EXPLORING THE VALIDITY RANGE OF THE POLARIMETRIC TWO-SCALE TWO-COMPONENT MODEL FOR SOIL MOISTURE RETRIEVAL BY USING AGRISAR DATA

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ABSTRACT

The recently proposed polarimetric two-scale two-component model (PTSTCM) in principle allows us obtaining a reasonable estimation of the soil moisture even in moderately vegetated areas, where the volumetric scattering contribution is non-negligible, provided that the surface component is dominant and the double-bounce component is negligible. Here we test the PTSTCM validity range by applying it to polarimetric SAR data acquired on areas for which, at the same times of SAR acquisitions, ground measurements of soil moisture were performed. In particular, we employ the AGRISAR'06 database, which includes data from several fields covering a period that spans all the phases of vegetation growth.

1. INTRODUCTION

In recent years considerable effort has been spent by the scientific community for research on soil moisture retrieval from multi-angle, -frequency or -polarization Synthetic Aperture Radar (SAR) data [1]. In particular, to this aim we proposed a Polarimetric Two-Scale Model (PTSM) [2-3] able to predict the second order statistics of the scattering matrix relevant to bare soils. Based on this model, we developed a retrieval algorithm able to get both soil moisture and ground roughness exploiting measured co-pol and cross-pol ratios [2], or the co-pol ratio and the HH-VV correlation coefficient [3]. Then, in order to account for the presence of a moderate vegetation, we inserted the PTSM in a two-component scattering model, so obtaining a polarimetric two-scale two-component model (PTSTCM); based on it, we developed a modified retrieval algorithm able to remove the (secondary) volume scattering contribution [4,5]. In particular, we used the PTSM to describe the surface scattering component, and a randomly oriented thin dipole model [6] to describe the volume scattering contribution from the vegetation layer which covers the scattering surface. We have shown that suitable combinations of the Normalized Radar Cross Section (NRCS) and HH-VV correlation, that we term "modified co-polarized ratio" and "modified HH-VV correlation coefficient", are related only to the surface parameters, because volumetric contribution cancels out. This in principle allows us obtaining a reasonable estimation of the soil moisture even in moderately vegetated areas, where the volumetric scattering contribution is non-negligible. In the present work, we first of all extend the employed volume scattering model by using not only a uniform distribution of dipole orientation, as in [4,5], but also a prevalently vertical or prevalently horizontal distribution. In addition, we test the PTSTCM by applying it to polarimetric SAR data acquired on areas for which, at the same times of SAR acquisitions, ground measurements of soil moisture were performed. In particular, we employ the large AGRISAR [7] database, which includes data from several fields covering a period that spans all the phases of vegetation growth. Results of PTSTCM are also compared with those of available three-component methods (3CMs) [8,9] employing more simplified surface scattering models.

2. THEORY

In order to get reliable soil moisture estimates not only in those areas for which the surface scattering is practically the only present scattering mechanism, we consider a two-component approach, in which the scattered field is modeled as the superposition of independent surface and volume scattering components. In particular, the former is modeled by using the PTSM [2],[3] and the vegetation layer which covers the soil surface is modeled by a cloud of randomly oriented thin cylindrical scatterers, whose scattering is described in [6],[10]. By assuming that, as it is reasonable, surface and volume scattering components are independent, the covariance matrix of a vegetated soil can be expressed as

$$\begin{cases} \left\langle \left|S_{vv}\right|^2 \right\rangle \cong s_0^2 f_s(\varepsilon, H_t)\left(1-\delta_V(\varepsilon)\sigma^2\right) + A\, f_v(\mathbf{u}) \\ \left\langle \left|S_{hh}\right|^2 \right\rangle \cong s_0^2 f_s(\varepsilon, H_t)\left|\beta_r(\varepsilon)\right|^2\left(1+\delta_H(\varepsilon)\sigma^2\right) + B\, f_v(\mathbf{u}) \\ \left\langle S_{hh}S_{vv}^* \right\rangle \cong s_0^2 f_s(\varepsilon, H_t)\beta_r(\varepsilon)\left(1+\delta_{HV}(\varepsilon)\sigma^2\right) + C\, f_v(\mathbf{u}) \\ \left\langle \left|S_{hv}\right|^2 \right\rangle \cong s_0^2 f_s(\varepsilon, H_t)\,\delta_X(\varepsilon)\sigma^2 + C\, f_v(\mathbf{u}) \end{cases} , \quad (1)$$

