POL-INSAR FOREST HEIGHT INVERSION USING TOMOSAR REFLECTIVITY PROFILES

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ABSTRACT

The realistic parameterization of the underlying (vertical) radar reflectivity profile is critical for a model-based inversion of forest height from polarimetric interferometric (Pol-InSAR) data. Indeed, an appropriate parameterization not only affects the final estimation performance, but also enables the inversion from a reduced observation space in terms of number of baselines and / or polarizations. Here, we investigate the possibility of using a full tomographic profile to parameterize the inversion. The proposed methodology is demonstrated and validated using Pol-InSAR and tomographic data acquired in the framework of relevant airborne campaigns.

Index Terms— Forest height, Synthetic Aperture Radar, polarimetric interferometry, tomography.

1. INTRODUCTION

Polarimetric interferometric SAR (Pol-InSAR) techniques have been established especially for accurate forest height estimation on large scales in the context of air- and spaceborne implementations (see e.g. [1]-[4]). In the last years, Pol-InSAR evolved from single- to multi-baseline and even tomographic (TomoSAR) configurations. These configurations allow the reconstruction of the 3D (radar) reflectivity using TomoSAR imaging algorithms, and build up sufficiently high-dimensional observation spaces to resolve even complex 3D scattering processes.

In a model-based Pol-InSAR forest height inversion the appropriate parameterization of the vertical reflectivity profile defining the Pol-InSAR coherences is a critical step. The (frequency-dependent) scattering model is essential for the significance and accuracy of the estimated parameters. The model must contain enough physical structure to interpret the interferometric measurements, and at the same time it must be simple in terms of number of parameters in order to be determinable with the available (in general limited) number of measured coherences.

Recently, several data-driven attempts have been made by using lidar data to constrain the height inversion problem [5]-[7]. Motivated by the promising results achieved so far, in this paper the use of reflectivity profiles estimated by means of TomoSAR techniques to invert forest height from Pol-InSAR coherences is proposed and investigated by processing real airborne data. A successful implementation of this synergic combination between Pol-InSAR and TomoSAR would bring several benefits for instance in terms of SAR space borne mission implementation. TomoSAR profiles could be obtained in an initial mission phase and used to initialize / constrain the estimation of height (and structure) changes in a successive mission phase, similarly to the ESA BIOMASS case. This allows a more dense temporal sampling and even an effective exploitation of the (more sensitive) long baselines. At the same time, it could allow to estimate forest height even in the presence of a moderate temporal decorrelation contribution with a limited number (two or even a single one) of interferometric coherence measurements.

2. FOREST HEIGHT INVERSION

The main InSAR measurement is the complex interferometric coherence. If temporal decorrelation is negligible (or even absent), after the compensation of system- and processing-related decorrelations, and range and azimuth spectral filtering, the observed coherence reduces to the volume decorrelation contribution $\tilde{\gamma}_{Vol}(\kappa_z, \vec{w})$ [1], [4]:

$$\tilde{\gamma}_{Vol}(\kappa_z, \vec{w}) = \frac{\int_{z_0}^{z_0+h_V} F(z, \vec{w}) \exp(i\kappa_z z) dz}{\int_{z_0}^{z_0+h_V} F(z)\, dz} \quad (1)$$

where κ_z is the vertical (interferometric) wavenumber and $F(z, \vec{w})$ (where z indicates the vertical axis) is the vertical reflectivity function (also referred as the vertical reflectivity profile) expressing the vertical distribution of scatterers seen by the interferometer. $\vec{w}$ indicates the polarimetric channel. The lower bound of $F(z, \vec{w})$ is given by the reference height z_0 associated to the location of the underlying ground. The upper bound of $F(z, \vec{w})$ is given by $z_0 + h_V$ which in the case of a forest scatterer corresponds to the (top) forest height. It is exactly the $\tilde{\gamma}_{Vol}(\vec{w})$ contribution that provides the sensitivity to the vertical structure of volume scatterers. Equation (1) constitutes the physical basis for the estimation of 3D forest structure parameters related to $F(z, \vec{w})$ from interferometric measurements at different spatial baselines and/or polarisations.

