A Hybrid Decomposition for Soil Moisture Estimation under Vegetation Cover Using Polarimetric SAR

Thomas Jagdhuber[1,3], Irena Hajnsek[1,2], Konstantinos P. Papathanassiou[1], Axel Bronstert[3]

[1]Microwave and Radar Institute, German Aerospace Center (DLR), PO BOX 1116, 82234 Wessling, Germany,
Phone/Fax: +49-8153-28-2329 / -1449
[2]ETH Zurich, Institute of Environmental Engineering, HIF D28.1, Schafmattstr. 6, CH-8093 Zurich
[3]University of Potsdam, Institute of Environmental Sciences, Karl-Liebknecht-Str. 24-25, 14476 Potsdam
Email: Thomas.Jagdhuber@dlr.de, Irena.Hajnsek@dlr.de, Kostas.Papathanassiou@dlr.de, axelbron@uni-potsdam.de

ABSTRACT

A hybrid polarimetric decomposition combining model-based and eigen-based techniques is developed to analyse its capability for soil moisture estimation under agricultural vegetation cover. The innovative algorithm is applied on L-Band fully polarimetric data acquired by DLR's E-SAR sensor. The flight campaign was conducted within the OPAQUE campaign carried out in 2008 on a test site in Eastern Germany. The applied approach indicates a great potential to invert soil moisture with a very high inversion rate (>98%) for a variety of crop types and for terrain with pronounced topography. A quality assessment of two scenes is carried out by a validation with FDR and gravimetric measurements. The RMSE-level ranges between 7.4Vol.% and 9.3Vol.% for all scenes including a variety of vegetation types and different terrain. However the local incidence angle affects the soil moisture retrieval and needs further investigation.

1. INTRODUCTION

In order to support hydrological applications for flood forecasting or precision farming techniques for intra-field irrigation the spatial assessment of soil moisture is of great importance. Polarimetric SAR remote sensing is capable to cover areas up to catchment scale with frequent coverage. Since most of the landscape in middle latitudes is at least seasonally covered by vegetation, the estimation of soil moisture increases in complexity due to the presence and gradual increase of vegetation along the growing season. Hajnsek *et al.* analysed in 2009 a variety of model-based polarimetric decompositions for soil moisture inversion under vegetation [1] and proposed in [2] a 'best of' version of these methods for application in rural areas. For this paper an eigen-based and a model-based polarimetric decomposition are combined to develop a so-called hybrid polarimetric decomposition for soil moisture inversion under vegetation cover.

2. HYBRID POLARIMETRIC DECOMPOSITION FOR SOIL MOISTURE INVERSION

Soil moisture retrieval from scattering of natural media like agricultural fields involves soil and vegetation components. Therefore the recorded SAR backscatter signal ($[T_{Data}]$) is decomposed into three canonical scattering components (surface $[T_S]$, dihedral $[T_D]$ and volume $[T_V]$, cf. Eq. 1) using analytically-solvable, polarimetric model-based decomposition algorithms [1,2]. * represents the complex conjugate operator.

$$\begin{bmatrix} T_{11} & T_{12} & 0 \\ T_{12}^* & T_{22} & 0 \\ 0 & 0 & T_{33} \end{bmatrix} = [T_{Data}] = [T_S] + [T_D] + [T_V] \quad (1)$$

A thorough introduction to polarimetric model-based decompositions is given in [3,4]. The linear system of equations for the new hybrid decomposition is generally based on an approach proposed in [4,p.198] and can be defined as in Eq. 2 [5]. Hence, the depolarizing rank-3 volume component $[T_V]$ due to vegetation cover is separated from the two rank-1 ground components (surface $[T_S]$, dihedral $[T_D]$) in order to retrieve the characteristics (i.e. moisture) from the underlying soil [1,4,5,6]. The model-based volume component uses a particle shape α_V modeling different vegetation geometries by a cloud of uniformly oriented particles. The vegetation shapes might range from spheres (α_V =0) to randomly oriented dipoles (α_V =π/4). In order to use in the next step the eigen-analysis for a hybrid decomposition (model-based/eigen-based), the corresponding eigenvalues (f_d, f_s) of the ground components ($[T_S]+[T_D]$) and the intensity of the volume component f_v ($[T_V]$) can be calculated. The eigenvalues (f_d, f_s) represent the intensity of the two different ground components (surface, dihedral). The components α_d and α_s symbolize the ground (dihedral, surface) scattering