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

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"statistical mean", the asterisk * stands for "complex conjugate",

$$f_s(\varepsilon, H_t) = k^4 \cos^4 \vartheta \left| F_V(\vartheta;\varepsilon) \right|^2 \; W_n\left(2k \sin\vartheta; H_t\right) \quad , \qquad (2)$$

$k=2\pi/\lambda$ is the wavenumber, $W_n(\cdot)$ is the normalised power spectral density (PSD) of the small-scale roughness, whose expression is reported in [2], $F_V(\vartheta_l,\varepsilon)$ and $F_H(\vartheta_l,\varepsilon)$ are the Bragg coefficients for vertical and horizontal polarizations [2], that depend on the soil relative permittivity ε,

$$\beta_r(\varepsilon) = \frac{F_H(\vartheta;\varepsilon)}{F_V(\vartheta;\varepsilon)} \quad , \qquad (3)$$

$$\delta_X(\varepsilon) = \frac{\left|1-\beta_r(\varepsilon)\right|^2}{\sin^2(\vartheta)} \quad , \qquad (4)$$

the full expressions of the other second order coefficients $\delta_V(\varepsilon)$, $\delta_H(\varepsilon)$, $\delta_{HV}(\varepsilon)$ can be obtained from [2, 3], and finally A=B=1 and C=1/3 for uniform dipole orientation, A=1, B=3/8 and C=1/4 for prevalently vertical dipole orientation, and A=3/8, B=1 and C=1/4 for prevalently horizontal dipole orientation.

The polarimetric channels can be combined in such a way to cancel out the vegetation contribution and to recover independence on small-scale roughness. In particular, we define a "modified co-polarized ratio" and a "modified co-polarized correlation coefficient" as follows

$$\begin{cases} Copol_{\mathrm{mod}} = \dfrac{\left\langle |S_{hh}|^2 \right\rangle - \dfrac{B}{C}\left\langle |S_{hv}|^2 \right\rangle}{\left\langle |S_{vv}|^2 \right\rangle - \dfrac{A}{C}\left\langle |S_{hv}|^2 \right\rangle} \\ Corr_{\mathrm{mod}} = \dfrac{\left| \left\langle S_{hh}S_{vv}^* \right\rangle - \left\langle |S_{hv}|^2 \right\rangle \right|}{\sqrt{\left(\left\langle |S_{hh}|^2 \right\rangle - \dfrac{B}{C}\left\langle |S_{hv}|^2 \right\rangle \right)\left(\left\langle |S_{vv}|^2 \right\rangle - \dfrac{A}{C}\left\langle |S_{hv}|^2 \right\rangle \right)}} \end{cases} . \qquad (5)$$

In fact, use of (1) in (5) shows that the terms containing f_v cancel out in the numerator and denominator of both ratios in (5). In particular, by using (1) in (5), expanding in Taylor series with respect to σ and retaining terms up to the second order, we obtain

$$\begin{cases} Copol_{\mathrm{mod}} \cong \left|\beta_r(\varepsilon)\right|^2 \left(1 + \delta_{copol}(\varepsilon)\sigma^2 + \delta'_{copol}(\varepsilon)\sigma^2\right) \\ Corr_{\mathrm{mod}} \cong 1 - \delta_{corr}(\varepsilon)\sigma^2 + \delta'_{corr}(\varepsilon)\sigma^2 \end{cases} , \qquad (6)$$

where

$$\delta_{copol}(\varepsilon) = \delta_H(\varepsilon) + \delta_V(\varepsilon)$$

$$\delta_{corr}(\varepsilon) = \tfrac{1}{2}\delta_H(\varepsilon) - \tfrac{1}{2}\delta_V(\varepsilon) - \mathrm{Re}\left\{\delta_{HV}(\varepsilon)\right\}$$

$$\delta'_{copol}(\varepsilon) = \frac{\delta_X(\varepsilon)}{C}\left(A - \frac{B}{\left|\beta_r(\varepsilon)\right|^2} \right)$$

$$\delta'_{corr}(\varepsilon) = \frac{\delta_X(\varepsilon)}{2C}\left(A + \frac{B}{\left|\beta_r(\varepsilon)\right|^2} - \mathrm{Re}\left\{ \frac{2C}{\beta_r(\varepsilon)} \right\} \right) . \qquad (7)$$

By using (6-7) it is possible to build up charts (see Fig. 2) or numerical look-up tables of (possibly modified) copol-corr loci parameterized by the dielectric constant ε (or, equivalently, the soil moisture content m_v) and the large-scale roughness rms slope σ.

