ON THE ESTIMATION OF FOREST VERTICAL STRUCTURE FROM MULTIBASELINE POLARIMETRIC SAR DATA

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ABSTRACT

Forest characterization and biomass estimation by means of remote sensing systems are nowadays "hot topics" within the remote sensing community, given their importance in the terrestrial carbon budget. In fact, forest vertical structure is a key variable for assessing biodiversity and structural degradation and/or regeneration. Moreover, the (vertical) structure information is important as it can allow the development of accurate and robust (alometric) estimators of the forest biomass. In this paper, potentials and challenges of forest vertical structure estimation with low frequency multibaseline polarimetric synthetic aperture radar are reviewed and discussed.

***Index Terms*—** Synthetic aperture radar (SAR), polarimetry, tomography, parameter inversion, spectral estimation, forest structure.

1. INTRODUCTION

Space borne synthetic aperture radar (SAR) systems result to be particularly appealing in forest remote sensing, as they can acquire data and provide the related products with high spatial and temporal resolution at a global scale. Moreover, the parameters of interest about the vertical structure can be extracted from the radar signal, depending on its penetration until the ground, which in turn is a function of the carrier frequency.

A significant advance in the analysis of forest vertical structure came with the coherent combination of polarimetry with interferometry for Pol-InSAR [1]. Here polarimetry provides the parameter diversity, while the interferometric baseline gives a user-defined control of the scattering entropy (generated by the forest environment) as well as the spatial separation of scattering components. In this way, the inversion of multi-layer scattering models has been made possible, with applications like forest height estimation (demonstrated over a wide range of forest types), classification, and biomass estimation. In parallel with the maturation of Pol-InSAR, the possibility of separating multiple scattering components in height has been demonstrated also with SAR Tomography (TomoSAR) [2], which in principle exploits only baseline diversity, but it can greatly be improved by coupling it with polarimetry.

Generally speaking, SAR provides information about the forest vertical structure by estimating a set of representative parameters (e.g. forest height, sub-canopy topography, etc.) or by estimating a continuous radar backscattering profile along height. The objective of this work is to review vertical structure estimation from multibaseline (MB) Pol-InSAR data, and to investigate potentials and challenges with particular reference to space borne missions. Results will be presented with L-band data.

2. ESTIMATION OF VERTICAL PARAMETERS

Pol-InSAR forest parameter estimation approaches are based on the fact that the (volume) interferometric coherence is directly related to the vertical distribution of scatterers seen by the radar at the given frequency and polarisation; and thus to the vertical structure of forests. The availability of (fully) polarimetric diversity of the interferometric measurements is essential for the interpretation and inversion of the measurements.

The estimation of vertical forest structure parameters in terms of Pol-InSAR measurements is then performed on the basis of model based inversion: The vertical forest structure function is parameterised in terms of a limited number of parameters, a step that is challenging when accounting the complexity of forest structures and then inverted using the interferometric (volume) coherences measured at different polarisations for a limited number of spatial baselines.

In the last years applications as forest height estimation matured and developed from pre-operational to operational Pol-InSAR products. At the same time new products, as underlying ground topography - a key parameter in the development of advanced forest products - and vertical forest structure, have been developed and validated on an experimental or even pre-operational status. This development was supported by an improved understanding of the sensitivity of the interferometric coherence to the vertical distribution of scatterers and the transition from single- to multi-baseline Pol-InSAR inversion techniques [3]. The possibility to combine coherently Pol-InSAR acquisitions at multiple baselines was finally the key for improving estimation performance.

