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Comparison of different polarimetric decompositions for soil moisture retrieval over vegetation covered agricultural area☆

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ABSTRACT

This study investigates and compares the potential of three model-based polarimetric decompositions, namely those developed by Freeman-Durden (1998), Hajnsek et al. (2009) and An et al. (2010), for soil moisture retrieval over agricultural fields covered by several crops. The volume scattering component was first removed from the full coherency matrix. Then, in order to reduce the effect of the incidence angle on the retrieval results, a normalization process at a reference incidence angle was conducted for the first time, on the dominant surface or dihedral scattering component from which the soil moisture was retrieved. The time series of Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) data and the ground measurements of soil and vegetation characteristics collected during the Soil Moisture Active Passive (SMAP) Validation Experiment in 2012 (SMAPVEX12) were used to compare the three decomposition methods with respect to the scattering mechanisms and the soil moisture retrieval performances. The results show that the performance of each decomposition method for soil moisture retrieval depends on the crop types and the crop phenological stages. Indeed, Freeman-Durden model provided the best results for corn and wheat, Hajnsek decomposition performed well for canola, while better results were obtained for soybean using An decomposition. At the early growth stage, both the surface and dihedral scattering components contributed to retrieve the soil moisture, while at a later crop development, the surface scattering component is almost the only scattering mechanism from which soil moisture was retrieved. Thus, the best performance for soil moisture retrieval was obtained a) at the early crop development stage from Hajnsek decomposition which better integrated the dihedral component and b) at a later growth stage from An decomposition which enhanced the surface scattering. Finally, an overall soil moisture underestimation with RMSE of 0.06–0.11 m^3/m^3 was observed from the three decompositions, and the highest retrieval rate of 33%–39% was obtained from An decomposition as a result of the enhanced surface scattering.

1. Introduction

Soil moisture is a crucial parameter for studying the hydrological processes, and is considered as an essential climate variable by the Global Climate Observing System (Bojinski et al., 2014; GCOS107, 2006). Remote sensing technique provides a powerful way to estimate the soil moisture at several high spatial and temporal resolutions. In contrast to optical remote sensing, Synthetic Aperture Radar (SAR) is independent of sun light, and the generated microwave signal can penetrate the soils, allowing the estimation of soil moisture and its timely monitoring. Furthermore, the polarimetric SAR increases the observation space, leading to a potential enhancement of soil moisture retrieval by considering the multiple signatures and their consistency (Cloude, 2010; Cloude and Pottier, 1997). Over bare soils, successful retrieval performances may be obtained by either theoretical scattering models (Allain et al., 2004; Allain et al., 2002; Fung and Chen, 2004; Fung and Li, 1992; Shi et al., 1997; Ulaby et al., 1982) or empirical approaches (Baghdadi et al., 2012a; Baghdadi et al., 2012b; Baghdadi et al., 2006; Dubois et al., 1995; Oh, 2004; Oh et al., 1992, 2002; Sahebi and Angles, 2010; Wang et al., 2016a; Wang et al., 2015; Zribi and Dechambre, 2002). However, for the agricultural areas which are seasonally covered by different crops, the backscattering from vegetation and soils are coherently superimposed in the SAR signature, complicating thus the soil moisture retrieval.

In order to obtain the ground scattering components associated with the soil moisture, many efforts were devoted in the past decades. For instance, the water cloud model (Attema and Ulaby, 1978; Gherboudj et al., 2011; Kumar et al., 2012; Kumar et al., 2015) assumes the vegetation layer as an uniform cloud composed of water particles with random spatial distribution. Consequently, the canopy backscattering coefficient is modeled as an incoherent summation of the scattering contribution

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from the vegetation, the underlying soil and the multiple scattering between the vegetation and soil surface. Furthermore, polarimetric decomposition (Cloude and Pottier, 1996) was established to isolate the individual scattering mechanism (e.g. surface, dihedral and volume scattering) from the polarimetric SAR signature. Among several types of polarimetric decomposition techniques (e.g. coherent decomposition using scattering matrix and Eigen-based incoherent method), the model-based incoherent decomposition especially has potential for the soil moisture retrieval over vegetation covered area, since each scattering component is physically interpreted. In this sense, Freeman and Durden (1998) model-based decomposition simulates i) the surface scattering component using Bragg scattering from relative smooth surface ($ks < 0.3$, with wavenumber k and surface root mean square height s), ii) the dihedral scattering component as the backscattering from two orthogonal surfaces with different dielectric constants, and iii) the volume scattering using dipoles with a random orientation. Thus, once the volume scattering is removed from the total signal, the soil moisture information is contained in the remaining surface and dihedral scattering components. The appropriate modeling of the volume component is crucial for the polarimetric decomposition, and consequently for the application in soil moisture estimation (Cui et al., 2014; van Zyl et al., 2011). However, prior the polarimetric decomposition, An et al. (2010) applied the deorientation process to the coherency matrix in order to remove the disturbance of stochastic orientation angles on the polarimetric scattering in each pixel. The deorientation process minimizes the cross-polarized scattering power and maximizes the co-polarized scattering power, which is expected to benefit to soil moisture retrieval from the ground scattering component.

