First Multi-Frequency Investigation of SAR Tomography for Vertical Structure of Agricultural Crops

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Abstract

In the last years tomographic SAR (TomoSAR) raised great interest in the field of vegetation remote sensing primarily focused on forest vertical structure. The focus of this work is to investigate the application of TomoSAR techniques for the retrieval of vertical structure of agricultural vegetation. A structural analysis for crops is the key to address especially the characterisation of the layers possibly with different orientations that are present inside a crop and the amount of scattering coming from the ground at high frequencies, two issues which are still open. First results on the retrieval of the 3-D scattering distribution from airborne multi-baseline polarimetric SAR data are shown and discussed regarding differences in crop types, polarisation and frequencies.

1 Introduction

Remote sensing using Synthetic Aperture Radar (SAR) and especially the coherent combination of polarimetric SAR (PolSAR) and interferometric SAR (InSAR), Pol-InSAR, shows great potential in vegetation monitoring exploiting the variation of the complex interferometric coherence with polarisation [1]. Furthermore, electromagnetic models were developed parameterising the dependency of the coherence on physical characteristics of the vegetation layer as extinction, height and underlying topography [1, 2]. The inversion of height from Pol-InSAR data using the modelling assumption of a layer of randomly oriented vegetation over ground (RVoG) is nowadays an established and validated technique. In parallel, polarimetric TomoSAR techniques were developed extending the Pol-InSAR principle [3]. They allow the separation of multiple scattering mechanisms in height by increasing the number of baselines and exploiting the herewith obtained amplitude and phase diversity. In addition, TomoSAR coupled with polarisation plays a significant role for the estimation and deeper understanding of forest vertical structure [4].
In case of agricultural vegetation, a two-layer model consisting of an oriented volume with ground contribution (OVoG) was proposed for Pol-InSAR accounting for orientation effects inside the vegetation volume [5]. Nevertheless, a single vegetation layer might not represent the orientation characteristics well enough.
In view of current or future spaceborne missions, (e.g. TanDEM-X, Radarsat-2, Sentinel-1, Tandem-L) it is crucial to foster the understanding of the dominant scattering mechanisms at different frequencies. For this purpose, multi-baseline (MB) polarimetric datasets offer an increased observation space enabling TomoSAR methodologies for (1) exploring data information content, (2) assessing penetration capabilities to determine the amount of ground scattering, (3) assessing scattering model assumptions in terms of number of layers and orientations, (4) identifying requirements, potentials and limitations for PolSAR and Pol-InSAR modes from space [6].
Unfortunately, there is a lack of fully polarimetric Pol-InSAR and/or MB datasets at high frequencies, which are known to be more sensitive to agricultural vegetation and hence more suitable for crop monitoring. A fully polarimetric MB SAR dataset acquired by DLR's airborne SAR system F-SAR at X-, C- and L-band over an agricultural area near Wallerfing, Germany, is used. The objective is to assess the capabilities of TomoSAR on agricultural crops. First results are presented and differences in polarisation as well as frequency are pointed out. Further investigations concerning interpretation attempts, methodologies and future acquisitions are discussed.

2 Experimental Results

2.1 Testsite and datasets

The study area is situated near the town of Wallerfing, Germany. The rather flat area is agriculturally cultivated with a big variety of crop types dominated by winter wheat, winter barley and corn. The acquisition date was in early July 2013 when most of the crop species were in an already developed stage. During a field campaign conducted on the same date as the acquisition, specific fields were investigated more in detail with respect to plant height, vegetation water content, soil moisture and cultivation characteristics. The maximum heights of the species were 2m for corn, 0.7m for wheat and 0.8m for barley. In order to be sensitive to the rather low vegeta-

