SOIL MOISTURE RETRIEVAL FROM POLARIMETRIC SAR DATA: A SHORT REVIEW OF EXISTING METHODS AND A NEW ONE

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ABSTRACT

Soil moisture retrieval from SAR data is not an easy task, especially in presence of vegetation cover. Accordingly, in recent years several methods for soil-moisture retrieval under vegetation cover have been developed, relying on model-based or hybrid polarimetric target-decomposition techniques. However, most of these decomposition techniques suffer from the so-called negative-power problem, which is mainly related to poor modelling of surface- and/or volume-scattering contributions. In this paper we, first, analyse the Polarimetric Two-Scale Two-Component Model and the Iterative Generalized Hybrid Decomposition method, proposing a way to combine the estimation results of the methods so that most vegetation conditions can be accounted for. Then, we introduce a method that tries to solve the case of dominant surface scattering and non-negligible dihedral scattering, which is the case not covered by the abovementioned model combination. Meaningful estimation results are presented and discussed using polarimetric L-band SAR data of the AgriSAR 2006 campaign.

1. INTRODUCTION

Soil moisture retrieval from remote sensing data is very useful for a number of applications, and even specific missions have been devised to this aim. When high-resolution soil moisture maps are needed, use of polarimetric SAR data is the obvious choice. However, soil moisture retrieval from SAR data is not an easy task, especially in presence of vegetation cover, because the radar return depends not only on the soil dielectric constant (and hence soil moisture) but also on several other parameters describing soil roughness and vegetation. Accordingly, in recent years some methods for soil-moisture retrieval under vegetation cover have been developed [1]-[3]. They rely on model-based or hybrid polarimetric target-decomposition techniques. Many of these decomposition techniques, in their original formulations, suffer from the so-called negative-power problem, which is due, on one side, to poor modelling of surface scattering, so that the whole cross-polarization effect is attributed to volumetric scattering, which is thus overestimated; and, on the other side, to the poor modelling of the vegetation scattering contribution itself. The approach of [1] (named Polarimetric Two-Scale Two-Component Model, PTSTCM) focuses on the former problem and tries to solve it by using a more refined surface scattering model that accounts for de- and cross-polarization due to surface roughness; the price to be paid is the need of ignoring double-bounce contributions and still using a simplified vegetation scattering model. Conversely, the approach of [3] (named Iterative Generalized Hybrid Decomposition, IGHD) focuses on improving the modelling of vegetation scattering, at the cost of still using a simplified, non-depolarizing ground scattering model. It turns out that PTSTCM provides the best results for moderately vegetated fields (vegetation height lower than 50 cm, or cross-polarized ratio smaller than 0.1, and negligible double-bounce component [1]), whereas IGHD provides the best results in the other cases and shows a wider range of validity [3].

In this work we, first of all, recall and analyse the results of the above mentioned two methods, and outline a method to combine them by choosing pixel by pixel in an adaptive way the most suitable one. In practice, the combination of the two approaches can take into account most of the vegetation-cover conditions. The only critical situation is the case of dominant surface scattering and secondary, non-negligible, dihedral component. Therefore, we propose a method that tries to fill this gap, to be used when the co-polarized correlation coefficient is significantly smaller than unity and the cross-polarized ratio is very small, so that the decreased correlation coefficient is not justified by roughness or volumetric effects and it is most likely due to the dihedral component. In this case, we suggest that the more refined surface model of PTSTCM is preliminarily used to compute the volumetric component, so that the latter is not overestimated. Then, with this estimate of the volumetric component, soil moisture can be retrieved by recurring to one of the usual model-based or hybrid decompositions.

Meaningful soil-moisture retrieval results are provided using the AgriSAR 2006 dataset. In particular, results obtained via the new proposed method are compared to PTSTCM results, highlighting the obtained enhancement of performance.

2. COMBINATION OF PTSTCM AND IGHD

In this section we consider two models introduced for the retrieval of soil moisture under vegetation cover. The PTSTCM has been recently proposed by some of the authors and is suitable for moderate vegetation cover, i.e. for vegetation height not larger than 50 cm [1]. It is a two-

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component model in which the scattered field is modelled as the superposition of independent surface and volume scattering components. In particular, the former is modelled through the Polarimetric Two-Scale Model (PTSM) [4], whereas the vegetation layer covering the soil surface is modeled by a cloud of randomly oriented thin cylindrical scatterers [1], [5]. The rationale of the model is that in moderate vegetation-cover conditions an effective modelling of surface-scattering, taking into account de- and cross-polarizations effects, can be more important than an accurate modelling of volume scattering. Following this guideline, PTSTCM uses an accurate surface-scattering model at the expense of using a simple vegetation model and neglecting double-bounce scattering [1].

