APPLICATION OF POLARIMETRIC SAR TOMOGRAPHY ON AGRICULTURAL VEGETATION FOR SCATTERING CHARACTERISATION

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ABSTRACT

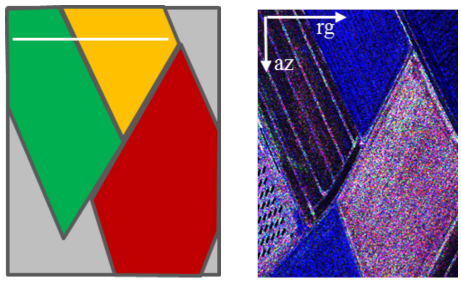
The SAR backscattering of agricultural vegetation is intrinsically rather complex, for instance due to possibly present orientation effects. In order to advance its understanding, this paper explores the application of tomographic SAR techniques for full 3-D information extraction. The possibility to detect variations of the scattering characteristics between species as well as between different growth stages is shown. Further, a procedure for the separation of ground and volume contributions is proposed and first results are discussed. This investigation has been carried out by using a multi-temporal multi-baseline fully polarimetric data set purposely acquired by DLR's airborne sensor F-SAR in 2014.

Key words: agricultural vegetation, synthetic aperture radar (SAR), polarimetry, tomography.

1. INTRODUCTION

The interpretation of scattering mechanisms occurring in agricultural vegetation at different frequencies is rather difficult, due to the increased complexity (compared to forest) of the scattering processes. Therefore a large observation space is required, provided for instance by multi-parametric, such as multi-temporal, multi-baseline and multi-frequency SAR acquisitions. Indeed, the vegetation volume might be oriented and, most importantly, the structure of the plants can change very fast over the phenological cycle as well as from one crop type to the other [1, 2]. (Polarimetric) SAR Tomography enables to resolve the scattering processes in the vertical dimension [3] and therefore to assess the differences in the 3-D scattering distribution with respect to species and development stage at different polarisations or frequencies.

In order to fill the lack of multi-baseline multi-frequency polarimetric SAR data sets over agricultural areas with a sufficient height resolution and a proper temporal sampling, a new campaign was conducted in 2014 with DLR's airborne sensor F-SAR over an agricultural area near Wallerfing (South Germany). This unique data set enables a thourough exploration of the 3-D information extraction capabilities in this complex scattering scenario. More in detail, in this work 3-D tomographic signatures at C-band for different species at different dates in the phenological cycle are presented and discussed. Finally, a procedure for the separation of ground and volume contributions is proposed. First results for the retrieved polarimetric signatures of ground and volume are shown and discussed.



(a) *Landuse of the patch. The white line indicates position of the range slice under study.* (b) *Pauli RGB composite image ($|HH+VV|$, $2|HV|$, $|HH-VV|$)*

	corn	wheat	barley
May 22nd	< 10 cm	65 cm	90 cm
June 12th	70 cm	95 cm	85 cm
June 18th	90 cm	90 cm	80 cm
July 3rd	150 cm	90 cm	80 cm

(c) *Vegetation heights on the dates under study.*

Figure 1: *Patch under study.*

2. EXPERIMENTAL DATA

The SAR campaign was conducted in 2014 with DLR's airborne sensor F-SAR over an agricultural area near Wallerfing (South Germany). Fully polarimetric multi-baseline SAR acquisitions in X-, C- and L-band were acquired almost weekly from May to August covering different moments of the phenological cycle. In order to image the low vegetation heights a high vertical resolution is desirable. The Rayleigh resolution ρ_z is defined as follows:

$$\rho_z = \frac{2\pi}{\max k_z} \propto B_{max} \tag{1}$$

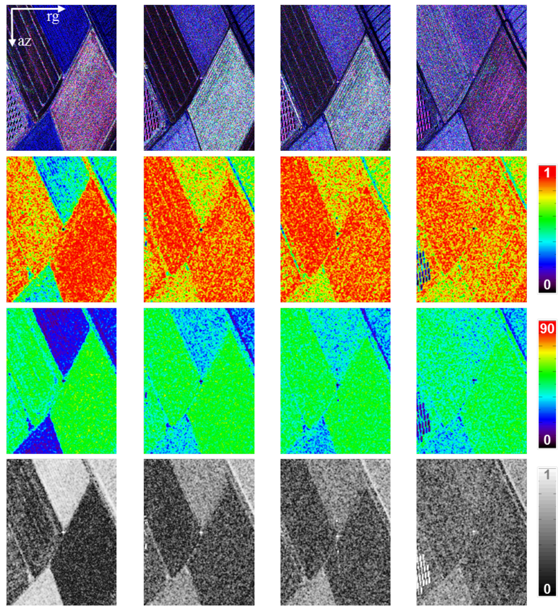
Although ρ_z is directly proportional to the maximum baseline, limitations in the baseline planning occur from the critical baseline and the limited acquisition time. Taking this tradeoff into account, the baselines were planned to be big enough to ensure a high vertical resolution but also in a sufficient number to allow accurate inversion. As a result, up to 9 parallel tracks have been acquired, per frequency and acquisition date, allowing a vertical resolution (in mid range) down to 0.5 m at X-band, 0.8 m at C-band and 1.4 m at L-band and a height of ambiguity bigger than 9 m at all frequencies. On each acquisition date, in situ measurements of soil moisture, vegetation height, vegetation water content and phenological stage were taken in parallel.

This study focuses on a small patch (180 m in range, 270 m in azimuth) of the SAR scene including three different species, wheat, corn and barley. In Figure 1(a) the landuse of the patch under study is schematically mapped. Figure 1(b) shows the corresponding C-band Pauli RGB composite image on May 22$^{\text{nd}}$. The species can be distinguished. On the corn field which is (almost) not vegetated yet surface scattering is apparent. The barley has reached its final height and double bounce scattering is dominant, mixed with some volume contribution. The wheat field appears very dark but still dominated by double bounce scattering. In the following, four growth stages were chosen for investigation. In Figure 1(c) the vegetation heights for the particular dates are displayed. The heights of wheat and barley are similar at all the dates and, for C-band, in the order of the Rayleigh resolution which is a limiting factor for the application of SAR Tomography. In contrast, the corn grows during the study period and reaches up to 1.5 m which is almost the double of the Rayleigh resolution.
Figure 2 shows the C-band Pauli RGB composite images, the polarimetric entropy, the polarimetric mean alpha angle and the copolar coherence on the four dates. Comparing the signatures, the increase of vegetation volume leads to an increasing volume decorrelation and therefore of entropy and the mean alpha angle. Consistently, the copolar coherence decreases. While in the earlier dates the fields are easily distinguished, once all the three fields are highly vegetated it becomes almost impossible to differentiate among them. This leads to the conclusion that polarimetric indicators alone may not be sufficient to indentify different fields, but an extended observation space is required, as for instance to include the variation over time (see Figure 2).

3. APPLICATION OF SAR TOMOGRAPHY

The application of tomographic SAR methodologies to agricultural vegetation can be challenging due to the small vegetation heights and therefore requires high vertical resolution. The SAR acquisitions provide a vertical resolution of $\rho_z = 0.8\,m$ in the position of the slice under study (see Figure 1(a)). Nevertheless, the vegetation heights of the corn and the wheat at the three dates are in the order of one height resolution unit. In order to still be able to detect changes in this short vegetation, spectral estimators with super resolution capabilities are applied. In the following, the results of the Capon beamformer and the MUSIC algorithm are presented and discussed. While the Capon result can be understood as an imaging of the radar reflectivities corresponding to their position in height, the MUSIC functional represents a degree of fitting in terms of point-like responses corresponding to the dominant phase centres [4]. Even though the MUSIC functional, from a physical point of view, does not represent the distribution of the radar intensities in height, it is applied for comparison in order to overcome the limitation of the Capon beamformer in terms of super resolution.