If a model $F_m(z, \vec{w}, h_V)$ is available for $F(z, \vec{w})$, the corresponding $\tilde{\gamma}_{Vol,m}(\kappa_z, \vec{w}, h_V)$ can be calculated according to (1), and the inversion problem is typically stated as:

$$\min_{h_v} \left\| \tilde{\gamma}_{Vol}(\kappa_Z, \vec{w}) - \tilde{\gamma}_{Vol,m}(\kappa_Z, \vec{w}, h_V) \right\| \quad (2)$$

Notice that $\tilde{\gamma}_{Vol,m}$ can actually depend on a number of additional unknown parameters that increase the dimensionality of the problem and of the observation space needed for a determined inversion.

2.1 RVoG model with exponential volume reflectivity

Under the two-layer assumption, $F_m(z, \vec{w})$ consists of an extended vegetation (volume) component $f_V(z, \vec{w})$ and a Dirac-like component $m_G(\vec{w})\delta(z - z_0)$ associated to the underlying ground (i.e. direct surface and dihedral vegetation-surface contributions) where $m_G(\vec{w})$ is the ground scattering amplitude. The associate volume coherence is:

$$\tilde{\gamma}_{Vol,m}(\kappa_z, \vec{w}) = \exp(i\, \varphi_0) \frac{\tilde{\gamma}_{V0}(\kappa_z, \vec{w}) + m(\vec{w})}{1 + m(\vec{w})} \quad (3)$$

where $\varphi_0 = \kappa_Z z_0$ is the phase related to the underlying ground height z_0, $\tilde{\gamma}_{V0}(\kappa_z, \vec{w})$ is the volume-only coherence:

$$\tilde{\gamma}_{V0}(\kappa_z, \vec{w}) = \frac{\int_0^{hv} f_V(z, \vec{w}) \exp(i\kappa_Z\, z) dz}{\int_0^{hv} f_V(z, \vec{w})\, dz} \quad (4)$$

and $m(\vec{w}) = m_G(\vec{w}) / \int_0^{hv} f_V(z, \vec{w})\, dz$ is the effective ground-to-volume (amplitude) ratio. A widely (and very successfully) used model for $f_V(z, \vec{w})$ is an exponential distribution of scatterers

$$f_V(z, \vec{w}) = m_V(\vec{w}) \exp(2\sigma(\vec{w}) z / \cos(\theta_0)) \quad (5)$$

i.e. $f_V(z, \vec{w})$ is described by an exponential defined by a single parameter, namely the exponential rate $\sigma(\vec{w})$. For a Random Volume, $\sigma(\vec{w}) = \sigma$ becomes polarisation independent. This model, known as the Random Volume over Ground (RVoG) model, comprises four unknowns: the forest height h_V, the extinction coefficient σ, the phase term φ_0 associated to the reference height z_0 and the polarisation depended ground-to-volume ratio $m(\vec{w})$. The unambiguous estimation of forest height is possible using just a single baseline, but this requires not only quad-pol data, but also the additional assumption of a zero-ground-to-volume amplitude ratio in one polarimetric channel, i.e. $m(\vec{w}_V) = 0$ [4].

2.2 Inversion using the TomoSAR profiles

The approach proposed in this paper consists in using an available TomoSAR estimate $P(z, \vec{w})$ of $F(z, \vec{w})$. First of all, $P(z, \vec{w})$ is resampled over a normalized axis z_n ranging between 0 and 1. Afterwards, the modelled volume coherence can be rewritten as:

$$\tilde{\gamma}_{Vol,m}(\kappa_z, \vec{w}) = \exp(i\, \varphi_0) \frac{\int_0^1 P(z_n, \vec{w}) \exp(i\kappa_Z\, z_n h_V) dz_n}{\int_0^1 P(z_n)\, dz_n} \quad (6)$$

In this way, forest height can be estimated already from single-baseline single-polarimetric interferometric (complex) coherences.

In practical applications, the use of the more "relevant" components of $P(z, \vec{w})$ might be suitable to filter out changes of the reflectivity profile between the TomoSAR and the Pol-InSAR acquisitions that could affect the height inversion performance (e.g. temporal dielectric changes). This is attempted here by calculating a "mean" reflectivity profile. For this the so-called profile matrix is formed by using a set of profiles within an area. The individual reflectivity profiles are normalized to unit height and stacked as columns of the profile matrix [P]. From the profile matrix a covariance matrix is formed and diagonalized

