SUB-CANOPY TOPOGRAPHY ESTIMATION: EXPERIMENTS WITH MULTIBASELINE SAR DATA AT L-BAND

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ABSTRACT

Synthetic aperture radar (SAR) systems in L-band and P-band are characterized by deep penetration capabilities into volumes, enabling new opportunities for the radar remote sensing of forests. In the last years, the interest has been continuously growing in the estimation of the sub-canopy topography, especially by exploiting multibaseline (possibly polarimetric) SAR data.

This work intends to contribute on this topic by presenting further experiments with real L-band data about ground topography estimation and by quantifying the obtained performance. Different forest scenarios are considered. Potentials and limitations are analyzed with particular reference to a multibaseline relaxation-based algorithm.

***Index Terms*—** Synthetic aperture radar, tomography, ground topography, radar signal processing

1. INTRODUCTION

The estimation of the ground topography in forest scenarios can be seen as a problem of separation between the ground and the canopy scatterers in the height dimension. To accomplish this objective, a possibility is to resort to SAR data acquired in some kind of diversity (polarization and/or baseline diversity). For instance, already operating with a single baseline, coherent scattering models can be related to the interferometric complex coherences in different polarizations (PolInSAR) in order to analyze the vertical structure of the scattering and turn to retrieve the sub-canopy topography [1, 2]. In the last decade, in parallel to single baseline Pol-InSAR, different strategies were investigated. In particular, SAR Tomography (TomoSAR) [3, 4] and its polarimetric version PolTomoSAR [5] demonstrated their potential in the 3-D analysis of volumetric scenarios. TomoSAR is a multibaseline (MB) extension of conventional cross-track SAR interferometry, employing many passes over the same area. Differently from interferometry, (Pol)TomoSAR can resolve multiple scatterers at different heights in each given range-azimuth cell.

Up to now, the performance of TomoSAR techniques in ground topography estimation has been quantitatively assessed mostly with P-band data. Thanks to the high semi-transparency of the canopy, the possibility has been demonstrated to reach an estimation precision in the order of magnitude of 1 m (see e.g. [4, 6]), even with non model-based TomoSAR approaches. Conversely, the estimation performance with L-band MB data has not yet been fully investigated.

This paper investigates further the performance in the estimation of the ground topography obtained by the relaxation based approach proposed in [7] which uses a simplified coherence model for the ground and the canopy scattering. Its potentials and limitations are analyzed by processing real airborne data acquired in L-band over different forest scenarios. The particular case of a dual-baseline acquisition is considered.

2. GROUND TOPOGRAPHY ESTIMATION

Accepting a model mismatch on the canopy scatterer, ground and canopy are assumed to be point-like scatterers (i.e. both with a vertical structure shaped as a Dirac-δ). The ground topography can then be estimated through an iterative method that for each iteration optimizes a one dimensional functional, and the global algorithm implementation results simple and fast. This is the principle on which the Multilook RELAX (M-RELAX) iterations are based. Under this assumption, the M-RELAX estimates are obtained by minimizing [8]

$$Q_N(\boldsymbol{\tau}_n, \mathbf{z}) = \sum_{n=1}^{N} \left\| \mathbf{y}(n) - \sum_{m=1}^{2} \tau_m(n)\mathbf{a}(z_m) \right\|^2, \quad (1)$$

where $\mathbf{y}(n)$ is the K-dimensional MB data vector in the pixel under test, being K the number of tracks, at the generic n-th ($n = 1, \ldots, N$) look, and $\mathbf{a}(z)$ is the response of the MB array to a point-like scatterer [4] calculated for the height z. The vector $\mathbf{z} = [z_1, z_2]^T$ contains the height of the two scattering centroids to be separated, whose complex amplitude are in the vector $\boldsymbol{\tau}_n = [\tau_1(n), \tau_2(n)]^T$.

The relaxation procedure operates by extracting the dominant component, subtracting it from the data, and then iterating for each of the two components to be estimated, until a convergence criterion is satisfied. In this way, the multidimensional non-linear minimization of (1) is transformed into a sequence of simpler one-dimensional problems, one decoupled from the other. After the estimation of z_1 and $\{\tau_1(n)\}_{n=1}^{N}$, define the residual data

$$\mathbf{y}_2(n) = \mathbf{y}(n) - \hat{\tau}_1(n)\mathbf{a}(\hat{z}_1), \quad (2)$$

and replace $\mathbf{y}(n)$ with $\mathbf{y}_2(n)$ in (1). By minimizing with respect to z_2 and $\tau_2(n)$, it results:

$$\hat{z}_2 = \arg\min_{z} \mathbf{a}^H(z)\hat{\mathbf{R}}_2\mathbf{a}(z), \quad (3)$$

$$\hat{\tau}_2(n) = \frac{1}{K}\mathbf{a}^H(\hat{z}_2)\mathbf{y}_2(n), \quad (4)$$

where $\hat{\mathbf{R}}_2$ is the multilook estimate of the covariance matrix of vectors $\mathbf{y}_2(n)$. The described procedure can then be repeated for z_1 and $\tau_1(n)$, and so on. Finally, after convergence is achieved, the minimum of $\hat{z}_1$ and $\hat{z}_2$ is labelled as the ground height.

It is worth remarking that in the signal processing literature it has been demonstrated that while M-RELAX is asymptotically statistically efficient when dealing with point-like scatterers [9], it is also robust to a model mismatch [8]. Moreover, in contrast to MB maximum likelihood techniques, the ground topography is estimated without the need of estimating the parameters of the canopy scatterer.

3. EXPERIMENTS WITH REAL DATA

In this Section, the performance obtained by M-RELAX in the estimation of the ground height is reported and discussed. The analysis has been carried out by processing two DLR's E-SAR L-band datasets acquired over the forest site of Krycklan (Sweden) and Traunstein (Germany) acquired in the framework of the campaigns BioSAR 2008 and TempoSAR 2008, respectively.

3.1. Description of the data sets

The Krycklan test site consists of a medium-height boreal forest with biomass levels of up to 200 tons/ha (at hectare-level resolution and above). Topographic variations are relevant, with many steep slopes. The processed dataset consists of 6 images with nominally uniform baselines and maximum horizontal baseline equal to 36m. With such a baseline, tree heights are mostly distributed around 0.6 Rayleigh resolution units in height. The Traunstein test site represents a temperate mixed mountain forest and is located in south-eastern Germany. Forest heights vary between 10m to 40m. Mean biomass level is on the order of 210t/ha while some old forest stands can reach biomass levels up to 600t/ha. Compared to other managed forests in this ecological zone (mean biomass of 121 t/ha) the biomass values of Traunstein forest are significantly higher. Typical for the pre-alpine character of the test site is the fairly flat relief disturbed by a few steep slopes. In this case, 5 images were processed with baselines 0, 5, 10, 15 and 25m with respect to the master acquisition. Such an acquisition results in to tree heights higher than 1 Rayleigh resolution unit for almost the 50% of the tested area. Both datasets have been acquired in a time span of approximately 1 hour, thus temporal decorrelation effects have been considered neglectable.

3.2. Results

The M-RELAX estimator has been applied to the HH and HV channels of both data sets, and the estimated heights have been compared with the corresponding LiDAR digital terrain models. In Fig. 1 the range-azimuth maps of the estimation errors SAR−LiDAR are shown for the two data sets in HH polarization. The histograms of the estimation errors are plotted in Fig. 2, while their bias and standard deviation (std) are reported in Tab. 1. In general, the estimation performance is very good, with an std around 2m and a bias that, depending on the polarization channel and the density of the forest stand, varies between an almost null value to around 1m. More in details, concerning the Krycklan data set, the estimated ground is globally almost unbiased and with an std of 2m in HH. A bias (0.6m) appears with HV data, consistently with the hypothesis that HV channel is more sensitive to the canopy volume. It is worth noting that these values of std are partially affected by the presence of high slopes. In fact, by excluding these areas from processing, a better std (1.5m) is obtained. In the more dense forest of Traunstein the std is higher than 2m. A non-negligible bias is observed in both the HH and HV channels, and it increases from 0.5m in HH to 0.8m in HV. The analysis of the estimation performance in bare areas reveals errors with std much higher in Krycklan than in Traunstein. This difference could have been caused by the different qualities of the MB phase calibration of the two data sets; further analyses are ongoing. In forested areas, small estimation biases are present in Krycklan, while std remains still around 2m. In Traunstein the situation is more critical as the bias reaches 1.3m in HV.

