Evaluating PolInSAR parameter estimation using tomographic imaging results

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Abstract—This paper concentrates on the forest height and ground topography estimation by means of polarimetric SAR interferometry and tomography. In polarimetric SAR interferometry, one of the most important methods described in literature is the line-fitting approach in the complex unitary circle [1]. Although it has shown their principal potential, an open issue is still the precise validation of the estimated parameters, as ground-truth collection is an extremely complex task in the case of forest parameters. SAR tomography is an alternative technique, which generates a fully three-dimensional representation of the imaged scene through coherent combination of a greater number of tracks [2][3]. Forest ground and canopy are directly visible in a tomographic image; a tomographic image can therefore be used as an ideal validation base for PolInSAR forest parameter estimation.

This paper compares high-resolution polarimetric SAR tomograms with PolInSAR forest height estimations, both derived from the same data set. This allows to identify areas of good applicability, as well as principal deficiencies of the different PolInSAR approaches.

I. INTRODUCTION

During the past few years, the combination of polarimetric and interferometric aspects of SAR data has been studied in several works. In particular, these techniques promise to be able to provide improved estimation of parameters like tree height, true ground topography and forest canopy density through inversion of special simple scattering models. Though some of these applications have already been demonstrated in several studies, a major question in PolInSAR is still the reliability and accuracy of the results. Additionally, the applicability of the involved scattering models as well as the correct choice of appropriate baseline and processing parameters are to be justified.

In contrast to the above, SAR tomography, as a three-dimensional imaging technique, opens the direct access to the scatterer distribution in height. As a true imaging technique, it is independent of an underlying scattering model. Therefore, SAR tomography has its greatest potential in resolving unknown or complicated scatterer distributions. However, since a large number of parallel tracks (>10) is required for generating a tomogram, the experimental effort for SAR tomography currently limits its large scale application. In this paper, a SAR tomogram is used as a reference measurement for evaluating the prerequisites and the quality of model-based PolInSAR parameter estimation.

This paper is organised as follows: In Sec. II and III, brief introductions into the fields of PolInSAR and TomoSAR are given. In Sec. IV, first several constraints on the baselines and the preprocessing parameters are identified. Then a PolInSAR inversion is performed on the best single image pair of the tomographic data set, identified during the steps before. This inversion result is then compared on a pixel-by-pixel basis with the tomographic imaging results. Finally, in Sec. V, some conclusions are given.

II. POLARIMETRIC SAR INTERFEROMETRY

The common representation of PolSAR data is the coherency matrix $T_6$, which is estimated by multi-looking from coherent scattering vectors $k_i$ in Pauli decomposition:

$$k_i = \frac{1}{\sqrt{2}} [S_{HH}, S_{VV}, S_{HV} - S_{VH}, 2S_{HV}]^T$$

(1)

$$T_6 = \langle kk^t \rangle = \begin{bmatrix} T_{11} & \Omega_{12} & \Omega_{13} \\ \Omega_{12} & T_{22} & T_{23} \\ \Omega_{13} & T_{23} & T_{33} \end{bmatrix}$$

(2)

where $S_{HH}$, $S_{VV}$ and $S_{HV}$ are elements of two ($i = \{1, 2\}$) polarimetric scattering matrices. $T_{ii}$ correspond to polarimetric coherency matrix of scattering vectors $k_i$, and $\Omega_{ij}$ to polarimetric interferometry between $k_1$ and $k_2$.

Forest is modelled as random volume over ground, as derived for the PolInSAR case in [4], [5]. The coherence of the coherency matrix $T_6$ in (3) is faced to forest related values in (4).

$$\gamma = \frac{\mathbf{w}^t \Omega_{12} \mathbf{w}}{\sqrt{\mathbf{w}^t T_{11} \mathbf{w} \mathbf{w}^t T_{22} \mathbf{w}}} = e^{i\phi_o} (\gamma_v + (1 - \gamma_v) L_{(w)})$$

(3)

where $\mathbf{w}$ is a normalised projection vector and can be interpreted as scattering mechanism. $\phi_o$ is related to the ground topography height simply by $h_o = \frac{\phi_o}{k_z}$ ($k_z$: vertical wavenumber). $\gamma_v$ is the volume coherence according to the random volume model and is computed by:

$$\sigma = \frac{2\pi}{\cos\theta_0 (e^{2\pi h_0 / \cos\theta_0} - 1)} \int_0^{h_v} e^{ik_z z + 2\pi z / \cos\theta_0} dz$$

(4)

In the equation above is the forest canopy density modelled as (polarisation independent) wave extinction in the random volume. $\theta_0$ is the incidence angle and $h_0$ corresponds to the height of the canopy. $L_{(w)} \in [0, 1]$ is a function of ground to volume ratio, which depends on the polarisation. With only one variable, $L_{(w)}$, the equation (4) describes a line in dependence of polarisation.