$$[R_P] = [P][P]^T = [U_P][\Lambda_P][U_P]^T \quad (7)$$

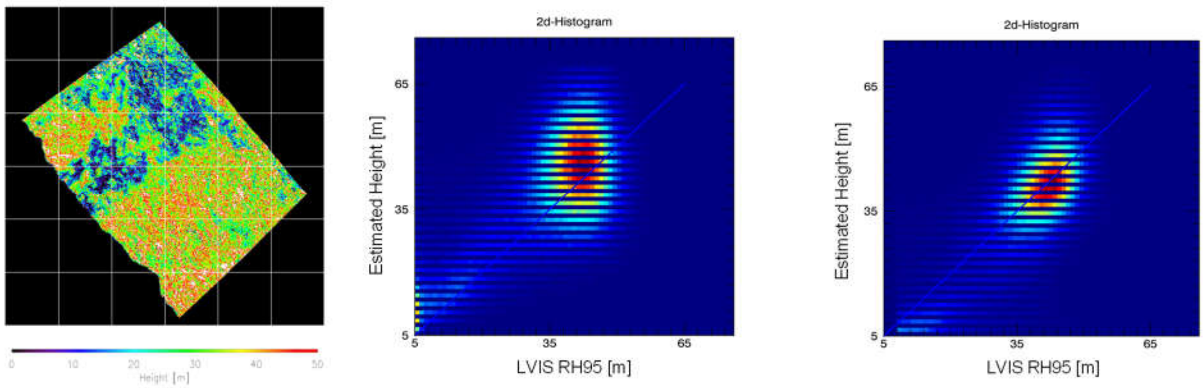
The diagonal matrix $[\Lambda_P]$ contains the positive real eigenvalues λ_n of $[R_P]$ while the columns $u_n(z)$ of $[U_P]$ are the orthogonal eigenvectors of $[R_P]$. It has been seen experimentally that typically the first 3-5 eigenvalues already represent more than the 90% of the total profile power (the sum of all the egenvalues). Higher order eigenvalues (and thus the associated eigenvectors) become less significant for the reconstruction of the profile. Further, higher order eigenvectors contain the higher spatial frequency components of the reflectivity profile along height. It is reasonable to assume that reflectivity changes affect the high spatial frequency components rather than the low frequency ones (see e.g. [8]). Thus, a "mean" profile suitable for the inversion is reconstructed by linearly combining the first *N* eigenvectors:

$$P_N(z) = \sum_{i=1}^{N} a_n u_n(z) \quad (8)$$

Note that (8) is very similar to the concept of orthogonal functions for describing the vertical radar reflectivity as proposed in [9] but addressed in terms of TomoSAR profiles rather than Lagrange polynomials. The eigenvectors $u_n(z)$ define an orthogonal basis that can be used for the decomposition or the synthesis of individual (vertical) reflectivity profiles.

3. FIRST RESULTS

First inversion results have been obtained by processing a P-band TomoSAR dataset over the Lopé National Park in Gabon acquired during the AfriSAR campaign by the DLR's F-SAR airborne platform on Feb. 10, 2016 [10]. The flown tracks are (nominally) uniformly spaced and the realized κ_z



(a) (b) (c)

Fig. 1. Lopé (Gabon): (a) Pol-InSAR forest height estimates obtained using the exponential profile with F-SAR data at P-band, (b) corresponding 2-D histogram against the LVIS RH95 lidar heights; (c) 2-D histogram comparing the Pol-InSAR foret height obtained using the TomoSAR profiles against the LVSI RH95 lidar heights.

lead to a vertical Rayleigh resolution of about 10 m at mid range.

The forest height map obtained using the classical Pol-InSAR inversion with the RVoG model in Section 2.1 is shown in Fig. 1(a). Pol-InSAR coherences at three different κ_z (0.04, 0.09, 0.13 rad/m at mid range) were used to cover the whole height range for this test site. The height estimates have been compared to the Land, Vegetation, and Ice Sensor (LVIS) lidar RH95 heights measured over the same site. The corresponding 2-D histogram is shown in Fig. 1(b).

TomoSAR profiles have been calculated by means of the Capon spectral estimator, and used for the height inversion as well. For this first result, for each coherence the corresponding full profiles has been used. In contrast to the Pol-InSAR inversion, only one κ_z (0.09 rad/m) has been used for the inversion. The comparison of the obtained estimates with the LVIS RH95 is shown in Fig. 1(c). It is apparent that using the TomoSAR profile the inversion performance improves with respect to the classical Pol-InSAR inversion with the exponential profile, demonstrating the potentials of the proposed technique. Residual estimation errors have been found in correspondence of slopes.

Additional real data results will be shown in the full paper. The obtained performance, also in the case in which a "mean" profile needs to be used, will be fully characterized.

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