For further analyses, ground and canopy parameters have been estimated by using the inversion method described in [9]. The MB covariance matrix of the canopy has been parameterized as a function of the forest height and of an extinction, obeying to the classical exponential vertical distribution of the power backscattered by the canopy [1, 2]. High extinction values correspond to a volume vertical distribution more concentrated around the backscattering height centroid. On the other hand, low extinction values (tending to 0) enlarge the volume extension in height and increase the model mismatch of M-RELAX. The estimated ground-to-volume power ratios (hereafter called μ for brevity) are plotted in Fig. 3, for the HH and HV channels in both test sites. As expected, due to the different biomass levels, μ results in average higher in

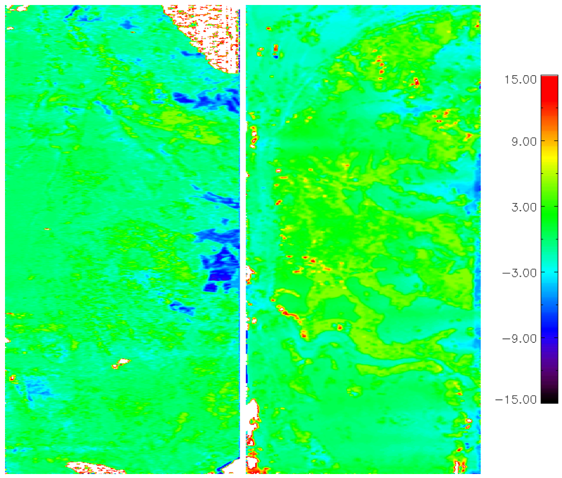

Fig. 1. Maps of height estimation error (in meters), HH. Left panel: Krycklan; right panel: Traunstein. Range from left to right, azimuth from bottom to top.

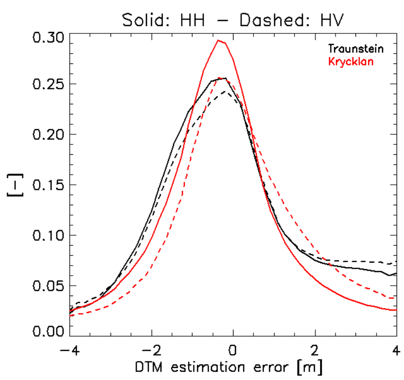

Fig. 2. Histograms of the DTM estimation error.

		KRYCKLAN		TRAUNSTEIN	
		Bias	Std	Bias	Std
GLOBAL					
	HH	0.1	2.0	0.5	2.3
	HV	0.6	2.1	0.8	2.5
BARE					
	HH	0.1	1.7	0.3	1.2
	HV	0.2	1.8	0.4	1.3
FORESTED					
	HH	0.1	2.0	0.9	2.4
	HV	0.5	2.1	1.3	2.5

Table 1. Estimation bias and std (in meters) for the two analyzed data sets.

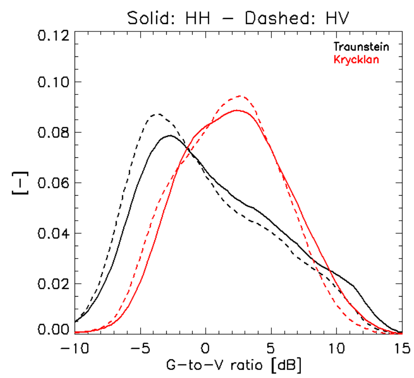

Fig. 3. Histograms of the ground-to-volume power ratios.

Krycklan than in Traunstein (around 2dB of difference). This increase in μ, together with a larger tomographic aperture, explains the better performance in ground estimation obtained in Krycklan, and coupled with the super-resolution capabilities of M-RELAX, it compensates the negative effects of a reduced forest height with respect to Traunstein. Notice also that in both test sites μ values in HV are generally lower than in HH, although no big differences are observable in the distributions.

To better understand the origin of the estimation errors, we plotted in Fig. 4 the histograms of μ for height errors lower than 1m and higher than 2m. For this analysis we considered only the HH channel, as it is more sensitive to the ground backscattering. In both test sites, it possible to observe that for very low μs (approximately lower than -3dB) there is a predominance of big errors, while for μs higher than 5dB small height errors are dominant. This matches with what expected. Nevertheless, in the low-μ region the presence of small errors can be observed too. For both data sets, small errors have been seen to correspond to high extinction values and forest heights higher than the Rayleigh limit. This phenomenon is more apparent in Traunstein, where higher forest stands are present. However, it is reasonable to expect that a model mismatch could have impaired the estimation performance for lower extinctions. It is worth noting that the Cramér-Rao bound analysis in [10] already highlighted that for small μs an acceptable (asymptotic) estimation performance can be reached only for higher trees with high extinction, as observed in the real data. Conversely, in the high-μ region, the model mismatch for the canopy scatterer is not relevant, as small errors are obtained independently of the extinction. The main limiting factor has been seen to be the forest height, especially for forest stands smaller than half Rayleigh unit, again consistently with the analysis in [10]. When μ assumes values between around -3dB and 5dB, higher errors are slightly predominant over small errors. It has been seen that the most part of the higher errors are in correspondence of small forest stands (smaller than the Rayleigh unit) with a small extinction, i.e. in presence of a model mismatch on the canopy scatterer. Sub-Rayleigh stands, but with higher extinctions, give in average small errors. Moreover, stands higher than Rayleigh resolution unit can provide small errors even with small extinctions.