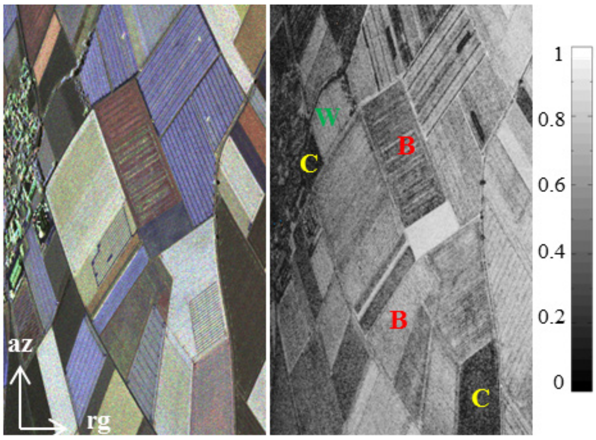
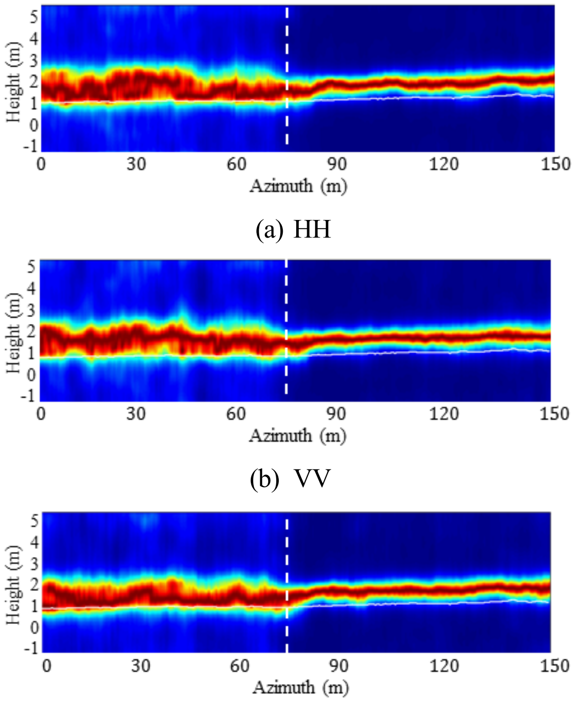


Figure 1: X-band Pauli RGB and cross-pol interferometric coherence of 25m baseline of area under study (wheat corn barley)

Figure 2: Structural pictures of corn (left) and wheat (right) on the acquisition date



(a) HH

(b) VV

(c) HV

Figure 3: X-band tomographic slices normalized to the peak at transition of corn to wheat (indicated by dotted white line) at different polarisations with Lidar DTM (white)

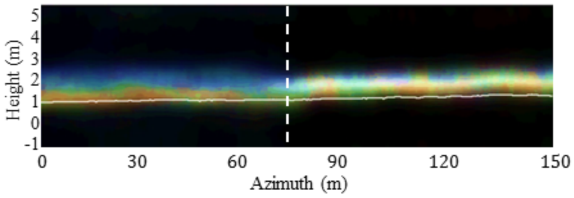
tion heights, a dedicated acquisition planning is crucial to ensure at the same time a very high resolution in height and a sufficient height of ambiguity. The maximum baseline has to be selected large enough for sufficient height resolution, but it is limited by the critical baseline in particular at lower frequencies where the critical baseline corresponds to a lower vertical wavenumber due to the smaller bandwidth. The minimum baseline should be small enough to ensure an adequate ambiguity height. For an accurate inversion, the number of baselines needs to be big enough, and this requirement has to be traded off with the MB acquisition duration. Indeed, especially at higher frequencies, temporal decorrelation might increase with a bigger time window. Fully polarimetric MB SAR data was acquired by DLR's airborne SAR system F-SAR in X- and C-band simultaneously. In total seven parallel tracks are available (hor. baselines 10, 15, 20, 25, 30, 40m w.r.t. the master acquisition) providing a vertical resolution of approximately 0.9m and an ambiguity height of 7m at X-band and 1.6m and 12.8m at C-band respectively which is a promising setting for a first investigation. For comparison, fully polarimetric MB SAR data with four parallel tracks were acquired at L-band (hor. baselines 40, 90, 118m w.r.t. the master acquisition) providing a vertical resolution of approximately 2.1m and an ambiguity height of 8.9m, which is worse than at the higher frequencies.