The range line chosen for this analysis is depicted in white in Figure 1. This line of 150 m crosses from a wheat to a corn field. The multi-baseline SAR data have been carefully phase calibrated in order to ensure radiometric fidelity. For both approaches a multi-look cell of 5 m by 5 m is used corresponding to approximately 100 independent looks.



(a) *May 22nd* (b) *June 12th* (c) *June 18th* (d) *July 3rd*

Figure 2: *Variation of the polarimetric signature at different dates. From top to bottom: Pauli RGB composite images ($|HH+VV|$, $2|HV|$, $|HH-VV|$), polarimetric entropy, polarimetric mean alpha angle, copolar coherence.*

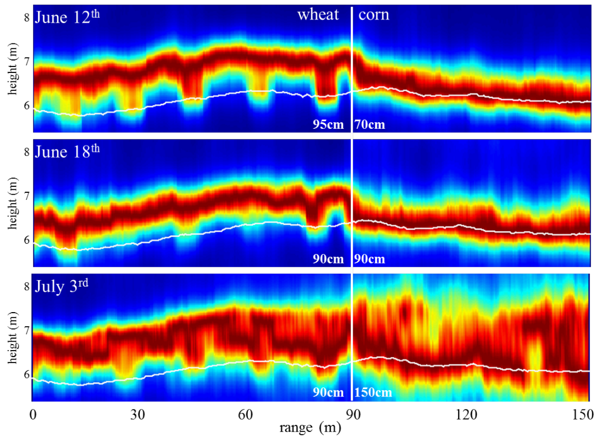


Figure 3: *Variation of a range slice for three different dates using the Capon Beamformer (VV-polarisation).*

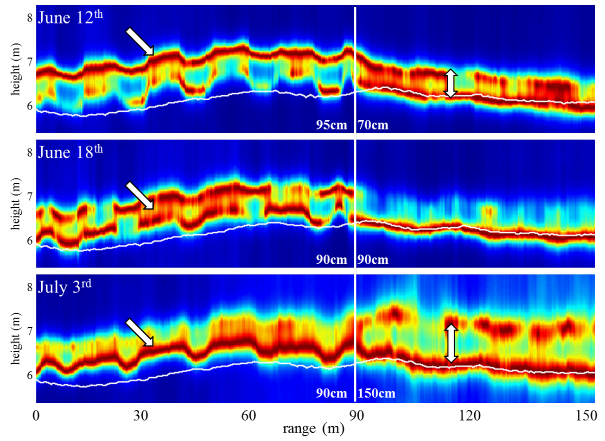


Figure 4: *Variation of a range slice for three different dates using the MUSIC algorithm (VV-polarisation).*

3.1. Capon

Figure 3 shows the tomographic slices in VV-polarisation obtained by the Capon normalized to the peak. The Lidar ground topography is superimposed in white and the height locations of the vertical tomographic profiles agree with the Lidar DTM. The average heights of the plants on these dates are written below the corresponding slices. Although the height in the wheat stays almost constant, the scattering characteristics change. In the part of the corn, the growth can be clearly detected especially comparing the first and the third date.

3.2. MUSIC

The tomographic slices (again in VV polarisation) obtained with the MUSIC algorithm (effective model order $k_{eff} = 2$) are shown in Figure 4. The effective model order k_{eff} is the dimension of the information space in terms of point-like responses orthogonal to the noise subspace. In the wheat, the ground is visible in all three dates, while the volume changes within them. In the first date the vegetation top appears to fit a point-like response while in the last date the ground is the only clear point-like contribution. Together with the information from the Capon result, this suggests a dominant ground in the last date. Indeed, ground measurements confirm a decrease of the vegetation water content of the wheat plants between these dates thus leading to a more electromagnetically transparent vegetation volume. Considering the corn, even in the first date, the two phase centres appear separated in contrary to the Capon result due to the increased super resolution capabilities of MUSIC. Again, the growth of the corn plants is apparent, comparing the first and the third date (pointed out by the white arrows). Regarding the differences between the first and the second date, the growth of the plants was only around 0.2 m, which is much lower than one Rayleigh resolution unit of 0.8 m in this case. Nevertheless, the scattering behaviour changes in terms of penetration characteristics. The volume phase centre almost disappears in the second date indicating a different type of volume scattering. These results underline the capapility of the MUSIC functional to provide insights about the volume shape.
A final remark is in order. For simplicity, $k_{eff} = 2$ has been heuristically chosen a priori. Tests have shown that, in particular for the lower vegetation heights, higher effective model orders lead to an overestimation of the information content and therefore to an introduction of noise in the retrieved functional. As a note of caution, it has to be mentionend that the use of the MUSIC methodology to characterise a vegetation volume is critical since it is not represented by point-like responses but rather by distributed layers. Nevertheless, it has been shown that the MUSIC functional can be indeed very useful for the estimation of the relevant phase centres and of their variations.

