3-D Structure Of Forests: First Analysis of Tomogram Changes Due to Weather and Seasonal Effects at L-Band

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Abstract

Due to its ecological importance, the monitoring of the vertical structure of forests is continuously raising the interest of the synthetic aperture radar (SAR) scientific community. SAR tomography allows reconstructing the 3-D distribution of the radar power backscattered by a volume by combining more than two SAR acquisitions with baseline diversity. Beyond specific estimation algorithms, the link between the estimated tomograms (depending in general on frequency, polarization and acquisition geometry) and physical forest structure is essential for establishing potential applications. In this work, we contribute to this topic by presenting first investigations aimed to characterize the changes on forest tomograms due to weather and seasonal effects, with the perspective of analysing potentials for monitoring forest ecosystem changes and discuss guidelines for an effective implementation of spaceborne forest structure sensing.

1 Introduction

Low frequency (L-/P-band) synthetic aperture radar (SAR) data are particularly appealing in forest remote sensing due to their penetration until the ground, therefore providing sensitivity to the vertical structure. A significant advance in the analysis of forest vertical structure came with the coherent combination of polarimetry with interferometry for Pol-InSAR [1]. Polarimetry can separate different scattering mechanisms, while interferometry can locate them in height. The possibility of separating multiple scattering components in height in a continuous profile of the backscattered power has been demonstrated also with SAR Tomography (TomoSAR) [2], which in principle exploits only baseline diversity, but it can be greatly improved by coupling it with polarimetry. Recent research on TomoSAR for forest applications has been focused mainly on the experimentation of techniques able to overcome the limits intrinsic of a simple Fourier-based focusing, model-based and not [3]-[5].

In general, the 3-D distribution of the backscattered power can change in time due to different weather conditions (due to changes in the dielectric properties of the vegetation layers), to seasonality (leaf-on/leaf-off condition), and to logging or disturbances. The characterization of these changes in TomoSAR profiles has not been carried out until now, although it is essential for establishing the link between the 3-D backscattered power and the physical forest structure towards potential TomoSAR-based applications, especially for documenting forest ecosystem changes.

In this work, we present some first investigations aimed at characterizing the changes of L-band forest tomograms due to weather and seasonal effects. The reported results have been obtained by processing a multitemporal-multibaseline (MB) airborne data set acquired by the DLR E-SAR platform in the frame of the TempoSAR 2008-2009 campaigns over the forest site of Traunstein (South of Germany).

2 Data sets

The Traunstein test site is located in the southeast of Germany. Topography varies from 600m to 800m amsl, with only few steep slopes. On a global scale this forest type is part of the temperate forest zone. It is a managed forest composed of even-aged stands which cover forest heights from 10 to 40m. The mean biomass level is on the order of 210t/ha, significantly higher than other managed forests in the same ecological zone, while some old forest stands can reach biomass levels up to 500t/ha.

Acq. day	Hor. baselines (m)	Conditions
10/06/2008	-15,-5,0,5,10	Dry
12/06/2008	-15,-5,0,5,10	Wet
11/05/2009	-15,-5,-10,0,5,10,15	Dry
28/10/2009	0,5,10,15	Dry

Table 1: TempoSAR 2008/2009 acquisitions selected for the analysis. Baselines are measured with respect to the master image. Conditions (wet/dry) are defined based on the precipitation data.

The repeat-pass DLR E-SAR system acquired fully polarimetric and interferometric L-band SAR data over the Traunstein test site. A total of 13 multibaseline radar acquisitions was carried out: five times (period 7 June-20 June 2008) in the TempoSAR 2008 campaign and eight times (periods 27 April-12 May 2009 and 28 October-5 November 2009) in the TempoSAR 2009 campaign. Meteorological data are also available for two weather stations close to Traunstein (Nilling and Schönharting). Baselines and weather classification for the acquisitions selected in this analysis are reported in Tab. 1[1].