On the opposite side, the IGHD method [3] is conceived to iteratively enhance vegetation-scattering modelling, at the expense of considering a simplified surface-scattering model. Therefore, this method is particularly well suited for high vegetation cover, where vegetation and/or dihedral scattering are expected to be dominant. Moreover, IGHD provides a rather wide range of validity [3].

Based on the above considerations, we here propose to combine the estimation results obtained via the two models by choosing pixel by pixel in an adaptive way the more suitable one, based on the values of the cross-polarized ratio (or, if known, of the vegetation height) and on the signum of the real part of the co-polarized correlation [1]. In particular, if the cross-polarized ratio is smaller than 0.1 and the real part of the HH-VV correlation is positive, then the PTSTCM must be used first: if retrieval is successful, the obtained value is the desired output; otherwise, IGHD must be used. If the cross-polarized ratio is larger than or equal to 0.1 and smaller than 0.15, and the real part of the HH-VV correlation is positive, then both methods must be used: if both are successful, then the output is computed as the average of the two retrieved values; otherwise, the output is the retrieved value of the successful method, if any. Finally, if the cross-polarized ratio is larger than or equal to 0.15 or the real part of the HH-VV correlation is negative, the IGHD must be used first: if retrieval is successful, the obtained value is the desired output; otherwise, PTSTCM must be used.

The combination of the two approaches covers most of the potential vegetation conditions. The only critical situation is the case of dominant surface scattering and secondary, non-negligible, dihedral component, i.e. those cases in which both the cross-polarized ratio and the real part of the HH-VV correlation are very small. To try to fill this gap, in the next section we propose a method based on the preliminary estimation of the volume scattering component through PTSTCM.

3. PROPOSED METHOD

When the co-polarized correlation coefficient is significantly smaller than unity and the cross-polarized ratio is very small, the decrease of the correlation coefficient is not justified by roughness or volumetric effects and, thus, it is most likely due to the presence of a non-negligible dihedral component. In this kind of situations, we propose to perform a preliminary estimation of the volumetric component via the PTSTCM model, thus exploiting its accurate modelling of the surface component. In particular, we note that the PTSTCM retrieval method in its original form does not perform the explicit estimation of the surface and volumetric components. However, both of them can be evaluated once the estimates of the relative permittivity ε and of the standard deviation σ of the large-scale roughness are obtained, as reported in [1]. In particular, in [1] it is also shown that in order to avoid the “negative power” problem for the surface component the cross-polarized ratio must be less than 0.3. This condition is usually not violated in moderately vegetated flat areas; anyway, when this condition is violated the PTSTCM provides no estimation result. This means that for PTSTCM the “negative power” problem does not occur for the surface component. However, it can occur for the volumetric one. In [1] it is shown that to avoid this a condition on the maximum value σ_{max} allowed for σ should be enforced. In these cases, the PTSTCM soil-moisture estimation can be repeated setting the volumetric component to 0 and σ to σ_{max}.

Once the value of the volumetric component $\hat{f}_v|_{PTSTCM}$ estimated via PTSTCM is obtained, we can exploit it within model-based or hybrid decompositions methods in order to retrieve the soil moisture. In particular, we can consider a three-component model, in which the returns are assumed to be the sum of three independent contributions related to surface, volume and double bounce [5]. We model the surface scattering via SPM, the double-bounce via a dihedral corner reflector model; the volumetric component is assumed to be $\hat{f}_v|_{PTSTCM}$. Therefore, we obtain for the elements of the covariance matrix:

$$\begin{cases} \langle |S_{hh}|^2 \rangle = f_s|\beta|^2 + f_d|\alpha|^2 + \hat{f}_v|_{PTSTCM} \\ \langle |S_{vv}|^2 \rangle = f_s + f_d + \hat{f}_v|_{PTSTCM} \\ \langle S_{hh}S_{vv}^* \rangle = f_s\beta + f_d\alpha + \frac{\hat{f}_v|_{PTSTCM}}{3} \\ \langle |S_{hv}|^2 \rangle = \frac{\hat{f}_v|_{PTSTCM}}{3} \end{cases} \tag{1}$$

where S_{vv}, S_{hh} and S_{hv} are the scattering matrix elements, with h and v standing for horizontal and vertical polarizations, respectively, the symbol $\langle \cdot \rangle$ stands for “statistical mean”, the asterisk * stands for "complex conjugate", f_s and f_d are the surface and double-bounce contributions respectively, β is a real (at least at microwave frequencies) parameter that depends on the dielectric permittivity and

$$\alpha = e^{j2(\gamma_h - \gamma_v)} \left(\frac{R_{th}R_{gh}}{R_{tv}R_{gv}} \right) \quad (2)$$