3. EXPERIMENTAL RESULTS

In this paper we evaluate the retrieval results obtained with SAR data acquired in the framework of the 2006 AgriSAR campaign [7]. 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. In particular, the soil water content was measured with different techniques (i.e., time-domain reflectometry, gravimetric and capacitive measurements) and different time-sampling scenarios (intensive campaigns over many fields, weekly measures on a limited set of fields, and via continuous measurements stations over few fields). The area of interest is characterized by the presence of several crop types: in this work we studied the soil moisture behavior of fields of sugar beet, wheat, winter barley, winter rape, grassland, and maize.

The retrieval procedure was applied on the available geocoded L-band quad-polarimetric images. We use here both East-West and North-South 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 can use the expressions in (6) to estimate ε and σ following the procedure described in [2-5]. Finally, the retrieved values are converted into volumetric moisture m_v using the mixing model in [11], considering that the soil in the Demmin area consists mostly of loamy sand, with percentages of sand and clay of 68% and 7%, respectively [8].

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.

The quantitative measures of performance for all the three periods are reported in Tab. I: the mean error (ME) on water volume percentage (vol.%), the error standard deviation (SDE), 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.

It can be seen that none of the approaches performs well on the whole vegetation cycle. In particular, as expected, in the first period, when vegetation is mostly in an early stage of growth, the highest values of N are obtained. In this case, the best results are provided by the method based on dipoles with random uniformly distributed orientations, which seems to be a favorable model for early stage vegetation. Acceptable performances are also obtained considering mainly horizontally oriented dipoles for the volume contribution. In the second period, conversely, the best performance in terms of both ρ and SDE is provided by the method based on mainly vertically oriented dipoles: this can be related to a preferential vertical orientation of the plants' trunks when the growth cycle is not yet in an advanced stage. Finally, in the third period, none of the methods provides reasonably accurate results, due to the presence of high and dense vegetation. Anyway, the best results are once again obtained considering mainly vertically oriented dipoles.

4. COMPARISON WITH 3CMs METHODS

Results presented above show that PTSTCM provides good estimates in presence of a moderate vegetation, when a dominant surface scattering component is accompanied by a non-negligible volume scattering component (first period); conversely, it provides poor (second period) or completely unreliable (third period) results when vegetation density and height increase, so that surface scattering is not the main scattering mechanism and, in addition to volume scattering, also a non-negligible double-bounce scattering component is present. In order to deal with this latter situation, three-component models (3CMs) are needed, that include also double-bounce scattering [8] and, possibly, more refined, parametric/variable volumetric scattering models [9]. We expect that our PTSTCM, which considers a more refined surface scattering model, is preferable for low to moderate vegetation, whereas 3CM-based methods are preferable for high or very high vegetation. In order to check this expectation, and also to give a more quantitative meaning to the expressions "low to moderate vegetation" and "high or very high vegetation", in Fig.1 we compare results of PTSTCM and 3CM over the corn field labeled as 222 in [7]. 3CM retrieval results are taken from [8].

In Fig. 1(a), "no compensation" indicates the standard PTSM of [3], "uniform compensation" indicates PTSTCM with a uniform distribution for dipole orientation, and "horizontal compensation" and "vertical compensation" indicate PTSTCM with a prevalently horizontal and prevalently vertical distribution for dipole orientation, respectively. In Fig. 1(b), blue symbols indicate that soil moisture is estimated from the surface component of the 3CM, whereas red symbols indicate that retrieval is obtained from the double-bounce component of the 3CM; in addition, "Bragg" indicates the usual three-component Freeman decomposition, "X-Bragg" indicates that the X-Bragg model [8-9], but with an a-priori fixed value of the roughness parameter, is used for the surface component, and "volume 1,2, and 3" indicate three modifications of the dipole-cloud model for the volumetric component. Further details can be found in [8].