$$[T_{Data}] = f_s \begin{bmatrix} \cos(\alpha_s)^2 & -\cos(\alpha_s)\sin(\alpha_s) & 0 \\ -\cos(\alpha_s)\sin(\alpha_s) & \sin(\alpha_s)^2 & 0 \\ 0 & 0 & 0 \end{bmatrix} + f_d \begin{bmatrix} \sin(\alpha_d)^2 & \cos(\alpha_d)\sin(\alpha_d) & 0 \\ \cos(\alpha_d)\sin(\alpha_d) & \cos(\alpha_d)^2 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \frac{f_v}{2} \begin{bmatrix} 2\cos(\alpha_v)^2 & 0 & 0 \\ 0 & \sin(\alpha_v)^2 & 0 \\ 0 & 0 & \sin(\alpha_v)^2 \end{bmatrix} \quad (2)$$

mechanisms and due to the orthogonality of the two scattering mechanisms the relation $\alpha_d=\pi/2-\alpha_s$ applies [4,5,8]. Therefore, the formulation of α_d and α_s from the acquired SAR data results in a physical separation between surface and dihedral scattering, because one alpha angle, which ranges between 0° and 45°, is assigned to surface scattering and the second alpha angle ranging from 45° to 90° is classified as dihedral scattering. Afterwards f_d and f_s are allocated according to the corresponding alpha angles.

Therefore a simple and low parameterized electro-magnetic model describing the canonical surface (Bragg scattering) scattering process is developed to retrieve the closest match between modeled (β_m,) and decomposed polarimetric surface α_s alpha scattering mechanism for subsequent soil moisture (mv) inversion [1,4,5].

$$\text{Surface: } \mathrm{mv} = \min\{|\beta - \beta_m|\} \quad \text{with} \quad \beta = -\tan(\alpha_s) \quad (3)$$

β_m is the link between the surface scattering mechanism α_s and the volumetric soil moisture [1,2], where R_{HH} and R_{VV} are the horizontal and vertical Bragg reflection coefficients [4,5,6]. These surface reflection coefficients (R_{HH}, R_{VV}) depend only on the incidence angle θ of the acquisition system and the dielectric constant of the soil ε_s. Finally the dielectric constant ε_s can be linked to the volumetric soil moisture by a universal polynomial of Topp *et al*. [9].

2.1. Physically Constraint Volume Intensity Component f_{vc} for Hybrid Polarimetric Decompositions

The hybrid decomposition in Eq. 2 uses the f_v-component, which depends solely on the cross-polarized channel (T_{33}) and the shape factor α_V. This causes problems for a quantitative analysis of soil moisture under vegetation cover, because in the presence of soil roughness together with distinct vegetation layer the f_v-component is overestimated leading to non-physical decomposition and inversion results.

Therefore a more sufficient characterization of the volume intensity component f_v is still an active area of research. Some retrieval approaches for soil moisture are already published using a mathematical constraint forcing positive eigenvalues for the volume intensity component f_v [5] or incorporating polarimetric ground-to-volume ratios to weight the intensity of the volume component [10] in order to improve the decomposition models for quantitative soil moisture analysis.

In this paper a Bragg surface scattering model is employed in the f_v-calculus to develop a physically constraint volume intensity component f_{vc}. Therefore the f_v-component is reformulated including a surface scattering mechanism α_b retrieved from the Bragg surface scattering model.

$$f_{vc} = \frac{4\left(T_{11} - T_{22} + \csc(2\alpha_b)^2 \sqrt{\left|(-T_{12} + T_{12}^* + (T_{12} + T_{12}^*)\cos(2\alpha_b))^2 \sin(2\alpha_b)^2\right|}\right)}{1 + 3\cos(2\alpha_v)} \quad (4)$$

In order to run the Bragg scattering model in a forward sense to obtain a α_b the incidence angle of the acquisition system θ as well as the average dielectric level ε_{est} of the scene must be included. As θ is known, ε_{est} must be estimated from the data.

Hence, the dominant alpha scattering angle α_1 is calculated from the data [4, p.98] and only the dominant surface scattering areas (α_1 < 25°) are taken for analysis. The calculus in Eq. 5 is done for a variety of ε_{est}-values (ε_{est} = {5,40}) leading to a collection of α_s-layers with different dielectric level ($\alpha_{s(f_{vc}(\varepsilon_{est}))}$). The mean-value of the difference between α_1 and the different α_s-layers, so called α_1-criterion, is evaluated to find the closest match for the appropriate average dielectric level ε_{est} as well as the fitting α_b, the fitting f_{vc} and the fitting surface scattering mechanism α_s for subsequent soil moisture inversion.