Assuming that surface scattering is the dominant mechanism, i.e. that α=–1 [5], and noting that the last equation in (1) is not necessary, we can recast the equations as

$$\begin{cases} \langle |S_{hh}|^2 \rangle - \hat{f}_v|_{PTSTCM} = f_s|\beta|^2 + f_d \\ \langle |S_{vv}|^2 \rangle - \hat{f}_v|_{PTSTCM} = f_s + f_d \\ \langle S_{hh}S_{vv}^* \rangle - \frac{\hat{f}_v|_{PTSTCM}}{3} = f_s\beta - f_d \end{cases} \quad (3)$$

Therefore, we have now three real equations in three real unknowns (f_s, f_d and β).

To devise an algorithm for the retrieval of the soil moisture we can now reason in a way similar to the one used for the definition of the modified co-polarized ratio in the case of PTSTCM [1]. In particular, in order to cancel out the dependence on the double-bounce component, we can define a new modified co-pol ratio as follows:

$$Copol_{mod} = \frac{\langle |S_{hh}|^2 \rangle + \langle S_{hh}S_{vv}^* \rangle - \frac{4}{3}\hat{f}_v|_{PTSTCM}}{\langle |S_{vv}|^2 \rangle + \langle S_{hh}S_{vv}^* \rangle - \frac{4}{3}\hat{f}_v|_{PTSTCM}} \quad (4)$$

which provides

$$Copol_{mod} = \beta = \frac{R_H(\varepsilon,\vartheta)}{R_V(\varepsilon,\vartheta)} \quad (5)$$

where R_H and R_V are the Fresnel coefficients for the horizontal and vertical polarizations, respectively. Therefore, (5) can be used to estimate ε and, hence, the volumetric soil moisture.

A block diagram of the proposed method is provided in Fig. 1. It is roughly made up of three steps. In the first step PTSTCM is used to estimate ε and σ, and in the second step these estimates are used, in turn, to estimate f_v. The obtained f_v value is then checked for the "negative power" problem, and, if necessary, a new ε is estimated, upon setting f_v=0 and σ=σ_{max}. Step three starts with a check on the values of cross-polarized ratio and of the real part of the co-polarized correlation coefficient: if the cross-polarized ratio is smaller than 0.1 and the real part of the co-polarized correlation is smaller than 0.75, the f_v estimated in step two is used to implement the method proposed in this paper; otherwise, the PTSTCM estimate is provided as output.

Note that in this section we have considered only the combined use of PTSTCM and the new three-component method, i.e. we have not considered the combination with IGHD. However, the use of IGHD could be easily introduced, simply adding further checks on the values of the cross-polarized ratio and of the real part of the co-polarized correlation, following the guidelines suggested in Section 2.