Based on this line–model, an inversion process to retrieve forest parameters $\sigma$, $h_v$, and $h_o$ was introduced in [1]. In a first step a line is fitted to a set of coherences in the complex space. This line simultaneously relates to the line
and in (4). The ground coherence $\gamma_0$ is one of the two intersection points of the line and the complex unitary circle. Its module is one and the phase is the ground phase $\phi_0$. An estimate for the volume coherence $\hat{\gamma}_v$ is a coherence point along the line farthest away from the ground coherence. Knowing the ground phase, volume coherences $\hat{\gamma}_v(\sigma, h_v)$ for a set of feasible volume extinction coefficients and canopy heights is computed according to (5). Parameters $\sigma$ and $h_v$ are finally retrieved from:

$$\{\sigma, h_v\} = \arg \min_{\sigma, h_v} |\hat{\gamma}_v - \gamma_v(\sigma, h_v)|$$

(6)

III. SAR Tomography

SAR tomography consists in focusing several SAR images in the third dimension, in order to image volumetric areas, such as forests or cities. This means to form a synthetic aperture along the direction perpendicular to azimuth and to the radar line of sight. The geometry of a tomographic data acquisition uses typically $K$ parallel tracks non uniformly spaced, which observe the same scene. From the $K$ images, 3D profiles might be extracted. This makes it possible to detect targets under covered volume or to generate 3D representation of the scene under study.

A tomographic data acquisition system is constituted by $K$ sensors, or interferometric paths. The signals $x_d$ received by each sensor $d$ provided by $D$ scatterers localised at height $\{z_d\}_{d=1}^D$ are arranged in the $K \times 1$ vector $x$:

$$x = As + n$$

(7)

where $s$ represents the backscattered power of the $D$ scatterers and $n$ denotes a vector formed by scalar $n_k$ representing a circular Gaussian white noise. The A matrix, with dimension $K \times D$, contains the phase response due to the sensor geometry only. This matrix is made up various vectors $a(z_d)$ representing the steering vector, which corresponds to the $d$-th scatterer:

$$a(z_d) = [e^{i\phi_1(z_d)}, \ldots, e^{i\phi_K(z_d)}]^T$$

(8)

with $\phi_k(z_d)$ denoting the phase caused by the distance between a scatterer at height $z_d$ and antenna $k$.

To focus such tomographic SAR data, the range of valid heights is scanned using the steering vector $a(z)$ of Eq. 8. The power, estimated by Fourier or Capon based focusing, is given by:

$$\hat{P}_F(z) = \frac{a(z)^H R a(z)}{K^2} \quad \text{and} \quad \hat{P}_C(z) = \frac{1}{a(z)^H R^{-1} a(z)}$$

(9)

with $R$ denoting the covariance matrix of the data vector $x$.

Another category spectral estimators is based on the principle of subspace estimation. In the case of tomographic SAR data processing, the MUSIC method has been used. The pseudo-beamforming of MUSIC, $\hat{P}_M(z)$, is given by:

$$\hat{P}_M(z) = \frac{1}{a^H (\hat{E}_N \hat{E}_N^H) a}$$

(10)

where $\hat{E}_N$ represents the noise subspace obtained after an eigendecomposition of the observed covariance matrix, $\hat{R} = \hat{E}_N \hat{E}_N^H$ [6]. The term pseudo-beamforming is employed here because $\hat{P}_M(z)$ is only usable to localise the target height but not to measure its backscattering power.
pairs have been ordered by their baseline length and range-filtered. Additionally, the flat-earth and topographic phase components have been removed from the interferograms.

Fig. 3 (top) shows the dependence of the mean interferometric coherence of the ROI in the two co-polar channels HH and VV, as well as the cross-polar channel XX. For the coherence estimation, a Gaussian smooth with a window size of 33 has been used, corresponding to an effective number of looks of about 210. As it can be observed, the coherence decrease quickly with increasing baseline, as it can be expected for volume scatterers. Interestingly, after a minimum around 20m, the coherence increase again to a secondary maximum around 35-40m. In theory, the volume decorrelation should follow the autocorrelation function of the FOURIER-transform of the vertical scatterer distribution. The observed shape is therefore an indication of the presence of a relatively homogeneous vertical scatterer distribution.

Another important parameter is the linearity of the cloud of complex coherences in the unitary circle, which can be reached by variations of the polarisation. As a measure, the pseudo-ellipticity [7]

\[ \chi = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2} \]  

formed out the two eigenvalues \( \lambda_1 \) and \( \lambda_2 \), obtained from an eigendecomposition of the cloud of complex coherences is used. It becomes one for linear shapes and 0 for circular shapes. Its dependence on the baseline is shown in Fig. 3 (bottom): Only at baselines smaller than 20m, the pseudo-ellipticity lies significantly above the constant level present at larger baselines. The relatively high values around 0.45 at larger baselines are an effect of the averaging during coherence estimation (as above with about 210 looks), which causes a tendency towards a linear shape [8].