α_1-criterion:

$$\{mean(\alpha_1 - \alpha_{s(f_{vc}(\varepsilon_{est}))})\}_{\alpha_1<25°} \rightarrow 0 \quad \Rightarrow \varepsilon_{est} \quad \Rightarrow \alpha_b \quad \Rightarrow f_{vc} \quad \Rightarrow \alpha_s \quad (5)$$

It was proven that the influence of α_V cancels out of the soil moisture inversion procedure if the physically constraint volume component f_{vc} is applied within the hybrid decomposition. Thus the soil moisture inversion is by definition independent of the particle shape representing roughly the vegetation geometry of the volume elements.

In the following chapter the developed hybrid decomposition including the developed physically constraint volume intensity component f_{vc} is applied to the acquired polarimetric SAR data for soil moisture inversion under vegetation cover in agricultural areas.

3. EXPERIMENTAL RESULTS

The hybrid polarimetric decomposition and soil moisture inversion algorithm were applied on the data set of the OPAQUE campaign. The OPAQUE campaign was conducted in the beginning of May 2008

by the University of Potsdam, the University of Stuttgart, the German Research Centre for Geoscience (GFZ) and the German Aerospace Center (DLR) in the Weißeritz catchment area near Dresden, Germany [11]. The OPAQUE campaign studies operational discharge and flooding predictions in head catchments and aims to reduce the uncertainties in flood forecasting and prediction of rainfall-runoff processes by identifying critical catchment states caused by saturated soil layers. The test site features a pronounced and fast changing topography.
Within this campaign full-polarimetric L-band data were acquired by DLR's airborne E-SAR system. Simultaneously to the overflights, soil moisture and vegetation parameters were measured on selected test fields with a great variety of different crop and soil types to characterize the soil and the biomass layer.

3.1. Hybrid Polarimetric Decomposition

Fig. 1 illustrates exemplarily the surface (α_s) and dihedral (α_d) scattering mechanisms for 8th of May 2008 retrieved by the hybrid decomposition described in chapter 2 including a physically constraint volume intensity component f_{vc} with ε_{est}=18.
A smooth and transient distribution of the scattering mechanisms over the scene, which follows the incidence angle conditions, indicates the natural and physically correct separation of the two scattering mechanisms by the orthogonality condition introduced in Chapter 2. Therefore the hybrid decomposition outperforms the classical model-based decomposition [3,4], because in the later case the non-dominant scattering mechanism has to be set to a pre-defined artificial value to keep the decomposition system analytically solvable [1,2].

Table 1: Estimated average dielectric level (ε_{est}-level) from the α_1-criterion of Eq. 5.

Date	ε_{est}-Level [-]
OPAQUE 08.5.2008 (master image)	18
OPAQUE 08.5.2008 (opposite image)	18

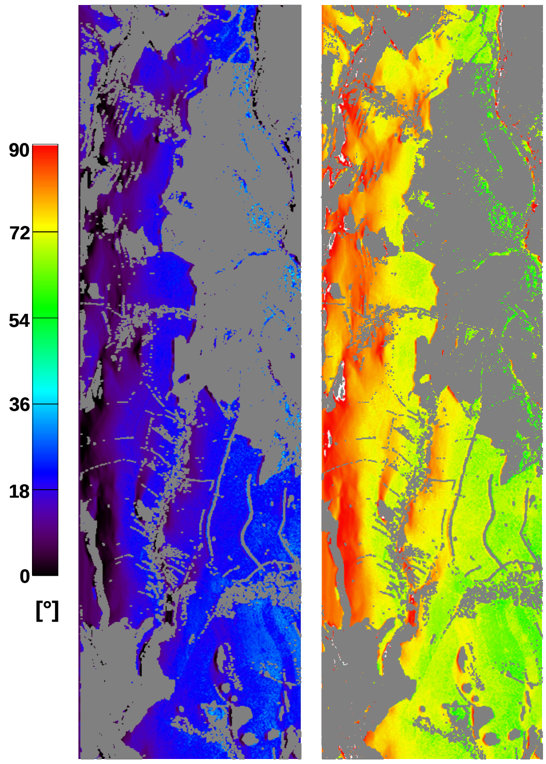

Figure 1: Surface (α_s) and dihedral (α_d) scattering mechanisms of 8th of May 2008 retrieved with the hybrid decomposition including the physically constraint volume intensity component f_{vc} with ε_{est}=18; Non-agricultural areas are masked grey.

