Model-based Inversion of Soil Parameters under Vegetation using Ground-to-Volume Ratios

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Abstract

An innovative model-based inversion of soil moisture and soil roughness under vegetation cover is developed using polarimetric ratios from the X-Bragg model and the modified three component decomposition. Normalized ground-to-volume ratios are incorporated for a substantial improvement of the estimation for soil parameters by splitting the cross-polarized scattering component S_{XX} into a roughness and a vegetation contribution. Results for soil moisture and soil roughness estimation under a variety of vegetation types covering the vegetation growth period are presented for the multi-temporal L-band data set of the AgriSAR campaign conducted in 2006. For the soil roughness and the soil moisture a root mean square error for all investigated dates and crop types of 0.1 and 6.7Vol.% is achieved. Despite the promising results for inversion of the soil parameters the standard deviation of the inversion estimates report a significant uncertainty, which has to be further investigated.

1 Introduction

Since most of the year agricultural areas are covered with vegetation in temperate latitudes, estimated soil moisture and soil roughness parameters for support of hydrological or ecological models has to account for this additional contribution. Therefore a modified three component scattering decomposition has been recently developed for soil moisture estimation under vegetation cover [1-3]. However a better characterization of the volume layer is still an active area of research and is revised and reformulated in this paper.
The cross-polarized component S_{XX} is characterized by a mixed scattering response of the vegetation cover and the soil roughness depending on the density of the vegetation and the radar wavelength. Hence a criterion derived directly from the polarimetric data for splitting the cross-polarized component into a roughness and vegetation contribution is highly desirable. Normalized ground-to-volume (g-to-v) scattering power ratios are an excellent criterion to approach this problem.

2 Model-based inversion of soil parameters under vegetation

A first method for separating ground components from vegetation has been already published and can be found under [2,3]. In order to adapt and improve all methods in terms of an inversion under vegetation cover normalized ground-to-volume ratios are incorporated. The normalized ground-to-volume ratios are based on the three power components (P_1, P_2, P_3) of the Pauli-decomposition.

Odd bounce: $$P_1 = \frac{1}{2}\left\langle \left|S_{HH} + S_{VV}\right|^2 \right\rangle \quad (1)$$

Even Bounce: $$P_2 = \frac{1}{2}\left\langle \left|S_{HH} - S_{VV}\right|^2 \right\rangle \quad (2)$$

Volume: $$P_3 = 2\left\langle \left|S_{XX}\right|^2 \right\rangle \quad (3)$$

Normalized ground–to–volume ratios:

Surface-to-volume ratio: $$\omega = \frac{P_1 - P_3}{P_1 + P_3} \quad (4)$$

Dihedral-to-volume ratio: $$\psi = \frac{P_2 - P_3}{P_2 + P_3} \quad (5)$$

Combined ratio: $$\zeta = \frac{P_1 + P_2 - 2P_3}{P_1 + P_2 + 2P_3} \quad (6)$$

Figure 1 displays the surface and dihedral g-to-v ratio for the 19th of April, where volume scattering indicates a g-to-v ratio close to zero and pure ground scattering a ratio close to one. However the model-based polarimetric ratios are derived from the ground coherency matrix $[T_G]$. This matrix is retrieved after subtraction of a model-based vegetation/volume component of the coherency matrix $[T_V]$, which is calculated in terms of fv and c_1-c_4 according to [3], from the acquired data $[T_{DAT}]$ as presented in (7).

$$T_G = T_{DAT} - T_V$$
$$\begin{bmatrix} T_{11G} & T_{12G} & 0 \\ T_{12G}^* & T_{22G} & 0 \\ 0 & 0 & T_{33G} \end{bmatrix} = \quad (7)$$
$$\begin{bmatrix} T_{11} & T_{12} & 0 \\ T_{12}^* & T_{22} & 0 \\ 0 & 0 & T_{33} \end{bmatrix} - fv \begin{bmatrix} c_1(1-\omega) & c_4(1-\zeta) & 0 \\ c_4(1-\zeta) & c_2(1-\psi) & 0 \\ 0 & 0 & c_3 \end{bmatrix}$$

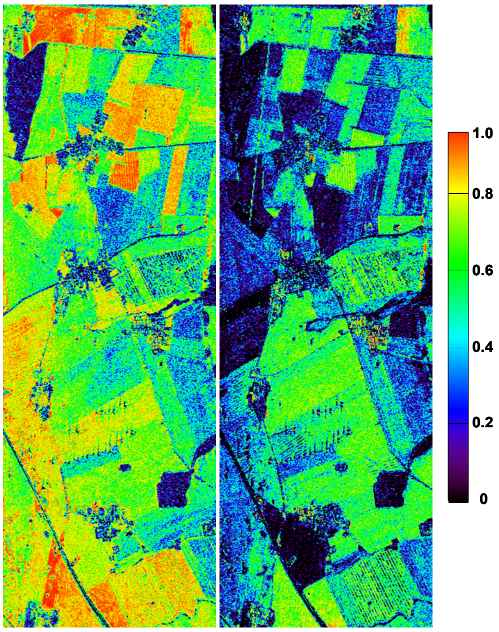

Figure 1 Normalized ground-to-volume ratios for the 19th of April (left: surface-to-volume ratio, right: dihedral-to-volume ratio)