3 Experimental results

A fundamental prerequisite for an accurate TomoSAR imaging is the MB phase calibration of the data, which here was performed with the method in [6]. Concerning the 3-D focusing, for the sake of simplicity, in this work we resort to the adaptive beam forming (i.e. Capon spectral estimator, abbreviated ABF), a low-complexity non-model based imaging solution that offers height super-resolution and sidelobe rejection. It is worth noting that, thanks to the calibration algorithm used, the ABF recovers a very good radiometric fidelity [6], although a small intrinsic bias can still be present due to well-known statistical reasons. This bias has been quantified by means of a simulated analysis for a single height-compact scatterer in terms of the radiometric loss between the scatterer power estimated by ABF and the linear Fourier focusing[2]. This radiometric loss in plotted in Fig. 1 as a function of the number of independent looks. In absence of baseline errors, it is apparent that already with 50 looks the radiometric loss is well below 0.5dB, while with a small miscalibration residual of 0.005λ (being λ the radar wavelength), the loss amounts to 1dB. For this reason, data have been processed with a square multilook cell with side length amounting to 15m, that scales to around 80 independent looks. A diagonal loading of the MB covariance matrix has been applied as well to compensate for the residual bias. It is therefore expected that the radiometric accuracy will result satisfactory also for volume scatterers.

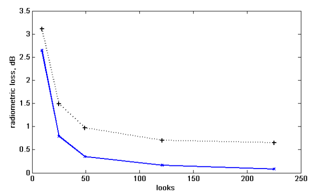


Figure 1: Radiometric loss of the ABF processor with respect to a linear Fourier focusing as a function of the number of looks with baseline errors (blue line) and without (black line).

3.1 Weather effects

The radar backscatter from forests is mostly related to the dielectric constant of the tree tissues, that depends strongly on their water content. During a rain event, the canopy can retain up to a certain amount of water, above which the extra amount drops to the ground, increasing moisture [8]. At the same time, the water content inside leaves and trunk increases as well, and the related absorption phenomena increase in turn the electromagnetic extinction of the canopy layers [8]. The extent of these effects will depend, in general, on the vegetation structure itself. Therefore, in terms of a TomoSAR vertical profile, with respect to an acquisition in a dry day, after a rainfall it is reasonable to expect (*i*) a decrease of the ground-to-volume ratio, (*ii*) an increase of the phase center height of the profile, and (*iii*) a general change in the backscattered power of each single layer.

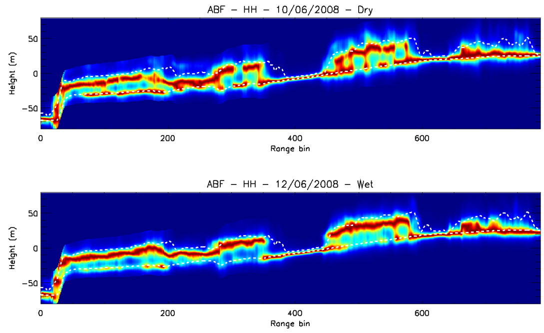
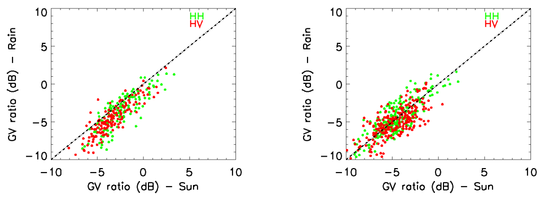
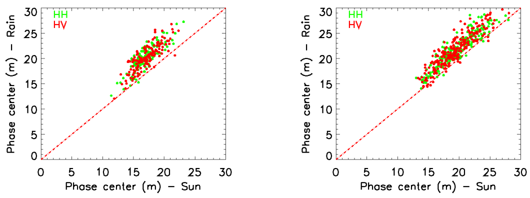


Figure 2: Traunstein data set, sample ABF tomographic slices before and after a rainfall. White dashed lines: lidar ground topography and top canopy height.