The α_1-criterion for the determination of the appropriate ε_{est}-level (Eq. 5) indicated a clear minimum for the different acquisitions stating a stable performance over a wide range of topography and over a diversity in vegetation phenology.

3.2. Soil Moisture Inversion

After the retrieval of the appropriate surface and dihedral scattering mechanism (α_s, α_d) as depicted for the 8th of May 2008 in Fig. 1, the soil moisture can be inverted for both ground components. Hence, as the intensity of the volume component is specifically adapted using a Bragg scattering forward model, the inversion rate of the dihedral component revealed to be negligible and the investigations are not shown in this paper.
Fig. 2 displays the soil moisture maps inverted for the OPAQUE campaign, where the level of ε_{est} was obtained as described in chapter 2.1. The ε_{est}-levels are equal and correspond well with measured soil moisture data from the campaigns within the test site (cf. Tab. 1). The soil moisture ranges from 0Vol.% to 50Vol.%. White areas are masked due to non-physical results in the inversion process, while forested as well as urban areas are set to grey. In Tab. 2 the inversion rate is

reported for the two scenes respectively.

Table 2: Inversion rate, root mean square error (RMSE) and maximum of vegetation height for the different scenes covering a variety of crop types in different phenological stages.

Date	Inversion Rate [%]	RMSE [Vol.%]	Max. Vegetation Height [cm]
OPAQUE 08.5.2008 (master image)	98.17	7.41	82
OPAQUE 08.5.2008 (opposite image)	98.38	9.27	82

Compared to methods in [1,2,10] an almost complete and continuous inversion can be achieved with an inversion rate of more than 98% for all scenes including a wide range of incidence angles (cf. Fig. 2). This is a very favorable result for supporting run off simulations and flood forecasting models, where a whole catchment needs to be monitored continuously.
Therefore the volume component including the physical constraint (Eq. 4) seems to compensate the influence of the vegetation cover quite well, despite the diversity of different scattering scenarios. This leads to the consistent and continuous inversion results for the scenes depicted in Fig. 2.

4. VALIDATION OF SOIL MOISTURE ESTIMATION

Ground measurements of soil moisture were taken with FDR and gravimetric probes during the campaign for a quantitative analysis of the inversion. A box of 13x13 pixels was drawn around each measurement location to realize 169 looks for comparison. The resulting scatter plots of measured soil moistures on ground compared with estimated soil moistures from the developed approach are presented in Fig. 3 for the two different acquisition covering different incidence angle scenarios.
The performance of the developed algorithm is constantly on a high level resulting in an root mean square error (RMSE) between 7.4Vol.% and 9.3Vol.%, as shown in Tab. 2, for all land uses, while an investigation for different aspect angle was made. Therefore a ‘master’-scene (master) in descending mode and an ‘opposite’-scene (opposite) in ascending mode were processed for soil moisture inversion. The RMSE for the ‘opposite’-scene is significantly increased to 9.27Vol.% compared to 7.41Vol.% for the ‘master’-scene (cf. Fig. 3 and Tab. 2). The winter wheat (WW) field and the summer oat (SO) field are located on the edge of the flight strips (cf. Fig. 2). For the ‘opposite’-scene the soil moisture inversion overestimates for the winter wheat field (in near range) and underestimates for the summer oat field (in far range). The situation is reversed, but appears less pronounced, for the ‘master’-scene as can be analysed from Fig. 3.
Hence, a certain dependency on the local incidence angle especially in near range is already visible on the images of Fig. 2. Furthermore, the effect of incidence angle variability on soil moisture inversion under vegetation cover with polarimetric decompositions is studied to a greater extend in [12].