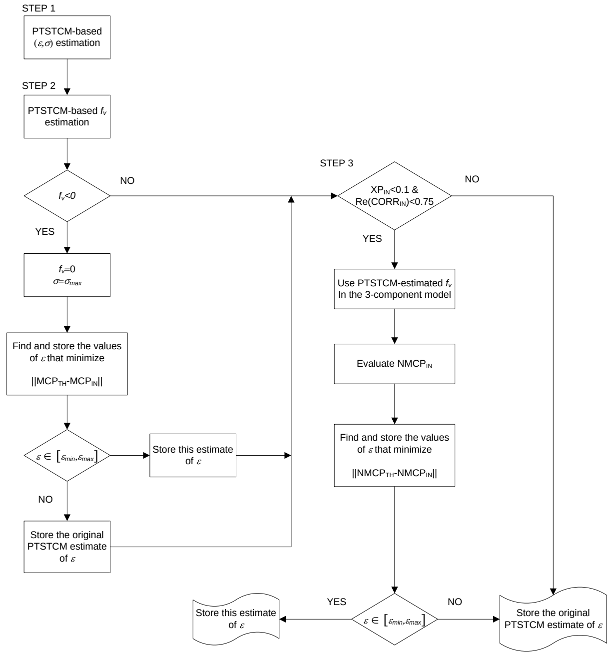

Figure 1. Block diagram of the proposed method. MCP_{IN} and $NMCP_{IN}$ are the input modified co-polarized ratios measured from SAR data for the PTSTCM and the new proposed method, respectively; MCP_{TH} and $NMCP_{TH}$ are their theoretical values. XP_{in} and $CORR_{in}$ are the cross-polarized ratio and the co-polarized correlation measured from SAR data. Finally, ε_{min}=2.5 and ε_{max}=40.

4. EXPERIMENTAL RESULTS

In this section we evaluate the performance of the proposed technique with SAR data acquired in the framework of the 2006 AgriSAR campaign [6]. In this context multifrequency SAR, optical and ground data over a whole vegetation-growing period were acquired in the site of Demmin in northern Germany. In particular, in this study we use L-band quad-polarimetric SAR data acquired by the DLR airborne experimental SAR (E-SAR) system.

Simultaneously to SAR acquisitions, a wide set of ground data was collected, regarding vegetation phenology, terrain conditions, precipitations and volumetric soil moisture. Among them, also the soil water content was measured with different techniques and different time-sampling scenarios. The area of interest is characterized by the presence of several crop types: in this work we studied the soil moisture behaviour of fields of sugar beet, wheat, winter barley, winter rape, and corn.

The retrieval procedure was applied on the available geocoded L-band quad-polarimetric images. In particular, we use here East-West SAR passes. The original pixel spacing of the data is 2 m x 2 m and, following a preliminary multilook step, it is degraded to 20 m x 20 m. Then we estimate ε and σ following the procedure described in Fig. 1. Finally, the retrieved values are converted into volumetric moisture m_v using the mixing model in [7], considering that the soil in the Demmin area consists mostly of loamy sand, with percentages of sand and clay of 68% and 7%, respectively [2].

We show the results for three different periods of the year. In the first period (April 19-May 16, 2006) the vegetation was mostly in an early stage of growth and its average height was low. In the second one (May 24-June 13, 2006) the various crop types were in an intermediate stage of growth, presenting significant average heights in many cases. Finally, in the last period (June 21-August 2, 2006) the vegetation was in an advanced stage of growth, with heights larger than one meter in most cases.

For the different periods we compare the results obtained using the PTSTCM method with vegetation modelled through dipoles with random uniformly distributed orientations and those obtained via the newly proposed method. In particular, in Fig. 2 we report the scatterplots for the different periods and for the two considered methods. Moreover, the quantitative measures of performance are reported in Tab. I: the mean error (ME) on water volume percentage (vol.%), the root mean square error (RMSE), the correlation coefficient (ρ) between in situ and retrieved volumetric soil moisture, and the number N of fields for which inversion is successful for all of the acquisition dates of the considered period. The total number of fields considered in this study is 13.

From the results in Fig. 2 and Tab. 1, it can be concluded that, as expected, the proposed method provides some improvement over PTSTCM mainly in the last two periods, when the double-bounce contribution is significant. However, the estimation results are still not satisfactory. This is probably due to the use of the very simple three-component model of (1). In some cases, the results could be improved through the combined use of the proposed method with IGHD discussed in Section 2.

5. CONCLUSION

In this paper, we discussed the potentials of retrieving the volumetric soil moisture using polarimetric SAR data. We highlighted how the PTSTCM method is a good candidate for the case of moderate vegetation, when surface scattering still represents the dominant component. Conversely, IGHD is a good candidate in case of dominant vegetation or double-bounce scattering. Therefore, we suggested a way to combine pixel by pixel the results of the methods. Finally, we proposed a retrieval method suitable for the case of dominant surface scattering component and secondary, non-negligible, dihedral one.

6. REFERENCES

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Table 1. Performance indicators.