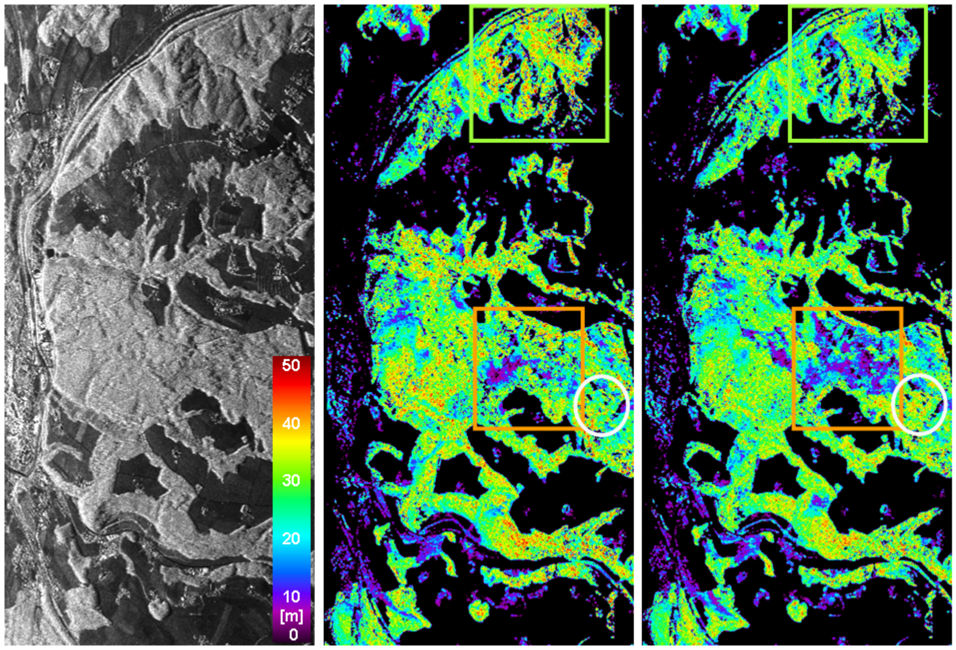


Fig. 1. L-band HV intensity image of the Traunstein test site (left). Forest height map computed from Pol-InSAR data in 2003 (middle) and 2008 (right).

An example of state-of-the-art Pol-InSAR forest height products is shown in Figure 1. On the left, an L-band SAR image of the Traunstein forest site, located in southern Germany is shown. The Traunstein forest is characterized by a large variety of forest stand conditions in the presence of locally variable topography and is one of the early Pol-InSAR validation sites imaged several times in the recent years. The unique Pol-InSAR database allows not only to validate the accuracy of Pol-InSAR forest height products, but also to demonstrate the potential to document forest ecosystem change. In this sense, in the centre and on the right of Figure 1 forest height maps derived from Pol-InSAR data acquired at L-band in 2003 and 2008 are shown, respectively. Comparing the two forest height maps a number of changes within the forest become visible: The logging of individual tall trees as a result of a change in forest management between 2003 and 2008 (marked by the green box); the damage caused in January 2007 by the hurricane Kyrill which blew down large parts of the forest (marked by the orange box); and finally forest growth on the order of 3 to 5 m over young stands as seen within the area marked by the white circle.

MB (possibly PolInSAR) data can be combined also coherently in order to estimate both ground and volume heights [4, 5, 6]. The possiblity has been demonstrated to estimate very accurately the topography exploiting MB data in P-band, especially over boreal forests [4, 5]. Thanks to the canopy semi-transparency, estimation accuracies have been obtained around 1m or less. Conversely, in L-band the higher volumetric scattering contribution of the canopy can lead to very poor ground-to-volume ratios. Nevertheless, the experiments in [6] have shown the possibility to estimate the ground topography with an accuracy ranging between 2 and 3.5m over different forest scenarios, even by processing a small number of baselines (lower than 5) and single-pol data. Experiments are still ongoing in further characterizing the topography estimation performance, especially considering the combination of different polarization channels.

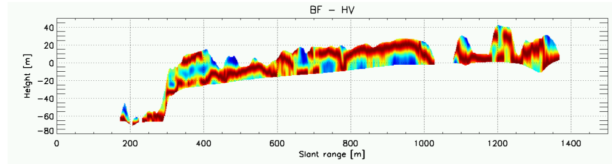
3. ESTIMATION OF THE VERTICAL BACKSCATTERING PROFILE

The coherent combination of MB and multipolarization data can be used also to extract information about the distribution of the scattering in height, i.e. to estimate a continuous profile of the backscattered power. The estimated ground and top-of-canopy height can be used to isolate the height components of interest or for the profile estimation itself, as detailed in the following.

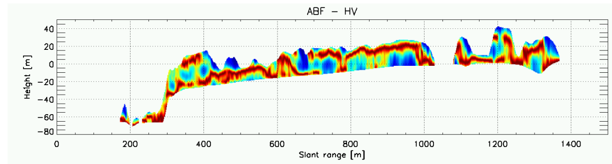
The derivation of a vertical profile (*viz.* tomogram) in a single range-azimuth cell can be casted as a spectral estimation problem from the covariance samples at the different baselines [7]. The discussion here is limited to non-model based approaches with a very low number of baselines (differently from [9]). Model-based techniques have been investigated in [8], also with reference to the number of baselines needed.

