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On the potential of Polarimetric SAR Interferometry to characterize the biomass, moisture and structure of agricultural crops at L-, C- and X-Bands

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ABSTRACT

Polarimetric SAR Interferometry (Pol-InSAR) has shown great promise for estimating the height of agricultural crops through the inversion of a scattering model of the plant canopy and the soil. The inversion also provides estimates of model parameters describing the microwave attenuation within the canopy and the relative scattering contributions from canopy and soil surface.

Here, we investigate how vegetation characteristics including biomass, water content (VWC) and canopy structure are related to these parameters and provide a first assessment of the potential of estimating such characteristics using Pol-InSAR time series in L-, C- and X-Bands.

The overall attenuation for maize is positively related to total VWC in L- and C-Bands. Furthermore, larger attenuation in VV than HH points toward the existence of anisotropic propagation effects due to vertical orientation of the stalks.

Conversely, for wheat in C- and X-Bands there is no consistent relation between attenuation loss and VWC. Rather, structural changes occurring within the plant growth cycle appear to have an appreciable polarization-dependent effect on the observed attenuation changes.

In addition, the estimated normalized volume backscattering power NVP (a measure of the relative scattering contribution from the canopy compared to the underlying soil) is associated with wet biomass. However, the contrasting sign of this relation (negative for maize in L- and C-Bands; positive for wheat in C- and X-Bands) indicates again the role of crop structural properties in the Pol-InSAR measurements. For instance, the NVP for maize in L- and C-Bands appears to decrease with increasing biomass due to the increasingly important double bounce ground-stalk scattering contribution as plants become taller and thicker.

Overall, these results indicate the sensitivity of the Pol-InSAR parameters to canopy structure and biomass; this sensitivity is however dependent, amongst others, on crop type and radar frequency. When choosing an appropriate baseline/frequency configuration, the Pol-InSAR attenuation loss and NVP may complement the information of the estimated crop height, especially if the latter shows very little variation over the plant growth cycle (e.g. as for wheat).

1. Introduction

An improved understanding of the biophysical properties of agricultural crops (e.g. canopy height, biomass and water content) is of great importance for forecasting crop growth or assessing plant health and pathologies. It can also provide additional insights into vegetation state and dynamics, which regulate carbon storage and hydrological responses (Schimel et al., 2001; Zhang et al., 2001).

Because of its relevance for questions related to science and economy, great effort has been made to estimate these biophysical properties using remote sensing techniques. Passive microwave remote sensing has been employed (Liu et al., 2011; Konings et al., 2016) to investigate the moisture and the structure of agricultural vegetation at the global scale. For instance, the vegetation optical depth retrieved from passive microwave instruments has been shown to be associated positively with the above-ground vegetation water content (Jackson

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and Schmugge, 1991; Van de Griend and Wigneron, 2004) and to be dependent on polarization due to the anisotropic orientation of leaves and stalks (Schwank et al., 2005). However, a key problem for agricultural applications is the relatively coarse spatial resolution of passive microwave instruments (typically above 10 km for space-borne sensors) compared to the size of the fields.

Table 1
List of symbols and acronyms.