2.1 Surface roughness retrieval under vegetation

From [4], a ratio of the coherency matrix elements can be defined as (8), which depends according to the X-Bragg model only on the surface roughness (δ) for bare soils:

$$\mathrm{sinc}(4\delta) = \frac{T_{22} - T_{33}}{T_{22} + T_{33}} \tag{8}$$

After eliminating the volume contribution from the T_{22} element (T_{22G}) and taking only the part of the measured T_{33} element, which is due to the soil roughness derived by (5), the ratio can be computed for an estimation of soil roughness under vegetation:

$$\mathrm{sinc}(4\delta) = \frac{T_{22G} - \psi \cdot T_{33}}{T_{22G} + \psi \cdot T_{33}} \tag{9}$$

The surface roughness expressed as ks, which is a combination of the wave number (k) and the standard deviation of the vertical roughness (s), is calculated by $ks = 2/\pi \cdot \delta$.

2.2 Soil moisture retrieval under vegetation

In the following three model-based polarimetric ratios are presented to retrieve soil moisture under vegetation. The first one is based on the X-Bragg model [4] after volume subtraction and the other two arise from the ground components of the modified three component decomposition [2,3]. Both ratios incorporate a T_{33}-component, which is split by the normalized g-to-v ratios into a soil roughness part and a vegetation volume part.

2.2.1 Ratio derived from the X-Bragg model

From [4], the polarimetric ratio derived from the X-Bragg model, which is sensitive to soil moisture and independent of roughness-induced depolarization on bare soils, is obtained from

$$\frac{|R_H - R_V|^2}{|R_H + R_V|^2} = \frac{T_{22} + T_{33}}{T_{11}} \quad , \tag{10}$$

where R_H and R_V are the horizontal and vertical Bragg coefficients.

Accounting for the influence of vegetation on the ratio and adapting the T_{33} element accordingly, the new polarimetric ratio without vegetation influence is defined as

$$\frac{|R_H - R_V|^2}{|R_H + R_V|^2} = \frac{T_{22G} + \zeta \cdot T_{33}}{T_{11G}} \quad . \tag{11}$$

2.2.2 Ratio derived from surface component of the modified three component decomposition

In [2,3] a polarimetric ratio from the surface component of the modified three component decomposition is introduced for estimation of soil moisture under vegetation cover incorporating also a roughness term (δ):

$$\frac{R_H - R_V}{R_H + R_V} = \frac{T_{12} - c_4 fv}{(T_{11} - c_1 fv) \cdot \mathrm{sinc}(2\delta)} \tag{12}$$

In (12) some volume scattering ($c_x fv$) is already considered by the modified three component decomposition, but the fv element is not explicitly separated into a vegetation volume part and a soil roughness part. This is done in the following equation (13), where only the vegetation volume part of fv is subtracted from the T_{11} and T_{12} elements using (4) and (6):

$$\frac{R_H - R_V}{R_H + R_V} = \frac{T_{12G}}{T_{11G} \cdot \mathrm{sinc}(2\delta)} \tag{13}$$

2.2.3 Ratio derived from dihedral component of the modified three component decomposition

Similar to the surface component, there is also the possibility to invert the soil moisture from the dihedral scattering component of the model-based decomposition as shown in [2,3].

$$\frac{|L_S|^2}{2} \left| R_{SH} R_{TH} + R_{SV} R_{TV} e^{i\varphi} \right|^2 = T_{22} - c_2 fv \tag{14}$$

$$\frac{R_{SH} R_{TH} - R_{SV} R_{TV} e^{i\varphi}}{R_{SH} R_{TH} + R_{SV} R_{TV} e^{i\varphi}} = \frac{T_{12} - c_4 fv}{T_{22} - c_2 fv} \tag{15}$$

R_{SH}, R_{SV} and R_{TH}, R_{TV} are the Fresnel coefficients for the surface and the trunk components respectively. L_S symbolises a roughness loss factor, which is estimated from the result of (9) (cf. [2] for details on L_S). After splitting the cross-component in a roughness and a vegetation volume part (14) and (15) are redefined:

$$\frac{|L_S|^2}{2}\left|R_{SH}R_{TH}+R_{SV}R_{TV}e^{i\varphi}\right|^2=T_{22G} \qquad (16)$$

$$\frac{R_{SH}R_{TH}-R_{SV}R_{TV}e^{i\varphi}}{R_{SH}R_{TH}+R_{SV}R_{TV}e^{i\varphi}}=\frac{T_{12G}}{T_{22G}} \qquad (17)$$

In this way all components for soil moisture retrieval under vegetation are calculated using only the vegetation part of the cross-polarized component for separation of vegetation from the ground components.