The classical Fourier-based beamforming (BF) suffers from low height resolution and high sidelobe level, and turns out to be inadequate for vertical structure estimation [2, 7]. Still in the category of the non model-based methods, the well-known Capon beamformer (or adaptive beamforming, ABF) offers superresolution and sidelobe rejection at the cost of a reduced radiometric linearity in presence of residual phase calibration errors [4, 7]. Nevertheless, the ABF estimator has become in the last years a standard technique in TomoSAR. Examples of BF and ABF TomoSAR slices are reported in Fig. 2, calculated in the range-height plane for a fixed azimuth coordinate. The data set used is composed by 5 images (hor. baselines 0, 5, 10, 15, 25m), and it has been acquired in the framework of the TempoSAR campaign by the DLR's E-SAR platform in 2008. For the sake of visualization, the tomograms have been calculated inside the height interval constrained by ground and the top-of-canopy heights measured by a LiDAR system. It is worth noting that this information has been used only in the visualization of the TomoSAR slices, but not to calculate them. The imaged area do not presents relevant slopes (apart from the one in near range), and it is covered by a forest taller than 20m. From the TomoSAR slices of Fig. 2(a)-(b), it is apparent that both BF and ABF are able to separate scattering contribution in height, however, as it is reasonable to expect, the ABF tomograms look sharper and more height-resolved. Notice also that, contrariliy to BF, the height resolution capability of ABF remains almost unaltered moving from near to far range, i.e. at the the decrease of the Rayleigh resolution limit due to the increase of the off-nadir angle from 25deg to 45deg. Particularly interesting is the comparison between the BF and ABF tomograms in the slant range interval 850-900m. A relevant scattering from the ground is observed with both method, but it results more powerful with ABF than with BF with respect to the canopy scatterer. This is an effect due to MB phase miscalibration residuals on ABF. In fact, it is reasonable to suppose that the ABF filter has partially rejected the most powerful canopy scatterer (self-cancellation phenomenon [4, 7]), thus reducing the ground-to-volume ratio. This effect is not visible with BF as it is more robust to residual phase offsets. A careful MB phase calibration is thus crucial to achieve a good level of radiometric fidelity of the vertical profiles, especially when a high vertical resolution is needed by means of adaptive processing. Nevertheless, the radiometric fidelity can be recovered by using refined calibration procedures [11].

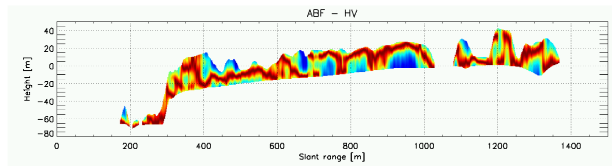
The imaging properties of ABF are preserved in large part also when only 3 tracks are employed (hor. baselines 0, 10, 25m), as shown in Fig. 2(c). The resulting baseline distribution has the same Rayleigh resolution limit, but slightly reduced ambiguity interval in height with respect to the full distribution. By comparing Figs. 2(a)-(b), it is apparent that the main scattering contribution is present at the same positions in height. Although the ABF tomoSAR slice results of



(a) BF - full baseline set



(b) ABF - full baseline set

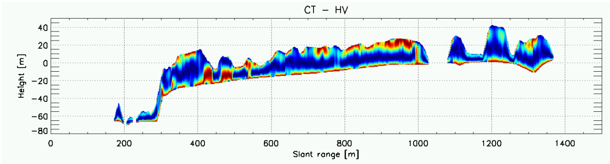


(c) ABF - dual baseline set

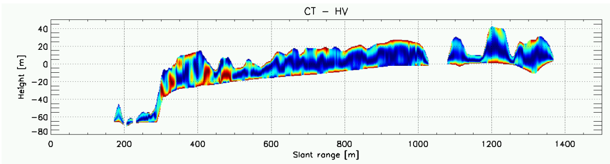
Fig. 2. Examples of BF and ABF TomoSAR slices, DLR's E-SAR TempoSAR campaign.

very good quality even with 3 tracks only, a reduced superresolution capability is observed. This is expected, as the ABF filter possesses less degrees of freedom for placing nulls in the adaptive beam formation [7].