(a) Average biomass: 300t/ha (b) Average biomass: 500t/ha

Figure 3: Estimated ground-to-volume ratios before (horizontal axis) and after (vertical axis) a rainfall in two different forest areas.



(a) Average biomass: 300t/ha (b) Average biomass: 500t/ha

Figure 4: Estimated phase center heights of the volume before (horizontal axis) and after (vertical axis) a rainfall in two different forest areas.

Fig. 2 shows two sample ABF tomographic slices obtained before (10/06/2008) and after (12/06/2008) a rainfall in the HH channel (average vertical Rayleigh resolution 15m). It is apparent that after the rainfall the ground power is in general reduced with respect to the canopy power. Moreover, for some range coordinates, the canopy

[1] A full description of the data set with detailed weather data can be found in [7].

[2] The same comparison is in general not valid for height-extended volume scatterers as ABF and Fourier image the volume in different ways.

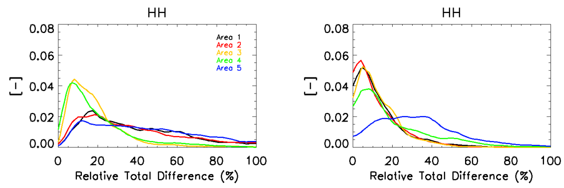
power distribution appears more sharp due to the increase of extinction, as expected. To quantify these variations, we selected two areas in the observed scene with the same average forest height (30m), but different average biomass levels (300t/ha and 500t/ha). We first of all analysed the variation of the ground-to-volume power ratio μ estimated using multibaseline separation techniques [9]. For the low-biomass area (Fig. 3, left panel), in HH polarization the majority of the points shows a decrease of μ of 1.45dB in average after the rainfall. In HV polarization, the values of μ in both days are usually lower with respect to the HH channel and also with a smaller average decrease after the rainfall (1.23dB). For the high-biomass area (Fig. 3, right panel), due to the higher variety of vertical structure and the lower penetration, the changes of μ show a higher dipersion, however the general trend is similar to the one observed in the low-biomass area, especially in HV. The normalized frequency of occurrence corresponding to the presence of the ground peak in the ABF profiles has also been quantified over the whole Traunstein area. It results that in the HH channel the occurring frequency of the ground peak amounts to 52% in dry condition, while it decreases to the 45% in wet conditions.

The variation of the profile phase center in height of the volume scatterer after its separation from the ground with the technique in [9] has been quantified as well. From the plots in Fig. 4, it can be observed that after the rainfall the phase center height increases of around 3m and 2m in the HH and HV channels, respectively, in the low biomass area. For the HH polarization, a higher increase (4m) can be seen in the high-biomass area. It has also been observed that not necessarily a decrease of ground-to-volume ratio corresponds to an increase of the phase center height, and vice versa. This may be an indication that a rainfall causes changes of the entire TomoSAR structure. To further investigate this issue, we evaluated the changes of the entire ABF tomogram in terms of the relative total difference (RTD) of the profiles, defined as:

$$\xi = \frac{\sum_{m=1}^{M}[f_1(z_m) - f_2(z_m)]^2}{\sum_{m=1}^{M} f_1^2(z_m)]}, \tag{1}$$

being $f_1(z)$ and $f_2(z)$ the two profiles under comparison, z_m, $m = 1, \ldots, M$ the heights at which they are sampled and M the total number of samples between the ground and the canopy top. Five different areas (including the two areas analysed before) with the same forest height (30m) and biomass increasing from 300t/ha and 500t/ha have been considered. The RTD histograms have been quantified and reported in Fig. 5, left panel. The areas analysed before have been labelled Area 1 (lowest biomass) and Area 5 (highest biomass). It is apparent that by considering the ABF focusing, the RTD can reach values much higher than 20%. For the sake of comparison, we also estimated the vertical profiles by means of Coherence Tomography (CT) [5] in the Legendre basis and by limiting the expansion until the third order polynomial[3], i.e. retaining only low-frequency vertical components of the profile. Interestingly, the RTD does not exceed the 20% for the high majority of the analysed pixels (see Fig. 5, right panel). Finally, we also observed that changes in μ, phase center height, and structure are independent from the particular tree species at a large extent.