3 Experimental results

The approach was applied on fully polarimetric L-band data acquired as part of the AgriSAR campaign conducted over four months covering the entire vegetation growth period of 2006 [5]. A European team consisting of 16 institutions performed the campaign, unique in scope and scale, to generate an image and ground database for examination and validation. The test site is located in Northern Germany and offers a variety of different soil and crop types. SAR data have been acquired by DLR's Microwave and Radar Institute's airborne E-SAR system. Three acquisition dates (19.04., 07.06., 05.07.) from the beginning of the vegetation growth period in April to the end in July were selected for analysis.

3.1 Estimation of surface roughness under vegetation

Figure 2 shows the result for the soil roughness (*ks*) estimation with polarimetric ratios under vegetation for the 19th of April and the 5th of July 2006. It is seen in **Figure 2**, that the two levels of roughness values are similar, despite the fact that the vegetation cover was significantly different (vegetation height: Max. 20cm in April, max. 170cm in July). The similar results independent of the date indicate the potential of soil roughness estimation under a growing vegetation cover using the described approach. A validation of the estimated soil roughness values compared to the measured soil roughness values from stereo-photography using mean of crop type values is shown in **Figure 3**. A box of 13x13 pixels was drawn around each measurement location to realize 169 looks for comparison. The standard deviations of the roughness measurements are calculated from the different sampling locations for each crop type. The standard deviations of the estimated roughness are computed from the mean of the standard deviations retrieved from each box around the measurement location. The average Root Mean Square Error (RMSE) of the roughness estimation over all crop types and all dates is 0.098, whereas a high standard deviation (Δ_{ks}>0.2) must be stated. This occurs mainly for the winter rape, sugar beet and summer corn fields in July with a mature vegetation layer of 45-170cm and 2-6kg/m² wet biomass and denotes the uncertainty introduced in the retrieval by the distinct vegetation layer.

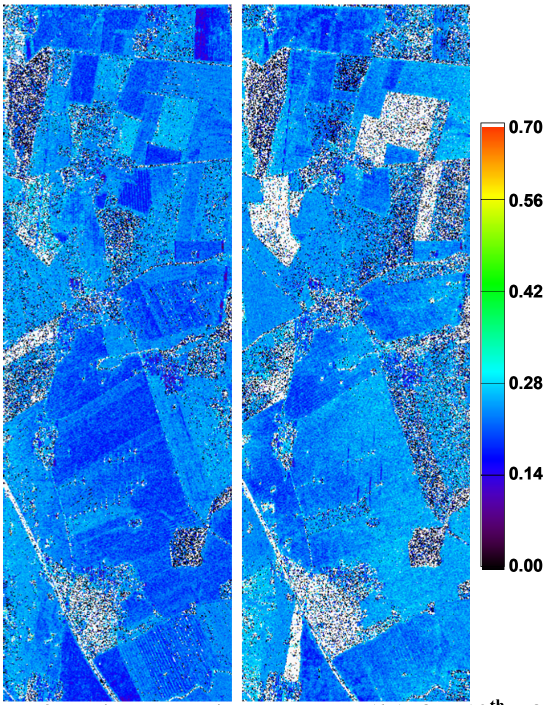

Figure 2 Estimated soil roughness (*ks*) for 19th of April (left) and 5th of July 2006 (right) ranging from 0 to 1 (Pixels with *ks* > 0.7 are masked white).

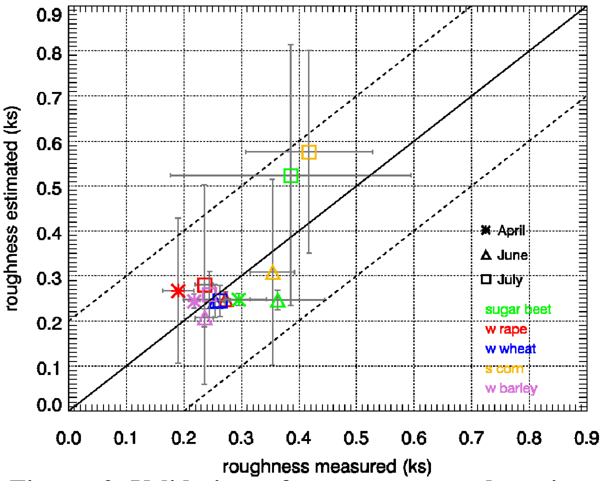

Figure 3 Validation of mean measured against mean estimated soil roughness values (*ks*) for the three acquisitions (April, June, July) and the different crop types (s=summer, w=winter); Grey bars indicate the measured and the estimated standard deviation for each crop type and each date.