4. SEPARATION OF GROUND AND VOLUME CONTRIBUTIONS

Although the phase centre information already allows an analysis of changes over time, it is only a subspace of both the necessary information and the available information content. In order to understand and characterise spatial and temporal changes, a first attempt consists in estimating the radar reflectivities at the scattering phase centres.
In order to achieve a separation of ground and volume contributions the following procedure has been applied. It is assumed that the ground remains at the same positions for all the polarisations and further the number of phase centres to be determined is fixed to two, i.e. ground plus one vegetation layer. At first, the phase centres for the ground and the volume, z_g and z_v, are estimated by means of the M-RELAX iterative procedure employing the fully polarimetric (rank-1) MUSIC functional [4, 5]. In a next step, the complex reflectivities corresponding to

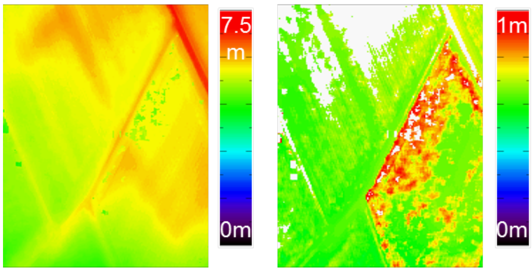
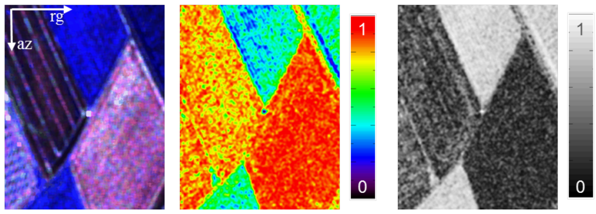


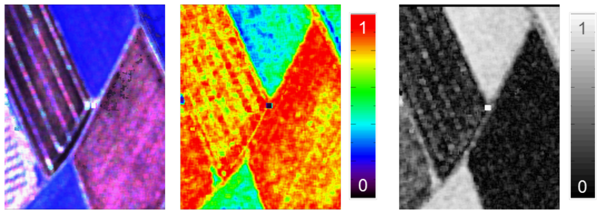
Figure 5: *Retrieved phase centres for the ground (left) and the volume relative to the ground (right) for May 22nd.*

the heights z_g and z_v are estimated for each polarisation seperately using a least squares optimization [5]. From them, the coherent estimates of the ground and volume covariance matrices C_g and C_v are obtained.

