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Multi-baseline Pol-InSAR Forest Height Estimation in the presence of temporal decorrelation

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Abstract

Polarimetric Synthetic Aperture Radar (SAR) Interferometry (Pol-InSAR) is a radar remote sensing technique, based on the coherent combination of radar polarimetry (Pol-SAR) and SAR interferometry (InSAR) which is substantially more sensitive to structural parameters of forest volume scatterers (e.g. forest) than conventional interferometry or polarimetry alone. However, temporal decorrelation is probably the most critical factor towards a successful implementation of Pol-InSAR parameter inversion techniques in terms of repeat-pass InSAR scenarios. In this paper the impact of temporal decorrelation in Pol-InSAR model is discussed. For compensating inversion height error induced by temporal decorrelation multibaseline Pol-InSAR inversion approach is proposed. The approach is supported and validated by using L-band E-SAR repeat-pass Pol-InSAR data acquired in the frame of TempoSAR 2008 campaign.

1 Introduction

In the last years, the coherent combination of both, interferometric and polarimetric observations by means of Polarimetric SAR Interferometry (Pol-InSAR) was the key for an essential break through in quantitative forest parameter estimation [1][2]. Indeed, quantitative model based estimation of forest parameters - based on a single frequency, fully polarimetric, single baseline configuration - has been successfully demonstrated. Several experiments demonstrated the potential of Pol-InSAR techniques to estimate with high accuracy key forest parameters like forest height over a variety of natural and commercial; temperate, boreal and tropical test sites [5] characterized by different stand and terrain conditions. However Pol-InSAR inversion models [1][2][5] account only for the volume decorrelation contribution of the interferometric coherence while other decorrelation effects are ignored. Such decorrelation contributions reduce the interferometric coherence, and increase the variation of the interferometric phase. Regarding forest height inversion applications, the effect of a biased volume decorrelation is important as it leads to overestimated height errors.

This paper focuses on the effect of temporal decorrelation on the inversion of forest height parameters using Pol-InSAR model. Temporal decorrelation induced height errors are corrected by means of coherent multibaseline inversion.

2 Pol-InSAR Inversion and Temporal Decorrelation

2.1 Pol-InSAR Forest Height Inversion

The complex interferometric coherence $\tilde{\gamma}$ estimated at different polarizations contains both, the normalized cross correlation coefficient (amplitude) and the interferometric phase and has been used as a parameter to characterize vegetation. The complex coherence depends on instrument and acquisition parameters as well as on dielectric and structural parameters of the scatterer. A detailed discussion of system induced decorrelation processes can be found in [3]. After calibration of system induced decorrelation contributions and compensation of spectral decorrelation in azimuth and range the estimated interferometric coherence can be decomposed into three main decorrelation processes [3]:

$$\tilde{\gamma} = \tilde{\gamma}_{temp} \tilde{\gamma}_{vol} \tilde{\gamma}_{SAR}$$ (1)

Volume decorrelation $\tilde{\gamma}_{vol}$ is the decorrelation form caused by the different projection of the vertical component of the scatterer into two SAR images. $\tilde{\gamma}_{vol}$ is directly linked to the vertical distribution of scatterers $F(z)$ through a (normalized) Fourier transformation relationship. The vegetation is modelled as a (volume) layer of given thickness containing randomly oriented particles with given backscattering amplitude per volume unit. The random volume is located over an impenetrable ground scatterer represented amplitude. A widely and successfully used model for $F(z)$ is the so-called Random Volume over Ground (RVoG) by its
own backscattering), a two-layer model, composed of a vegetation layer (comprising the canopy and the trunks) and a ground component comprising all scattering components with a phase centre located on the ground.

\[ \tilde{y}_{rv} = \exp(i \kappa z_o) \tilde{y}_{v} + m \frac{1}{1 + m} \]  

(2)

where \( z_o \) is related to the ground topography, \( \kappa \) the effective vertical (interferometric) wavenumber that depends on the imaging geometry and \( m \) the effective ground-to-volume amplitude ratio accounting for the attenuation through the volume \( m = m_v / (m_v + m_i) \). \( \tilde{y}_{rv} \) is the volume decorrelation caused by the vegetation layer only, given by (1):

\[ \tilde{y}_{rv} = \exp(i \kappa z_o) \int \exp(2 \sigma z' / \cos \theta_s) \frac{d z'}{d' z'} \int \exp(2 \sigma z' / \cos \theta_s) \frac{d z'}{d' z'} \]  