Summarising, at baselines above 20m, phase ambiguities between ground and canopy can be expected and no useful results can be obtained by means of PolInSAR parameter inversion. On the other hand, at very small baselines no significant phase differences are occurring between ground and canopy, hindering a PolInSAR analysis as well. Additionally, at small baselines temporal decorrelation can have strong effect on the inversion results. Therefore, for the ROI selected, PolInSAR inversion should ideally take place at baselines between 5 and 20 metres.

B. Inversion quality

To evaluate the quality of the PolInSAR data inversion, the ground and canopy height has been extracted from the SAR tomogram. To do so, the two main maxima in each vertical profile within the ROI has been searched. The lower one is used as the ground height. The higher one corresponds not necessarily to the top of the canopy, but to its strongest backscattering. Therefore, the height above the canopy peak, where the backscattering intensity is reduced to -6dB compared to the peak value is used as the canopy height. The difference of both is the forest height \( h_{V\text{tomo}} \), as estimated by SAR tomography. It is shown in Fig. 4a. Since SAR tomograms are formed at the full resolution of the sensor, the resulting forest height map has high resolution in all three dimensions. In addition, a validity mask has been generated, masking out pixels without two distinct peaks and pixels with two peaks closer than 5 metres.

In the following, PolInSAR parameter inversion has been performed on all data pairs with baselines between 0.0 and 21.0 metres, as well as on some pairs with larger baselines. Again a 210 look Gaussian smooth has been used for spatial averaging during coherence estimation. Also for the PolInSAR
case, a validity mask must be generated. It is based on the intersection of the $\gamma_V$ curves with the line fitted through the complex coherences. They are compared with the two coherence values the furthest away from the two intersection points of the line with the unitary circle, respectively. If for both possibilities no distance smaller than 0.1 is found, this pixel is rejected.

The estimated forest heights $h_{\text{polin}}$ for 3 different baselines are shown in Fig. 4b-4d, other parameters like ground phase and attenuation coefficient have not been taken into account in this study. The estimations using baselines of between 10-15m (Fig. 4e) show a relatively good accordance with the results obtained from tomography, although the variations in height within the ROI do not perfectly match. As expected, at too small baselines the height cannot be extracted precisely; the same is the case at baselines close to the minimum of the coherence around 20m and above, where the interferometric $2\pi$-ambiguity height is smaller than the mean forest height.

In Fig. 5, a summary of the estimated deviations is given, based only on pixels valid in both tomographic and PolInSAR results. It shows the error in the height maps $h_{\text{tomo}} - h_{\text{polin}}$, as well as its standard deviation in function of effective baseline. At baselines of below 10m, where only small phase effects between ground and canopy are occurring, PolInSAR strongly over-estimates the heights. However, between 10 and 20m, the mean heights are matching well with those obtained by SAR tomography, even though a relatively large standard deviation of about 0.1 is present. As mentioned above, at longer baselines PolInSAR inversion is not expected to work; the values given only reflect what happens outside the region of validity for PolInSAR. Here, the forest height becomes strongly underestimated, while the PolInSAR validity mask contains fewer but still many pixels of the ROI ($\sim$40%).

V. DISCUSSION

At baselines around 10-15m, a good agreement between the mean forest height observed in SAR tomograms and those estimated by PolInSAR can be observed. The spatial resolution of PolInSAR results is much lower due to the involved averaging when estimating the coherence. This might explain why the small regions with higher trees within the ROI are not always well detected by PolInSAR. In all pairs a relatively large standard deviation is occurring. At baselines below 10m, PolInSAR seems to overestimate the tree heights, which might be caused by temporal decorrelation effects, which have not been considered in this study. As expected, at baselines above 20m, PolInSAR estimation leads to poor results, which is in many cases not detected by the used validity check.

It has to be noted that also the tomographic results are not absolutely accurate. In particular, it is hard to precisely locate the canopy top in the backscattering profiles. However, the tomographic image represents what is seen by the sensor, therefore any SAR based technique should ideally estimate heights similar to the tomographic ones, even if they don’t correspond precisely to the true tree heights.

From this limited study, based only a single ROI, it can be concluded that PolInSAR inversion is able to deliver correct estimates of tree heights, but at low spatial resolution and with a relatively large standard deviation. An important condition seems to be the correct choice of baseline, which has to lie in a relatively small range for correct inversion results. Presumably, this range depends also on the height of the forest. Finally, the used validity check seems to be not sufficient to detect invalid pixels.

REFERENCES