Nevertheless, so far, the Freeman-Durden decomposition and its modified formulation which accounts for the deorientation (An et al., 2010) are widely used for image classification and the identification and interpretation of the scattering mechanisms (Adams et al., 2013; Cui et al., 2012; Singh et al., 2013; Zhang et al., 2015). Very few efforts focused on quantitative soil moisture retrieval. Indeed, a pioneer study of Hajnsek et al. (2009) and others investigations presented great advances in the potential of model-based decomposition for soil moisture retrieval over vegetation covered agricultural fields. Therefore, based on the current progress in polarimetric decompositions and considering the encouraging results previously obtained, the objective of this study is to investigate and compare the potential of Freeman and Durden (1998), Hajnsek et al. (2009) and An et al. (2010) decompositions for quantitative soil moisture retrieval. It is understood that each algorithm has its advantage and limitation. Nevertheless, considering the spatiotemporal variability of crop characteristics with the crop types and the phenological development stages, we assumed a possibility to appropriately remove the volume scattering from the decomposition algorithms, and use resulting surface or dihedral scattering component for soil moisture retrieval. In this paper, Section 2 describes the time series of the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) data and ground truth measurements of interest collected in the framework of Soil Moisture Active Passive Validation Experiment in 2012 (SMAPVEX12). The three polarimetric decomposition methods for soil moisture retrieval are described in Section 3. The results are analyzed and discussed in Section 4 and the main conclusion is presented in Section 5.

2. Study site and dataset description

2.1. Study site

The study site is the SMAPVEX12 experimental area (Fig. 1) which covers 15 km × 70 km (49°20′–50°0′N, 97°40′–98°30′W) and is located at the bottom of the Red River watershed in Winnipeg, Canada. The area experiences a humid continental climate with an average annual precipitation of approximately 505 mm (http://www.winnipeg.climatemps.com/). It consists of pasture, forests and agricultural areas. The landscape is characterized by an extremely flat topography, and the main crops over the agricultural area are canola (13.2% of the area), corn (7%), soybean (6.7%) and wheat (32.2%).

2.2. UAVSAR time series

In the framework of SMAPVEX12, the polarimetric UAVSAR image acquisitions covered 14 dates between June 17 and July 17, 2012, a nominal swath of 21 km and 25°–65° incidence angle. In this study, the multi-look product (MLC) of flight line #31606 with spatial resolution of 5.0 m in range and 7.2 m in azimuth is used. This flight line covers all the investigated agricultural fields. The coherency matrix [T] was extracted using the PolSARpro5.0 software and a boxcar filter with 7 × 7 window size is applied to reduce the speckle effect (Lee and Pottier, 2009). As the terrain is flat, no topographic correction was implemented.

2.3. Ground measurements

In coincidence with the UAVSAR acquisitions, the SMAPVEX12 ground campaign was carried out over 55 agricultural fields between June 6 and July17 2012 to measure both the soil and vegetation parameters. More details about these measurements can be found in McNairn et al. (2015) and in SMAPVEX12 website (https://smapvex12.espaceweb.usherbrooke.ca/).

1) Volumetric soil moisture was measured at 6 cm depth using calibrated hand-held Hydra probes. For each field, sixteen points were sampled with three replicate measurements at each point in order to obtain a representative soil moisture value. The daily rainfall was also recorded to understand the soil moisture variability. As shown in Fig. 2, there is an agreement between the temporal evolution of the mean value of soil moisture measurements and the rainfall amount. A peak of mean soil moisture value usually follows a rain event, then the lack of precipitation and/or evaporation process leads to the decreasing trend of soil moisture (Fig. 2).
2) On each field, the surface roughness was measured at two locations using a digital camera and a 1-m long profilometer installed in the look direction of UAVSAR. At each location, the roughness parameters RMS height s and autocorrelation length l were determined from the digitized pictures of 3-m profiles. The mean values of s and l are 1.22 cm and 9.25 cm for canola field, 1.21 cm and 9.75 cm for corn field, 0.91 cm and 11.66 cm for soybean field, 1.12 cm and 11.75 cm for wheat field. The observed surface roughness variability over different fields was mainly caused by the tillage and sowing practices.
3) Crop growth parameters such as height and biomass were measured in order to account for the vegetation effect on soil moisture retrieval from UAVSAR signature. For instance, Fig. 3 shows the temporal variation of measured crop height, which can be successfully fitted to the classical logical growth equation (Yin et al., 2003): $f(x) = H_{max} / (1 + e^{-n(x - m)})$, with maximum height ($H_{max}$), sigmoid midpoint day (m) and growth speed indicator (n). It also proves the robustness of SMAPVEX12 ground measurements on vegetation growth. In addition, for a given crop type especially canola, there is a variability between different fields due to the difference in soil and plant growth status.

3. Methods

The interest in the model-based decompositions for soil moisture retrieval relies on the physical interpretation of each scattering components. In this context, the present study aims to compare the suitability of three model-based polarimetric decomposition algorithms, namely Freeman and Durden (1998), Hajnsek et al. (2009)