(3)

where \( h_i \) is the height of the volume, \( \lambda \) the radar wavelength, \( \theta_s \) the local incidence angle and \( \sigma \) the mean extinction coefficient [1]. In case of a single baseline Quad-pol interferometric acquisition three measured complex coherences \( \{ \tilde{y}(\vec{w}), \tilde{y}(\vec{w}), \tilde{y}(\vec{w}) \} \) each for any independent polarization channel [5] are available to estimate six real unknowns \( (h, \sigma, m_1, \phi_1) \). Assuming no response from the ground in one polarization channel (i.e. \( m_1 = 0 \)), the inversion problem has a unique solution and is balanced with five real unknowns \( (h, \sigma, m_1, \phi_1) \) and three measured complex coherences

\[ \min_{h_1, \sigma, m_1} \left| \begin{array}{c} \tilde{y}_{v} \\ \tilde{y}_{v} \\ \tilde{y}_{v} \end{array} \right| - \left| \begin{array}{c} \tilde{y}_{tv} \\ \tilde{y}_{tv} \end{array} \right| \exp(i \phi_1) \]  

(4)

2.2 Temporal Decorrelation in Pol-InSAR Model

Equation (2) accounts only for the volume decorrelation contribution and other decorrelation effects are ignored. Note here that one has to distinguish between real and complex decorrelation contributions: Both of them bias (reduce) the absolute value of the interferometric coherence and increase variance of the interferometric phase. But, while complex decorrelation biases the expectation value of the (interferometric) phase, the expectation value remains the same in the case of real decorrelation.

2.2.1 General Temporal Decorrelation

One of the most prominent decorrelation contributions in the case of non-simultaneous acquisitions (repeat pass system) is temporal decorrelation, caused by changes within the scene occurring in the time between or even during the two acquisitions. Such changes can effect the location and/or the (scattering) properties of the scatterers within the scene inducing the most general case a complex decorrelation. Temporal changes within the scene occur, in general, in a stochastic manner and can be therefore incorporated in scattering models only in a rather abstract way. Regarding Equation (2), temporal decorrelation may affect both, the volume component that represents the vegetation layer and the underlying ground layer

\[ \tilde{y}(\vec{w}) = \exp(i \phi_1) \frac{\tilde{y}_{tv}(\vec{w})}{1 + m(\vec{w})} \]  

(5)

\( \tilde{y}_{tv} \) denotes the correlation coefficient describing the temporal decorrelation of the volume layer and \( \tilde{y}_{rv} \) the correlation coefficient describing the temporal decorrelation of the underlying surface scatterer. As indicated, both coefficients may be polarisation dependent and complex: For example, changes in the dielectric properties of the canopy layer (due to changes in moisture content) or even more changes in its structural characteristics (caused by the annual phenological cycle or fire events) lead to different amount of change at different polarisations in the volume scatterer. Furthermore, a change in the dielectric properties of the ground scatterer - as for example due to a change in soil moisture - alters the scattering properties in each polarisation in a different way and leads to a polarisation dependent temporal decorrelation of the ground scatterer.

The decorrelation processes within the volume layer occur at different - in general much smaller - time scales than the decorrelation process on the ground (that includes both surface and dihedral scattering). While the vegetation layer starts already to decorrelate at temporal baselines on the order of seconds to minutes and is completely decorrelated for temporal baselines on the order of 1-2 months, the ground scattering remains partially coherent even for very long temporal baselines on the order of months. Especially dihedral scattering mechanisms - related in forest environments to the ground-trunk interaction - appear to be very stable and remain coherent even over the period of several months. However, the individual values and temporal characteristics of \( \tilde{y}_{tv} \) and \( \tilde{y}_{rv} \) are, of course, frequency dependent but depend also on the tree/stand and canopy architecture characteristics. The overall temporal decorrelation is then – according to Equation (5) – a function of the ground to volume ratio \( m \) that defines the ratio of more to less temporal stable components. In other words, stands with a higher ground contribution are obviously expected to have a higher temporal coherence than stands characterized by a weak “visible” ground scattering component.
addressed in Equation (5) - cannot be solved under any (repeat-pass) observation configuration, as any additional measurement – at a different polarisation and/or temporal baseline – introduces always two new unknowns, \( \hat{\gamma}_{rr} \) and \( \hat{\gamma}_{rw} \). However, even if the general temporal decorrelation scenario leads to an under-determined problem, special temporal decorrelation events may be accounted under certain assumptions, as it will be discussed in the next section.

### 2.2.2 Wind Induced Temporal Decorrelation

The most common temporal decorrelation effect over forested terrain at small temporal baselines is wind-induced movements of scatterers (e.g. leaves and/or branches) within the canopy layer. In terms of the RVoG model, this corresponds to a change of the position of the scattering particles within the volume in the two acquisitions that introduces a non-volumetric decorrelation. However, in this case the scattering amplitudes as well as the propagation properties of the volume remain the same. Assuming further that the scattering properties of the ground do not change the RVoG model (Equation (2)) with temporal decorrelation in the volume component becomes [4]:

\[
\hat{\gamma}_{rr} (\vec{\hat{w}}) = \exp(i \kappa \cdot z_{w}) \frac{\gamma_{temp} \gamma_{vol} + m(\vec{\hat{w}})}{1 + m(\vec{\hat{w}})} \tag{6}
\]

\( \gamma_{temp} \) denotes the correlation coefficient describing the absolute temporal decorrelation (\( |\hat{\gamma}_{rr}| \)) of the volume scatterer. The inversion of Pol-InSAR coherences contaminated by temporal decorrelation using Equation (2) by means of Equation (6) leads to overestimated forest height. The lower coherence values (due to the temporal decorrelation) are interpreted by the RVoG model as if where caused by a taller forest.