Beyond this discussion on the estimation methodology, it should be noticed that the estimation of the vertical structure from MB SAR is particularly challenging, especially when addressed in terms of the implementation of a space borne mission. In particular, the lack of space borne SAR configurations able to perform multiple simultaneous acquisitions, combined with (temporal) scene decorrelation, reduce the number of suitable acquisitions in a realistic space borne scenario drastically. It has already be seen that the ABF can retrieve the vertical structure reliably even with only three tracks. Alternatively, the vertical structure can be either extracted by model based inversion from the interferometric coherences [12] or by approximating the structure function through a weighted sum of a series of (orthogonal) basis functions, as in the (Polarization) Coherence Tomography (here CT) [13]. The individual parameterization has then to be inverted using a (limited) number of interferometric measurements at the same or different polarizations, provided that ground and top-of-canopy height are known or estimated from the data. Fig. 3(a) shows the CT TomoSAR slices calculated at the same coordinates of the slices of Fig. 2 by inverting the coherence at all of the available baselines and by using the LiDAR heights. The profiles have been calculated here by using the Legendre polynomial basis until the third order. Despite that the CT tomograms are just a low



(a) Full-baseline set



(b) Dual-baseline set

Fig. 3. CT TomoSAR slices extracted at the same azimuth coordinate of Fig. 2.

vertical frequency approximation of the true radar profile, a good agreement is observed between the CT tomograms and ABF ones in locating the main scattering contributions. Fig. 3(b) shows the CT tomograms derived in the same conditions of the ones in Fig. 3(a), but inverting only the dual-baseline coherences mentioned before. The resulting coefficients correlate more than the 80% with the full-baseline ones, demonstrating a good inversion robustness with respect to the number of baselines. It is worth remarking that CT is affected by phase calibration residuals as well [14]. Moreover, the reconstruction performance is highly affected by estimation errors of both the ground and the top-of-canopy heights. A first analysis has been carried out in [14], where a robust inversion has also been proposed. Nevertheless, the investigation and exploitation of CT-based inversions is particularly attactive in view of single pass (polarimetric) interferometric mission (e.g. the DLR's Tandem-L proposal), where an interferometric coherence is available at each pass of the interferometer without relative phase difference and problems of temporal decorrelation.

4. REFERENCES

[1] S. Cloude, K. Papathanassiou, "Polarimetric SAR Interferometry," *IEEE Trans. on Geoscience and Remote 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 Geoscience and Remote Sensing*, Vol. 38, No. 5, pp. 2142-2152, May 2000.

[3] S.K. Lee, F. Kugler, K. Papathanassiou, I. Hajnsek, "Multibaseline Polarimetric SAR Interferometry Forest Height Inversion Approaches," *Proc. of ESA PolInSAR Workshop*, Frascati, Italy, Jan. 2011.

[4] F. Lombardini, M. Pardini, "Experiments of Tomography-Based SAR Techniques With P-Band Polarimetric Data," *Proc. of ESA PolInSAR Workshop*, Frascati, Italy, Jan. 2009.

[5] S. Tebaldini, "Single and Multipolarimetric SAR Tomography of Forested Areas: A Parametric Approach," *IEEE Trans. on Geoscience and Remote Sensing*, Vol. 48, No. 5, pp. 2375-2387, May 2010.

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

[7] F. Lombardini, A. Reigber, " Adaptive Spectral Estimation for Multibaseline SAR Tomography with L-band Airborne data," *Proc. of IEEE International Geoscience and Remote Sensing Symposium* (IGARSS), Toulouse, France, Jul. 2003.

[8] M. Nannini, R. Scheiber, A. Moreira, "Estimation of the Minimum Number of Tracks for SAR Tomography," *IEEE Trans. on Geoscience and Remote Sensing*, Vol. 47, No. 2, pp. 531-543, Feb. 2009.

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

[10] K. Iribe, K. Papathanassiou, I. Hajnsek, M. Sato, Y. Yokota, "Coherent Scatterer in Forest Environment: Detection, Properties and its Applications," *Proc. of IEEE International Geoscience and Remote Sensing Symposium* (IGARSS), Honolulu, Hawaii (USA), Jul. 2010.

[11] M. Pardini, V. Bianco, K. Papathanassiou, A. Iodice, "Phase Calibration of Multibaseline SAR Data Based on a Minimum Entropy Criterion," *Proc. of IEEE International Geoscience and Remote Sensing Symposium* (IGARSS), Munich, Germany, Jul. 2012.

[12] M. Neumann, L. Ferro-Famil, A. Reigber, "Estimation of Forest Structure, Ground, and Canopy Layer Characteristics From Multibaseline Polarimetric Interferometric SAR Data," *IEEE Trans. on Geoscience and Remote Sensing*, Vol. 48, No. 3, pp. 1086-1104, Mar. 2010.

[13] S. Cloude, "Polarization Coherence Tomography," *Radio Science*, vol. 41, RS4017, Sep. 2006.

[14] M. Pardini, K. Papathanassiou, "Robust Estimation of the Vertical Structure of Forests With Coherence Tomography," *Proc. of ESA PolInSAR Workshop*, Frascati, Italy, Jan. 2011.