Symbol	Description	First appearance
s_i	Backscattered signal	Eq. (1)
γ_{int}	Interferometric coherence	Eq. (1)
Γ, ϕ_{int}	Magnitude and phase of γ_{int}	After Eq. (1)
S_{pq}	Scattering coefficient, the subscripts represent receive and transmit polarizations	Eq. (2)
$\vec{k}$	Pauli vector	Eq. (2)
γ	Pol-InSAR coherence	Eq. (3)
$\vec{\omega}$	Projection vector	Eq. (3)
VoG	Volume over ground	Fig. (1)
H, V	Subscripts for "horizontal" and "vertical" polarizations	Fig. (1)
p, q	Subscripts for polarizations	Eq. (4)
v, g/d	Subscripts for "volume" and "ground/double-bounce"	Eq. (4)
f	Structure function	Eq. (4)
m', m	Backscattering strength	Eq. (4)
σ	Two-way extinction coefficient	Eq. (4)
z_0	Ground reference height	Eq. (4)
h_V	Vegetation height	Eq. (4)
θ, θ_0	Radar incidence angle	Eq. (4)
κ_z	Phase-to-height sensitivity	Eq. (4)
γ_v	Pol-InSAR volume coherence	Eq. (5)
μ	Ground-to-volume scattering ratio	Eq. (5)
ϕ	Ground phase	Eq. (5)
%VWC	Relative gravimetric vegetation water content in % (in situ)	Fig. 3
$h_{V,meas}$	Vegetation height (in situ)	Fig. 3
N_b	Number of spatial baselines	Fig. 6
L_{pp}	Pol-InSAR loss factor, the subscripts identify the polarization channel	Eq. (7)
ΔL	Pol-InSAR differential loss ($L_{VV} - L_{HH}$)	After Eq. (7)
P_V	Volume power	Eq. (8)
β^0	Radar brightness	Eq. (8)
NVP	Normalized volume backscattering power	Eq. (9)
$[T_1]$,$[T_2]$,$[\Omega]$	Coherency matrices (averaging all pixels within the field)	Eqs. (10)–12
$[T_1^{(N)}]$, $[T_2^{(N)}]$, $[\Omega^{(N)}]$	N-look coherency matrices (simulated, fully-developed speckle)	Eq. (13)
κ_V	Product $\kappa_z h_{V,meas}$	Fig. 7
RCS, RCS^{dBsm}	Radar cross section of a sub-foliage target	Eq. (16)
RCS_0, RCS_0^{dBsm}	Vegetation-free (reference) radar cross section	Eq. (16)
l_{pp}, $\overline{L}_{pp}$	Loss factor of a sub-foliage target, the subscripts identify the polarization channel	Eq. (16)
SFCR	Sub-foliage corner reflector	Fig. 9
$\overline{\delta L}_{pp}$	Difference in SFCR loss between two acquisitions at different times, the subscripts identify the polarization channel	Eq. (18)
$\overline{\Delta L}$	SFCR differential loss ($\overline{L}_{VV} - \overline{L}_{HH}$)	Eq. (20)
VWC	Total vegetation water content in kg m^{-2} (in situ)	Fig. 21
L_{avg}	Pol-InSAR mean loss factor	Fig. 21
st, ea	Superscript for "stalks" and "ears"	Eq. (21)
σ_{eff}	"Effective" extinction coefficient	Fig. 29

Synthetic Aperture Radar (SAR), by contrast, achieves meter-scale spatial resolutions. SAR backscatter is sensitive to crop biophysical parameters (e.g. biomass, water content and Leaf Area Index; Jiao et al., 2010; Wiseman et al., 2014) and soil moisture, and is able to resolve the variability of such parameters between and within the fields. However, both soil and vegetation contribute to the total backscatter; even the use of different polarizations may not provide, in some cases, sufficient information to separate the corresponding scattering contributions (Hajnsek et al., 2009a).

Polarimetric SAR Interferometry (Pol-InSAR) (Cloude and Papathanassiou, 1998) is directly sensitive to the vertical structure of crops and has the potential to resolve the scattering within the canopy and separate the scattering contributions from the canopy and the underlying soil. This is achieved by inverting a two-layer "volume over ground" (VoG) scattering model consisting of a vertically homogeneous vegetation volume of particles on top of a rough surface impenetrable for the microwaves (Papathanassiou and Cloude, 2001; Cloude and Papathanassiou, 2003). The vertical variation of the scattering through the vegetation volume is governed by the crop height and the two-way extinction coefficients; the relative scattering contribution from the canopy compared to the ground is described by the normalized volume backscattering power NVP.

In recent years, many studies have estimated the vegetation height of crops (Lopez-Sanchez et al., 2007, 2012; Pichierri et al., 2016) and forests (Garestier et al., 2008; Hajnsek et al., 2009b; Neumann et al., 2010) using Pol-InSAR observations. By contrast, only a few investigations have drawn attention on the estimation of the extinction and the NVP parameters (Lopez-Sanchez et al., 2006; Pichierri et al., 2016). Consequently, the relationship between these parameters and vegetation characteristics such as biomass, moisture and structure is not fully understood. There is some evidence to suggest that the NVP may be sensitive to variations in the vegetation water content. For instance, as the vegetation canopy gets drier the relative scattering contribution from the underlying soil is likely to increase, and hence the NVP decreases. Furthermore, a non-zero difference between the extinction coefficients of two polarimetric channels may indicate that stalks and leaves within the vegetation canopy share a preferred orientation, as already shown for maize in L- and S-Bands (Ulaby et al., 1987; Lopez-Sanchez et al., 2006).

The investigation presented in this paper has two main objectives. First, we intend to elucidate how Pol-InSAR model parameters such as extinction coefficients and NVP are related to crop biophysical properties as a function of frequency, crop type and plant growth stage. To this end, we estimate these Pol-InSAR parameters using the VoG inversion scheme proposed in Pichierri et al. (2016) over multi-temporal Pol-InSAR observations of wheat and maize fields in L-, C- and X-Bands, and we compare the inversion results with in situ measurements of wet biomass and vegetation water content. This analysis sheds some light, for the first time, on the potential of Pol-InSAR to estimate the biophysical properties of crops and may provide new insights into the assumptions and limitations of the adopted VoG scattering model.