5. SUMMARY AND CONCLUSIONS

Fully polarimetric L-band SAR data were acquired by DLR’s E-SAR sensor together with ground measurements for the OPAQUE test site in Eastern Germany covering a variety of crop types as well as a plurality of topographical conditions. The hybrid polarimetric decomposition incorporating a physically constraint volume intensity component is developed and applied for inversion of soil moisture under vegetation cover. The approach is independent of a volume particle shape α_V and results in a physically meaningful separation of surface and dihedral scattering mechanisms using an orthogonality condition. The α_I-criterion to retrieve the appropriate ε_{est}-level (Eq. 5) indicated a clear minimum for the different acquisitions stating a stable performance over a wide range of topography and over a diversity in crop types (cf. Tab. 1). A continuous and consistent inversion of the surface scattering component is achieved for the two dates including diverse land uses on variable ground (cf. Fig. 4). The inversion rate remains always higher than 98%.
A quality assessment of the two scenes is carried out by a validation with FDR and gravimetric measurements. The RMSE-level ranges between 7.4Vol.% and 9.3Vol.% for the two scenes including a variety of vegetation types and different topographical conditions. However, the influence of the local incidence angle should be diminished using a regionalization approach for the α_I-criterion.

ACKNOWLEDGMENTS
The authors would like to thank the OPAQUE science teams for their contribution to the campaign and BMBF for supporting the activities.

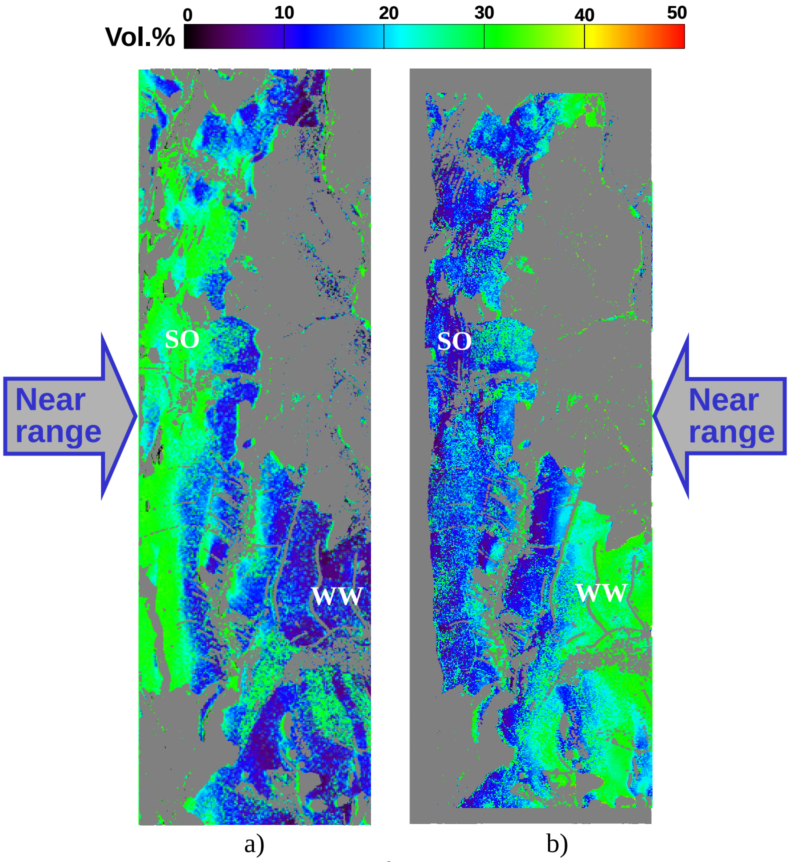

Figure 2: Result for soil moisture inversion in Vol.% for 8th of May 2008 with ε_{est}=18: a) OPAQUE campaign 'master'-image b) OPAQUE campaign 'opposite'-image; Forested and urban areas as well as areas without DEM-coverage in the 'opposite'-scene are masked grey; Invalid regions are masked white. Near range to far range are indicated with arrows on the image; SO= summer oat, WW=winter wheat.