[3]Such decomposition can express the 90% of biomass [5].



(a) ABF (b) CT (Legendre)

Figure 5: RTD between vertical profiles before and after a rainfall in 5 different homogeneous areas quantified as in (1).

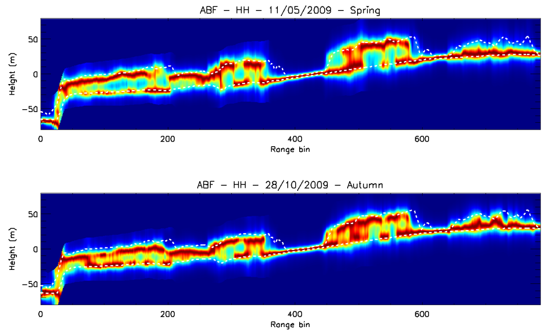
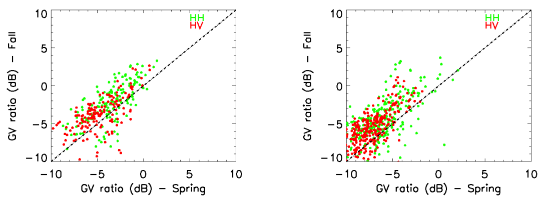


Figure 6: Traunstein data set, sample ABF tomographic slices in spring and in autumn. White dashed lines: lidar ground topography and top canopy height.



(a) Average biomass: 300t/ha (b) Average biomass: 500t/ha

Figure 7: Estimated ground-to-volume ratios in spring and in autumn in two different forest areas.

3.2 Seasonality

Seasonal effects in temperate regions are mainly characterized by the absence of leaves in autumn and winter, and therefore a reduction of water transpiration and quantity of water in the tree trunks. In radar terms, this means an increase of penetration into the forest volume.

Seasonal effects on the tomograms have been analysed by comparing the two TempoSAR 2009 acquisition, one in spring (11/05/2009) and one in autumn (28/10/2009).

Sample ABF tomographic slices for the spring and the autumn data sets are shown in Fig. 6. It is worth noting from Tab. 1 that the two acquisitions have different baselines, thus different tomographic resolution and ambiguity. Therefore, for a fair comparison, the multibaseline data vectors corresponding to the two ABF slices have been first interpolated to a common baseline distribution [10]. It is apparent that in leaf-off conditions the penetration in the canopy volume is higher and the ground is in general more visible, as expected.

Variations of the ground-to-volume power ratio μ have been quantified also in this case. Fig. 7 compares the μ estimated in spring and autumn and for both the low and the high biomass areas considered previously in HH and HV channels. It is apparent that, differently from the case of weather variations, in the leaf-off case μ is almost uniformly higher than in the leaf-on case, and the increase amounts to 3dB in average, with a maximum of even 5dB. This is visible independently of the biomass level. Reasonably, it has also been assessed that variations depends on the species. Indeed, for broad-leaved stands the ground power increases by 2dB (average) in autumn with respect to spring, while for conifers the increase does not reach 1dB. In addition, volume powers of broad-leaved stands decrease of about 1dB while for conifer stands they are almost constant.