Figure 1 shows the X-band Pauli RGB (left) and the cross-pol interferometric coherence resulting from the 25m baseline (right) of the area under study. The Pauli image shows a big variety with the species but even among one single species, underlining the complexity of agricultural vegetation. The interferometric coherence shows remarkable volume decorrelation on the vegetated fields depending on the height of the plants.

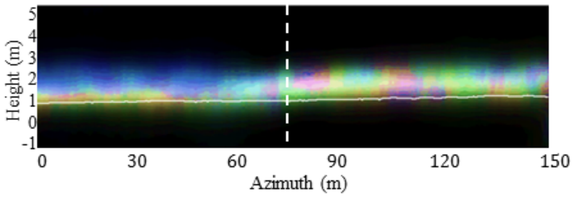
2.2 Estimation of vertical profiles

The objective of this first 3-D analysis is to get a first qualitative impression and understanding of the goodness of the MB phase calibration, the characteristics of the occurring scattering and the main differences in species, polarisation and frequency. For this purpose, the Capon beamformer has been chosen to reconstruct the power distribution along height. A careful phase calibration of the MB SAR data is mandatory prior to any tomographic processing [4] to compensate for a residual phase screen resulting from platform motion. For improving the radiometric fidelity, a minimum entropy criterion is applied in addition [7]. It is worth remarking that at higher frequencies an accurate phase calibration becomes challenging since the phase distortion is proportional to the baseline error normalized to the wavelength. Nevertheless, the method in [7] succeeds for a sufficient phase calibration of this dataset.

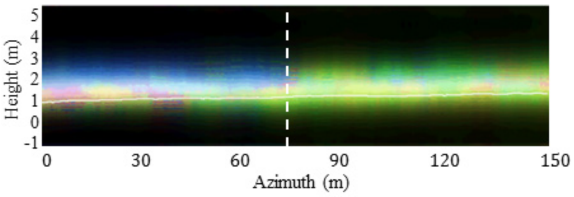
A first analysis is carried out at the transition of a corn



(a) X-band



(b) C-band



(c) L-band

Figure 4: Transition of corn to wheat (indicated by white dashed line) at different frequencies in Pauli decomposition (|HH − VV||2HV||HH + VV|) with Lidar DTM (white)

field to a wheat field. **Figure 2** gives an idea of the state of the species on the date of the acquisition. **Figure 3** shows the tomographic slices normalized to the peak at fixed range in X-band in the polarisations HH (top), VV (middle) and HV (bottom). The Lidar ground topography (DTM) is plotted in white. The tomographic slices follow the Lidar DTM. The transition of corn to wheat (indicated by white dashed line) can be clearly distinguished already from the profile width with respect to the ground topography. In general, it can be said that X-band is sensitive to the ground and the vegetation volume of the corn, whereas the scattering in the wheat seems to come from the volume since the slice deviates from the ground topography. In the corn a stronger variation of the main phase centre in height with the particular polarisations than in the wheat is apparent. Due to the lack of space, the corresponding single-pol tomographic slices at C- and L-band are not shown. It is worth mentioning, that with decreasing frequency the dominant phase centre varies less with polarisation in the corn and moves closer to the ground in the wheat. These points underline that a general statement about orientation effects of agricultural vegetation is difficult, and may suggest different modelling attempts for different species at different frequencies.

In order to identify the dominant scattering mechanisms and to get a better understanding of the variation with polarisation, a full rank polarimetric spectral estimation approach is applied to determine the 3-D polarimetric