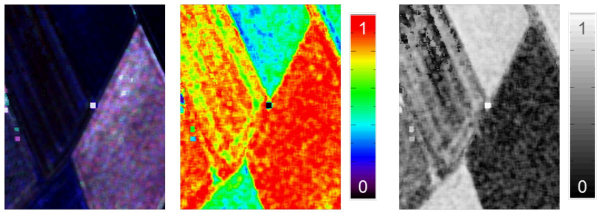
The procedure has been applied to the patch mentionend in the beginning for the first date, May 22nd, since at that moment the corn field was almost bare enabling an evaluation of the reliability of the results. In fact, over a bare field the retrieved ground intensities should correspond to the ones of the single look complex image (SLC). Figure 5 shows the retrieved phase centres. The ground topography, on the left, is estimated with a standard deviation lower than 0.1 m with respect to the Lidar DTM and therefore within the accuracy of the Lidar itself. The volume phase centre, on the right, is corrected for the ground topography. For instance, in the barley field the estimated heights range from 0.7 m to 1 m which is reasonable compared to a vegetation height of around 0.9 m measured for this date. The volume phase centre retrieved over the bare field saturates to the maximum. Since the separation procedure always looks for a second scatterer besides the ground a noise component is actually labeled as volume on the bare field. The retrieved estimates of the bare field correspond in all channels to the SLC powers, while the volume powers are around 10 dB below the ground powers, being close to noise, as expected. In Figure 6 the Pauli RGB image, the polarimetric entropy and the copolar coherence of the SLC (top), the retrieved ground (middle) and the retrieved volume (bottom) are compared. The polarimetric signature of the ground over the bare field seems to be consistent with the SLC polarimetry This indicates that the least squares procedure does not distort the polarimetric signature of single point-like scatterers. The interpretation for the vegetated fields is more difficult. The polarimetric signature of the retrieved ground in vegetated areas is not expected to correspond to the one of a bare field. The dominant double bounce scattering coming from the interaction of ground and volume layer is located at the ground as well [6] causing a mixture of scattering mechanisms. For instance, in some parts of the barley field the entropy of the ground is lower than the one of the volume, but nevertheless the entropy values still appear higher than presumed. Furthermore, the copolar coherence in the barley is lower at the ground level than the one at the volume level, contrarily to what expected.



(a) SLC polarimetry



(b) ground polarimetry



(c) volume polarimetry

Figure 6: *Retrieved polarimetric signatures in comparison to the SLC polarimetry for May 22nd (left: Pauli RGB composite image ($|HH+VV|$ $2|HV|$ $|HH-VV|$), middle: polarimetric entropy, right: copolar coherence).*

These results stress again that an interpretation of the retrieved signatures is difficult and clear conclusions cannot be drawn straightforwardly. It is once more important to consider the vertical resolution compared to the vegetation heights. If two layers are not separated by at least one Rayleigh resolution unit, the estimates might be distorted by leakage from the volume to the ground and vice versa, introducing interferences. Besides the vertical resolution, this leakage depends also on other factors, such as baseline spacing, relative position of the layers, shape of the layers and the power ratio. Most importantly, this crosstalk affects not only power estimation but also phase estimation and therefore the polarimetric signature is influenced even more severly. This phenomenon is known in tomographic SAR applications but not fully understood yet.

5. CONCLUSION

In this paper, tomographic SAR methodologies have been applied to agricultural vegetation. Even though the Rayleigh resolution in height was in the order of the vegetation heights, changes in the scattering characteristics could be detected. Differences could be clearly observed between species and between stages of the phenological cycle, such as changes in growth or penetration capabilities. The added value of SAR Tomography for agricultural vegetation is that it provides an increased observation space without the need of model assumptions. For instance, polarimetric interferometric SAR enables the separation of scattering centres in height using one baseline together with the polarimetric variation of the interferometric coherence but requires a model assumption for the vegetation volume [2, 7]. However, it has been found that there is a difference in terms of reliability of phase centres and complex reflectivities estimated from SAR Tomography. While phase centres could be reliably estimated, complex reflectivities appeared more challenging. In this regard, the interpretation of the related polarimetric signatures turned out to be rather difficult. One reason is the cross-talk from the ground to the volume layer and vice versa in which a key role is played by height resolution. Future investigations will be carried out to further characterise the accuracy in the estimation of the separated complex reflectivities. It has to be assessed if complex reflectivity estimation is intrinsically critical from the data information content. At the same time, suitable methodologies have to be developed and applied to improve the reliability of reflectivity estimation. In future also other frequencies and dates in the phenological cycle will be investigated to foster the understanding of this phenomenon. Further, the application of model-based attempts as in [8] might help to characterise the shape of the volume layer(s). This information can be useful in order to evaluate possible limitations and also to validate existing modeling approaches in polarimetric and polarimetric interferometric SAR for agricultural vegetation.

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