4 Discussion and conclusions

In this paper, different MB data sets acquired in different days over the same area have been processed in order to carry out a first analysis of radar tomogram changes as a function of weather conditions and seasonality. In general, the presented experiments have shown that even with a low number of tracks (around 5) and a moderate Rayleigh resolution in height (around 15m) it is possible to observe effects of weather changes and seasons, which, in general, look different on the retrieved 3-D information. Interestingly, the sensitivity of TomoSAR structure to rain might be of help for improving the quantification of the amount of intercepted rain in forest canopies, which has applications in hydrology. On the other hand, the relationship between biomass components and the SAR tomograms of the vegetation has been demonstrated to be partially ambiguous, since it depends on the dielectric properties of the forest volume. This discloses a new issue for applications of forest classification and biomass estimation using the TomoSAR profiles, and even more for monitoring the sources of forest 3-D structure changes. Nevertheless, first investigations reported here have shown that the former problem can be mitigated by considering the low vertical frequency components of the profile.

Considering the implementation of TomoSAR for vegetation monitoring in future missions under study (e.g. DLR's Tandem-L and ESA's BIOMASS), dielectric variations between the images constituting the TomoSAR stack should be carefully considered. Indeed, first results (not reported here for lack of space) show that the retrieved tomogram can change by more than the 20% in terms of RTD just by changing the weather conditions of one single image, depending on the forest stand. Beyond continuing to characterize profile variations, future work will be devoted to the investigation of robust 3-D parameter extraction.

References

[1] S. Cloude, K. Papathanassiou: *Polarimetric SAR Interferometry*, IEEE Trans. on Geosci. and Rem. Sensing, Vol. 36, No. 5, pp. 1551-1565, May 1998.

[2] A. Reigber, A. Moreira: *First Demonstration of Airborne SAR Tomography Using Multibaseline L-band Data*, IEEE Trans. on Geosci. and Rem. Sensing, Vol. 38, No. 5, pp. 2142-2152, May 2000.

[3] F. Lombardini, A. Reigber: *Adaptive Spectral Estimation for Multibaseline SAR Tomography with L-band Airborne data*, Proc. of IEEE Int. Geosci. and Rem. Sensing Symposium (IGARSS), Toulouse, France, Jul. 2003.

[4] O. Frey, E. Meier: *Analyzing Tomographic SAR Data of a Forest With Respect to Frequency, Polarization, and Focusing Technique*, IEEE Trans. on Geosci. and Rem. Sensing, Vol. 49, No. 10, pp. 3648-3659, Oct. 2011.

[5] M. Pardini, A. Toraño-Caicoya, F. Kugler, et al.: *Biomass Estimation from Forest Vertical Structure: Potentials and Challenges for Multi-Baseline PolInSAR Techniques*, Proc. of ESA POLinSAR Workshop, Frascati, Italy, Jan. 2011.

[6] M. Pardini, K. Papathanassiou: *A Two-Step Phase Calibration Method for Tomographic Applications with Airborne SAR Data*, Proc. of European SAR Conference (EUSAR), Berlin, Germany, Jun. 2014.

[7] S.K. Lee, F. Kugler, K. Papathanassiou, et al.: *Quantification of Temporal Decorrelation Effects at L-Band for Polarimetric SAR Interferometry Applications*, IEEE Journal of Sel. Topics in Earth Obs. and Rem. Sensing, Vol. 6, No. 3, pp. 1351-1367, Jun. 2013.

[8] J.J.M. De Jong, W. Klasseen, P.J.C. Kuiper: *Monitoring of Rain Water Storage in Forests With Satellite Radar*, IEEE Trans. on Geosci. and Rem. Sensing, Vol. 40, No. 2, pp. 338-347, Feb. 2002.

[9] M. Pardini, K. Papathanassiou: *Sub-Canopy Topography Estimation: Experiments With Multibaseline SAR Data at L-Band*, Proc. of IEEE Int. Geosci. and Rem. Sensing Symposium (IGARSS), Munich, Germany, Jul. 2012.

[10] F. Lombardini, M. Pardini: *3D SAR Tomography: The Multibaseline Sector Interpolation Approach*, IEEE Geosci. and Rem. Sensing Letters, Vol. 5, No. 4, pp. 630-634, Oct. 2008.