### 3 Coherent Multibaseline

If multiple acquisitions are available that allow to form multiple interferograms at different spatial (and temporal) baselines, forest height estimates can be improved by combining the available measurements and temporal decorrelation can be at least partially compensated. There are two different ways to combine multibaseline inversion results. The first one is to invert individually each available baseline using equation (4) (i.e. without accounting for temporal decorrelation) and then combine the inverted forest heights. This approach works well at low temporal decorrelation levels and is referred as an in-coherent approach [7]. The second one is to use the complete set of complex coherence estimates obtained at all possible baseline combination for the inversion of equation (4), and is referred as coherent approach [6]. This coherent approach is investigated in the following.

By minimizing the ground contribution \( m \), i.e. \( m \to 0 \) the polarisation \( \hat{\gamma} (\vec{w} | \kappa') \) with the lowest ground contribution is taken so that equation (6) becomes:

\[
\hat{\gamma} (\vec{w} | \kappa') = \gamma_{temp} \gamma_{vol} \exp(i \kappa' \cdot z_{w}) \tag{7}
\]

In a second step, the estimated \( \hat{\gamma} (\vec{w} | \kappa') \) at each baseline are used to resolve

\[
\begin{vmatrix}
\hat{\gamma}_{1} (\vec{w}, \kappa) \\
\hat{\gamma}_{2} (\vec{w}, \kappa) \\
\vdots \\
\hat{\gamma}_{N} (\vec{w}, \kappa)
\end{vmatrix}
= 
\begin{vmatrix}
\gamma_{temp} (\kappa, \{h_{i}, \sigma, \gamma_{temp}^{x}\}) \\
\gamma_{temp} (\kappa, \{h_{i}, \sigma, \gamma_{temp}^{x}\}) \\
\vdots \\
\gamma_{temp} (\kappa, \{h_{i}, \sigma, \gamma_{temp}^{x}\})
\end{vmatrix}
\]

In the next section the application of equation (8) on experimental data is discussed.

### 4 Experimental Results

Pol-InSAR acquisitions performed by DLR’s E-SAR system operating in a repeat-pass mode at L-band can have small temporal baselines on the order of minutes. In the frame of the TempoSAR 2008 campaign, system acquired Pol-InSAR data over Traunstein forest. The selected data set consists of 6 tracks with nominal spatial baselines of 5 - 25m (mean \( \kappa \): 0.04 - 0.38). Temporal baselines vary from 10 minutes to about 1 hour.

The short term temporal baselines (minutes to hours) are usually affected by temporal decorrelation due to the wind induced movements of scatterers within the canopy layer.

Forest height was estimated by means of Equation (4) and temporal decorrelation was reduced or mitigated by Equation (6) and (8). Figure 1 shows Pol-InSAR forest height map for Traunstein forest obtained at L-band, scaled 0 to 40m, using the multibaseline coherent approach.

In Figure 2, Pol-InSAR inversion height profiles and the corresponding lidar measurements are plotted. The green points represent the lidar measurements and vary between 0 and 35m. The red points are height estimates obtained under the assumption of no temporal decorrelation using RVoG model, see equation (4) and using the in-coherent multibaseline approach. The overestimation of forest height as a consequence of the biased volume coherence due to temporal decorrelation becomes clean. To compensate for temporal decorrelation and correct for height overestimation the Pol-InSAR data are inverted by means of Equation (8). The obtained estimates are plotted as blue points in Figure 2. The overestimation is significantly reduced.
5 Conclusions

In this paper Pol-InSAR inversion height were estimated by RVoG model and multibaseline coherent approach considering the effect of temporal decorrelation. The proposed multibaseline approach demonstrates that the biased volume coherence due to temporal decorrelation can be compensated and corrected. Volume coherence improves height inversion performance.

References

[7] Pol-InSAR in Orbit Demostration, Final Report, ESA ESRIN Contract No. 19666/06/1-EC

Figure 1 Trastein test site. Top: L-band HV amplitude image; 700×2500 pixels, 1.49m range and 1.84m azimuth resolutions, Bottom: Pol-InSAR height map; scaled 0 to 40m.

Figure 2 Pol-InSAR height profiles and lidar measurement profiles. Red: inversion height by using multibaseline in-coherent approach, Green: lidar measurement height, Blue: inversion height by using multibaseline coherent approach (AA' line in Figure 1).