	I Period (April 19-May 16,2006) Early stage of growth				**II Period (May 24-June 13,2006) Intermediate stage of growth**				**III Period (June 21-August 2,2006) Advanced stage of growth**			
	ME [vol.%]	RMSE [vol.%]	ρ	N	ME [vol.%]	RMSE [vol.%]	ρ	N	ME [vol.%]	RMSE [vol.%]	ρ	N
PTSTCM	-4.4	9.1	0.64	12	-0.2	12.0	0.10	9	12.0	17.0	0.11	10
Proposed method	-2.8	11.2	0.31	9	-3.0	10.3	0.22	6	10.9	13.2	0.28	10

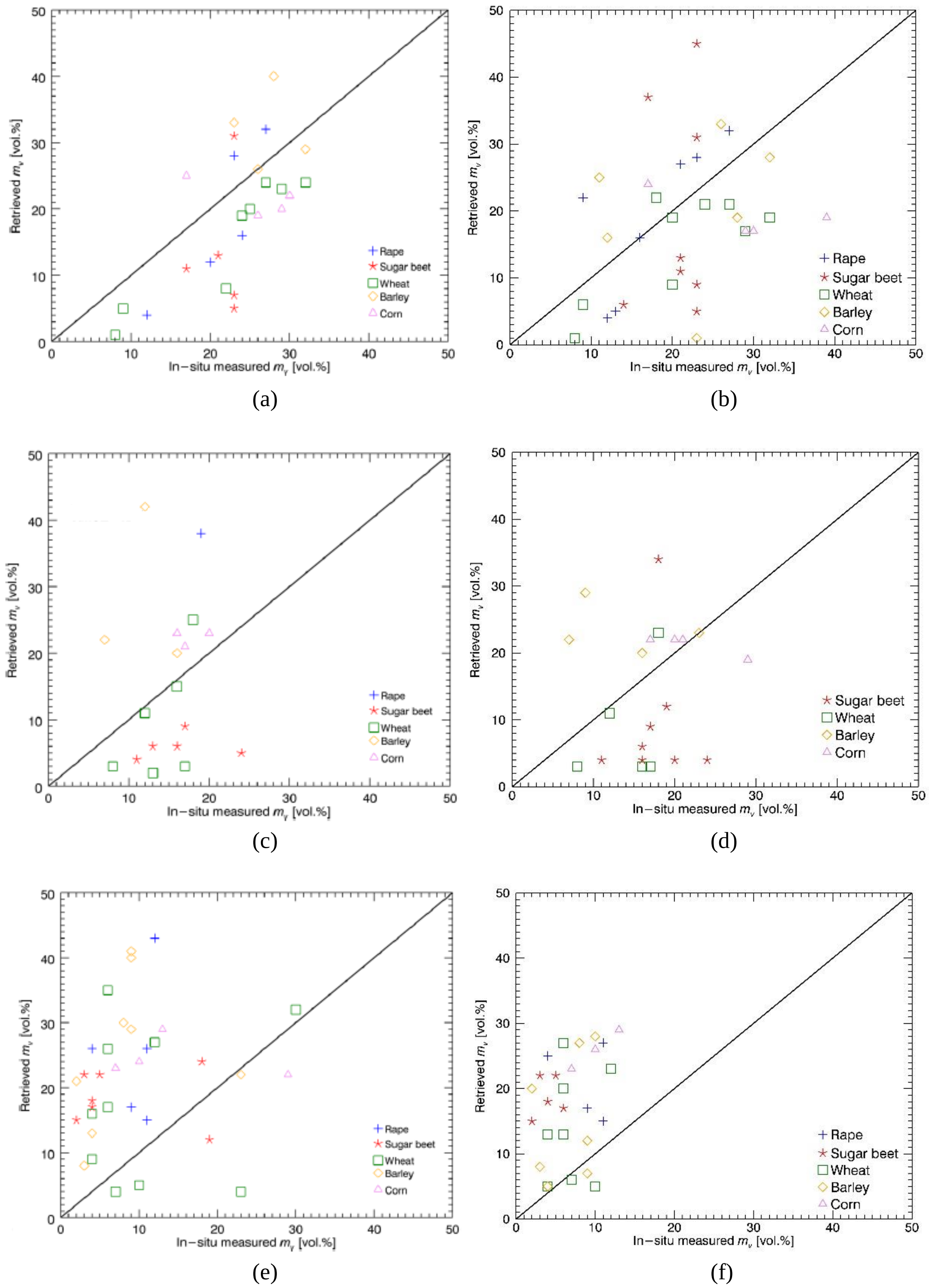

Figure 2. Scatterplots of the retrieval results versus measured ground truth. (a), (c), (e) PTSTCM with vegetation modelled through dipoles with random uniformly distributed orientations. (b), (d), (f) Proposed method. (a), (b) First period. (c), (d) Second period. (e), (f) Third period.