3.2 Estimation of soil moisture under vegetation

Soil moisture was estimated according to the three methods introduced in 2.2. The roughness parameter (δ) was acquired from equation (9) as a pre-processing step and was incorporated in the soil moisture retrieval from the surface and the dihedral component (δ, L_S). The validation between measured and estimated soil moistures as mean of crop type values is shown in **Figure 4** for a variety of crops (sugar beet, winter rape, winter wheat and summer corn).

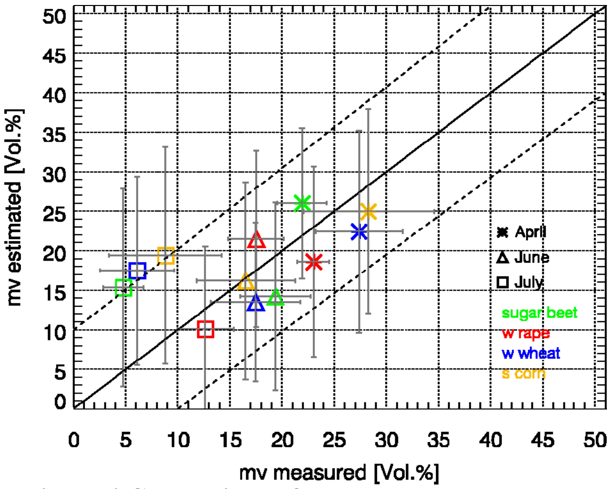

Figure 4 Comparison of mean measured and mean estimated soil moisture (mv) values in Vol.% for the three acquisitions (April, June, July) and a variety of crop types (w=winter, s=summer); Grey bars indicate the measured and the estimated standard deviation for each crop type and each date.

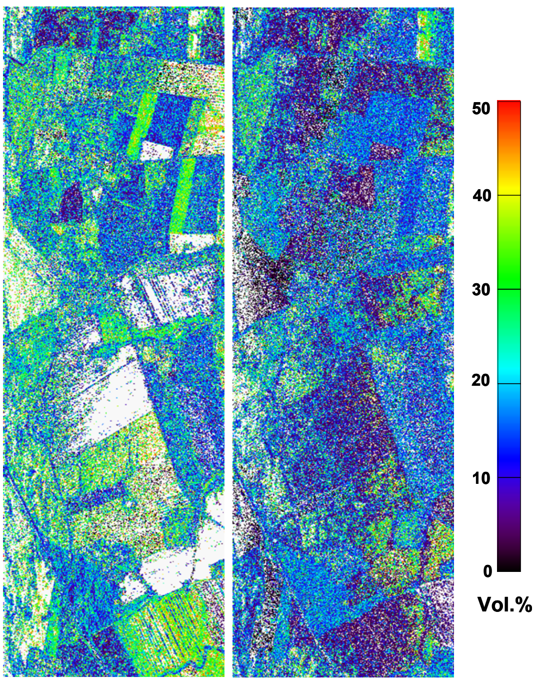

Figure 5 Estimated soil moisture in Vol.% for the 19th of April (left) and the 5th of July (right) (image smooth: 4x4).

The RMSE between the mean measured and the mean estimated values of the three acquisitions, which cover the entire vegetation growth period, results in 6.67 Vol.%. However the uncertainty of the method is also indicated by the standard deviation of the estimates having a two to three times higher level than the standard deviation of the measurements.

The soil moisture inversion results are depicted in **Figure 5** for the 19th of April and the 5th of July. The soil moisture ranges from 0 to 50Vol.% and non-invertible pixels are masked white. Hence, a distinct difference in soil moisture level is observed between the two dates (spring: 19.04., summer: 05.07.), which can also be confirmed by analysis of the ground measurements on the test fields (see **Figure 4**).

4 Summary

The developed approaches for soil roughness and soil moisture retrieval under vegetation cover were applied to the multi-temporal L-band AgriSAR data set of 2006. The results indicate a high potential in terms of soil roughness and soil moisture estimation under a variety of vegetation cover conditions (max. height: 170cm and max. wet biomass: 6kg/m²) over the whole growth period (April-July) as well as under different soil moisture conditions resulting in a RMSE of less than 0.1 for the estimation of soil roughness and a RMSE of less than 6.7Vol.% for the estimation of soil moisture. Despite the promising results for both soil parameters, the standard deviations of the inversion estimates report a significant uncertainty, which has to be further investigated.

Acknowledgment

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