Comparison of Figs. 1 (a) and (b) shows that up to the last acquisition of June (day 172), corresponding to vegetation height smaller than about 50 cm, PTSTCM provides better results than 3CMs. In addition, all the three considered dipole orientation distributions provide similar results, which are better than results obtained by PTSM. Conversely, for the acquisitions of July and August, corresponding to vegetation higher than about 1 m, the best results are obtained by 3CMs; in particular, in the last two acquisitions, results obtained from the double-bounce component are better than those obtained from the surface scattering component. This shows the importance of including double-bounce for such a high vegetation (more than 2 m). However, it must be noted that even in these last acquisitions, our PTSTCM provides results that are just outside the ±30% variation region if a prevalently vertical dipole orientation distribution is used. Similar results are obtained by considering the wheat field labeled as 230 in [7].

5. CONCLUSION

Experimental results presented in this paper suggest that PTSTCM is preferable up to a vegetation height of about 50 cm, whereas 3CM-based methods are preferable for vegetation height of about 80 cm or higher. In intermediate situations (i.e., vegetation height between 50 and 80 cm) results of the two approaches are usually similar, with a slight preference for 3CMs.

6. REFERENCES

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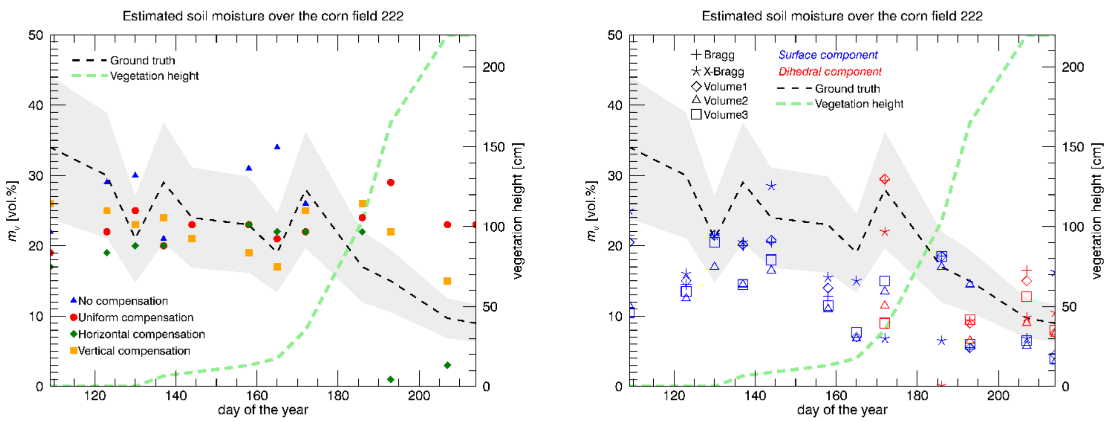
TABLE I

PERFORMANCES OF THE VOLUMETRIC SOIL MOISTURE RETRIEVAL APPROACHES

	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. %]	SDE [vol. %]	ρ	N	ME [vol. %]	SDE [vol. %]	ρ	N	ME [vol. %]	SDE [vol. %]	ρ	N
No compensation	4.0	13.0	0.34	9	10.0	14.0	0.10	6	24.0	17.0	–0.13	8
"Uniform dipoles" compensation	–4.4	8.0	0.64	12	–0.2	12.0	0.10	9	12.0	12.0	0.11	10
"Horizontal dipoles" compensation	–0.6	9.0	0.59	12	3.6	12.0	–0.18	8	17.0	14.0	–0.03	10
"Vertical dipoles" compensation	–3.8	12.0	0.34	12	–7.4	6.9	0.38	5	8.6	14.0	0.11	9



(a) (b)

Figure 1. Estimated average soil moisture over the corn field 222 inverted via the PTSTC method (a) and the 3CM method of [8] (b). The in situ estimated soil moisture is indicated by the black dashed line and the ±30% variation region is highlighted in gray.