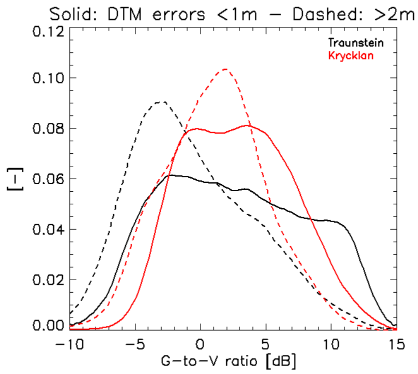

Fig. 4. Histograms of the ground-to-volume power ratios conditioned to the DTM estimation errors.

A final issue to be addressed is the evaluation of the capabilities of M-RELAX in estimating the ground topography with a dual baseline acquisition. Limiting the number of baselines of repeat-pass acquisitions is of interest in order to reduce temporal decorrelation effects. This experiments have been carried out by processing the HH channel of the more critical Traunstein data set. The considered track distribution is composed by the master and the passes with horizontal baselines 10m and 15m. The ground estimates in bare areas results to be almost not biased and with an std around 1.5m. A higher std has been observed in forested areas, increasing from 2.4m of the full-track dataset to 3.1m of the considered dataset, with a bias still around 1m. Although some worsening in the performance is expectable at the reduction of number of baselines available for processing, the results obtained are still satisfactory.

4. CONCLUSIONS

In this work, the performance obtained by M-RELAX in the estimation of the sub-canopy ground topography with L-band MB acquisitions has been investigated with repeat-pass real data collected over a boreal (Krycklan) and a temperate mixed (Traunstein) forest, with different levels of biomass. The ground height has been estimated in both cases with a very satisfactory precision, with a standard deviation equal to or slightly higher than 2m. The best results have been obtained by processing the HH channel. In the HV channel an estimation bias appears, which reaches around 1m in the most dense forested areas. A satisfactory precision (nearly 3m) has been achieved in a dual-baseline case.

The experiments carried out have shown that the volume mismatch plays a role mostly for intermediate ground-to-volume power ratios in sub-Rayleigh forest stands and in particular with a very low extinction. First experiments have also started in order to understand the role of model mismatches at the ground level.

Future work will be dedicated in further extending this performance analysis. Comparison with other estimation techniques will be carried out. The effects of coherently processing more than one polarization channel will be evaluated.

5. 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] C. Lopez-Martinez, X. Fabregas, A. Alonso, K. Papathanassiou, ”Ground Topography retrieval on Forested Areas Based on Polarimetric SAR Interferometry,” *Proc. of 2010 European SAR Conference (EUSAR)*, Aachen, Germany, Jun. 2010.

[3] 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.

[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] Y. Huang, L. Ferro-Famil, A. Reigber, “Under-Foliage Object Imaging Using SAR Tomography and Polarimetric Spectral Estimators,” *IEEE Trans. on Geoscience and Remote Sensing*, in press, Sept. 2011.

[6] 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.

[7] M. Pardini, K. Papathanassiou, “Sub-Canopy Topography Estimation With Multibaseline Pol-InSAR Data: A RELAX-Based Approach,” *Proc. of ESA FRINGE Workshop*, Frascati, Italy, Sept. 2011.

[8] F. Gini, F. Lombardini, M. Montanari, “Layover Solution in Multibaseline SAR Interferometry,” *IEEE Trans. on Aerospace and Electronic Systems*, Vol. 38, No. 4, pp. 1344-1356, Oct. 2002.

[9] J. Li, P. Stoica, “Efficient Mixed-Spectrum Estimation with Apllications to Target Feature Extraction,” *IEEE Trans. on Signal Processing*, vol. 44, no. 2, pp. 281-295, Feb. 1996.

[10] M. Pardini, K. Papathanassiou, F. Lombardini, “Theoretical Performance Bounds on the Estimation of Forest Structure Parameters From Multibaseline SAR Data,” *Proc. of ESA FRINGE Workshop*, Frascati, Italy, Sept. 2011.