual-polarimetric decomposition and inversion including a synthesized cross-polarization signature with in situ measurements of FDR probes from the beginning (12th of April) until the end (31st of July) of the vegetation growth period in 2011 based on three different crop types: Summer corn, winter wheat and winter rape; The transfer polynomial of [3] was applied; Validation box: 13x13 pixels.