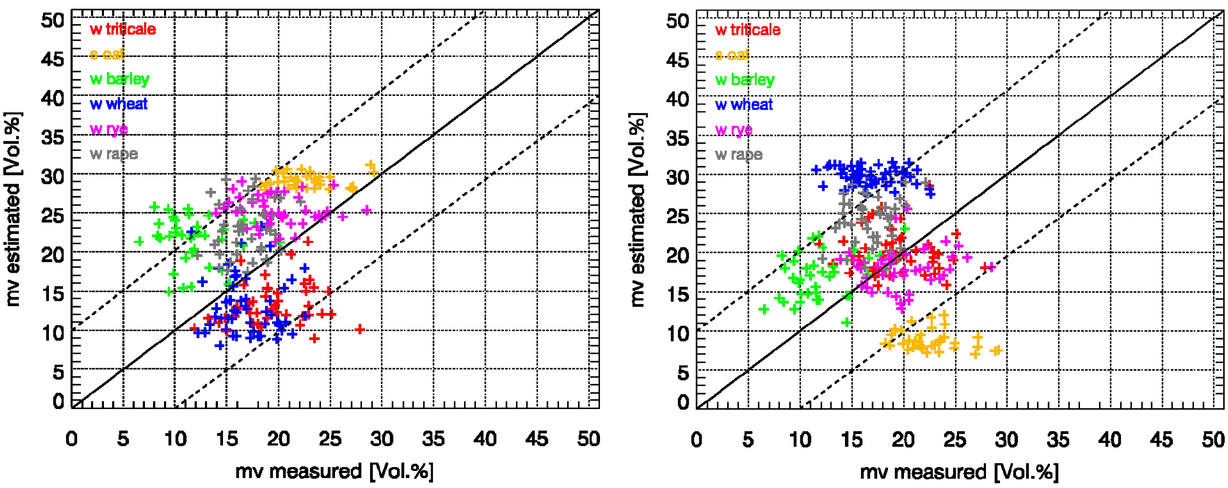

Figure 3: Scatter plots of measured soil moisture (mv) values from FDR and gravimetric probes against estimated soil moisture values from the proposed algorithm in Vol.% for a variety of land use types (winter wheat, winter rape, winter triticale, winter barley, winter rye, summer oat). Validation of OPAQUE 2008 campaign for different aspect angles at 8th of May: 'master'-scene (left) and 'opposite'-scene (right).

REFERENCES

1. Hajnsek, I., Jagdhuber, T., Schön, H. & Papathanassiou, K.P. (2009). Potential of Estimating Soil Moisture under Vegetation Cover by means of PolSAR, IEEE Trans. Geosci. Remote Sensing, 47(2), 442-454.
2. Jagdhuber, T., Schön, H., Hajnsek, I. & Papathanassiou, K.P. (2009): Soil Moisture Estimation under Vegetation applying Polarimetric Decomposition Techniques, Proc. of the 4th International Workshop on Science and Applications of SAR Polarimetry and Polarimetric Interferometry, Frascati, Italy, January 26-30, 1-8.
3. Cloude, S.R. & Pottier, E. (1996). A Review of Target Decomposition Theorems in Radar Polarimetry. IEEE Trans. Geosci. Remote Sensing, 34(2), 498-518.
4. Cloude, S.R. (2010). *Polarisation: Applications in Remote Sensing*, Oxford, Oxford University Press.
5. Jagdhuber, T., Hajnsek, I., Papathanassiou, K.P. & Bronstert, A. (2010). Estimation of Soil Moisture under Vegetation Cover applying a Hybrid Decomposition on Polarimetric SAR Data. Proc. of 1st European Conference on Moisture Measurement, Weimar, Germany, October 5-7, 203-211.
6. Lee, J.S. & Pottier, E. (2009). *Polarimetric Radar Imaging: From Basics to Applications*, Boca Raton, CRC Press.
7. Cloude, S.R. & Papathanassiou, K.P. (1999). Surface Roughness and Polarimetric Entropy. Proc. of IEEE International Symposium on Geoscience and Remote Sensing, June 28 – July 2, Hamburg, Germany, 2443-2445.
8. Van Zyl, J.J. (1992). Application of Cloude's target decomposition theorem to polarimetric imaging radar data. Radar Polarimetry, Vol. SPIE-1748, 184-212.
9. Topp, G.C., Davis, J.L. & Annan, A.P. (1980). Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines. Water Resources Res., 16(3), 574-582.
10. Jagdhuber, T. & Hajnsek, I. (2010). Model-based inversion of Soil Parameters under Vegetation using Ground-to-Volume Ratios, Proc. of 8th European Conference on Synthetic Aperture Radar (EUSAR), Aachen, Germany, June 7-10, 495-498.
11. Jagdhuber, T. & Hajnsek, I. (2009). OPAQUE 2008: Kampagnen- und Prozessierungsbericht. DLR-report, Oberpfaffenhofen, Germany.
12. Jagdhuber, T. Hajnsek, I., Papathanassiou, K.P. & Bronstert, A.. Soil Moisture Estimation under Vegetation Cover using a Multi-angular Polarimetric Decomposition. IEEE Trans. Geosci. Remote Sensing, submitted.