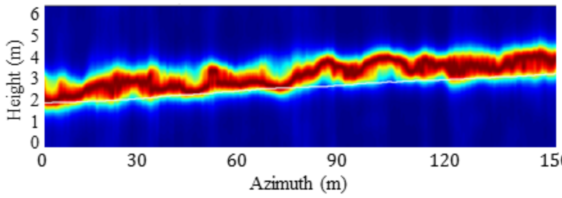


Figure 5: X-band cross-pol tomographic slice normalized to the peak of barley with Lidar DTM (white)

signature [8]. In **Figure 4** the Pauli decomposition of the spectral power is displayed for varying frequencies for the same slice as above (top: X-band, middle: C-band, bottom: L-band). At X-band the ground can be clearly separated from the volume in the part of the corn. The ground appears in a mixture of red and green, suggesting sensitivity to the roughness of the ground (causing volume scattering), while in the vegetation volume single-bounce seems to be dominant. In the wheat, no dominant scattering mechanism can be identified and it seems that there is a higher variation of the scattering mechanisms. Moving to C-band, there is again a clear discrimination of the ground and the volume in the corn. The scattering in the wheat appears to be more uniform than at X-band and again volume-dominated, though the yellowish colour close to the ground indicates dihedral contribution. At L-band, especially for the wheat, it might be argued from the location of the phase centre that there is more ground than at higher frequencies. However, even if polarimetry helps to improve the height resolution slightly, the poorer height resolution makes the comparison difficult. Nevertheless, a difference in scattering mechanisms between the corn and the wheat can still be identified. In fact, before the transition a layer of double bounce scattering can be distinguished from a layer dominated by single bounce. In the wheat mainly volume scattering is present. Closer to the ground, the yellow colour may suggest a dihedral contribution.

A sample tomographic slice over barley at another position in the scene is shown in **Figure 5** in the cross-pol channel. The spread in height is wider as for wheat, though the barley was only slightly higher than the wheat on the acquisition day. It also seems that the scattering centre varies stronger than in the case of the wheat, especially in the horizontal direction.

3 Discussion and Summary

In this paper, first results on the application of TomoSAR on agricultural crops have been shown. For the first time, a complete fully polarimetric MB dataset at different frequencies over an agricultural area is available and enables thorough investigations towards the 3-D characterisation of scattering in crops. The increased observation space made possible the analysis of the variation of the scattering centre along height by applying polarimetric TomoSAR techniques without the need of scattering models. It has been stated that an accurate phase calibration is an important factor for the performance of tomographic techniques especially at higher frequencies. Furthermore, it has been shown that there are structural differences depending on the species. The coupling of TomoSAR with polarimetry has led to 3-D polarimetric signatures underlining the variation with polarisation as well as with frequency. This observation points out the need for adaption of models used for PolSAR or Pol-InSAR applications in natural environments according to the frequency used.

In general, tomogram interpretation over crops is difficult due to several reasons rising from limitations related to the acquisition scenario as well as the methodological frame. In details:

- It is difficult to distinguish baseline induced effects from temporal effects since the size of the baselines increased almost linearly with time in this acquisition.
- A comparison of frequencies is limited since the L-band data stack does not provide sufficient height resolution.
- The dataset does not represent the variation of agricultural vegetation over the phenological cycle, but it only represents one specific day. It might be insufficient to draw conclusions based on a one-day acquisition.
- The Capon beamformer may be limited by insufficient resolution in this challenging scenario.

To overcome the first three points, future acquisitions will be adapted. In order to evaluate temporal effects, the baselines will not be planned to be increasing linearly with time, but they will be distributed to cover a 2-D support in the time-baseline space. Moreover, the number of baselines acquired at L-band will be increased to achieve higher resolution in height. Finally, to investigate the variation of the species over the phenological development, acquisitions are planned covering the whole growth cycle from May to August.

From the methodological point of view, other spectral estimation methods (model-based and not) will be investigated evaluating their benefit for tomographic applications on agricultural crops. It is of interest to examine if a two-layer model is sufficient to represent agricultural crops in a Pol-InSAR context.

As concerns interpretation, a final note of caution is made, because it is not only necessary to take into account the differences in species, but also variations within the same species due to for example different moisture conditions of the underlying soil in the same or in different fields, the vegetation moisture content itself or simply the position of the field in the scene that might be more affected by miscalibration, temporal decorrelation or a different look angle. All of these aspects will be carefully addressed in the future.

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