The Effect of Temporal Decorrelation on the Inversion of Forest Parameters from Pol-InSAR Data

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Abstract—: This paper addresses the effect of temporal decorrelation on the inversion of forest parameters using Pol-InSAR techniques. The modeling of temporal decorrelation and the inversion of single-baseline Pol-InSAR data in the presence of temporal decorrelation is discussed. Model based simulations and experimental multi-temporal fully polarimetric and repeat pass interferometric data from the SIR-C Space shuttle mission are used for the performance analysis of the proposed approach.

Keywords-component: Polarimetric SAR interferometry (Pol-InSAR), Forest Parameter Estimation.

I. INTRODUCTION

The ***Random Volume over Ground (RVoG)*** scattering model as addressed in [1-2] does not account for dynamic changes within the scene occurring in the time between the two acquisitions. Such changes effecting the location and/or the scattering properties of the effective scatterers within the scene reduce in general the correlation between the acquired images and lead to erroneous and/or biased parameter estimates. This is an essential limitation especially with respect to all next-future spaceborne polarimetric systems that are designed to operate in a repeat-pass interferometric mode with long temporal baselines of several days.

In general, the temporal changes within the scene occur in a stochastic manner and cannot be accounted for without having detailed information about the environmental conditions in the time between the two observations. Hence, temporal decorrelation effects can be incorporated in scattering models only in a very abstract way. Regarding the two-layer RVoG model, temporal decorrelation may affect both, the volume component that represents the vegetation layer and the underlying ground layer

$$\tilde{\gamma}(\vec{w}) = \exp(i\varphi_0)\frac{\gamma_{TV}(\vec{w})\ \tilde{\gamma}_V + \gamma_{TG}(\vec{w})\ \ m(\vec{w})}{1+m(\vec{w})} \qquad \text{-1)}$$

$0 \le \gamma_{TV}(\vec{w}) \le 1$ is the correlation coefficient describing the temporal decorrelation of the volume scatterer and $0 \le \gamma_{TG}(\vec{w}) \le 1$ the correlation coefficient describing the temporal decorrelation of the underlying surface scatterer. Both coefficients may be polarisation dependent: 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 - as for example due to a change in soil moisture - effects the scattering properties in each polarisation in a different way and leads to a polarisation dependent decorrelation of the ground scatterer.

Rewriting Eq. 1 as

$$\tilde{\gamma}(\vec{w}) = \exp(i\varphi_0)\left[\tilde{\gamma}_V\gamma_{TV}(\vec{w}) + \frac{m(\vec{w})\gamma_{TG}(\vec{w})}{1+m(\vec{w})}(1-\tilde{\gamma}_V\gamma_{TV}(\vec{w}))\right] \text{-2)}$$

makes clear that the line in the complex plane generated by the loci of the complex coherence values at different polarisations under the RVoG model collapses [1-2]. From the parameter inversion point of view, the RVoG model with general temporal decorrelation cannot be solved under any (repeat-pass) observation configuration, as any additional measurement – at a different polarisation and/or baseline – introduces always two new unknowns, γ_{TV} and γ_{TG} in the inversion problem. However, even if the general temporal decorrelation scenario cannot be accounted, special cases of dynamic processes may be accounted under certain assumptions, as it will be discussed in the next section.

II. DECORRELATION OF THE VOLUME LAYER

The most common temporal decorrelation effect over forested terrain is wind-induced movement of "unstable" scatterers within the canopy layer as for example leaves and/or branches etc. This leads to a relative change in the positions of the effective scatterers inside the resolution cell in the two acquisitions, and thus to an additional loss of coherence. In terms of the RVoG scattering model, this corresponds to a change of the position of the scattering particles within the volume. However, this does not influence the second order polarimetric scattering properties of the volume scatterer. Hence, the scattering amplitudes as well as the propagation properties of the random volume remain, in this case, the same.

Moreover, assuming that the scattering properties of the ground do not change in the time between the two observations, then, the ground-to-volume amplitude ratios $m(\vec{w})$ do not change as well. In this case, the RVoG model with temporal decorrelation in the volume component becomes

$$\tilde{\gamma}(\vec{w}) = \exp(i\varphi_0)\frac{\gamma_{TV}\ \tilde{\gamma}_V + m(\vec{w})}{1+m(\vec{w})} \qquad \text{-3)}$$

The temporal correlation coefficient γ_{TV} is no longer polarisation dependent. It is important to note that – according

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to Eq. 3 - the presence of γ_{TV} leads to a degradation of the amplitude of the interferometric coherence, but do not affect the position of the effective phase center and thus the interferometric phase. Eq. 3 can be rewritten as

$$\tilde{\gamma}(\vec{w}) = \exp(i\varphi_0)\left[\gamma_{TV}\tilde{\gamma}_V + \frac{m(\vec{w})}{1+m(\vec{w})}(1-\gamma_{TV}\tilde{\gamma}_V)\right] \qquad \text{-4)}$$

indicating that the line generated according to the RVoG model by the loci of the complex coherence values in the complex plane is preserved.

Fig. 1 demonstrates the geometrical interpretation of the effect of γ_{TV} in Eq. 4: Let the three points on the continuous red line to indicate the loci of the interferometric coherences for three different polarisations for the case of no temporal decorrelation (i.e., $\gamma_{TV}=1$). The left-hand-side point should represent the "volume only" coherence point $\tilde{\gamma}(\vec{w}_{m=0}) = \exp(i\varphi_0)\ \tilde{\gamma}_V$. Starting now to decrease continuously γ_{TV} from 1 to 0, the interferometric coherence decreases and the "volume-only" coherence point moves radially towards the origin. However, the three loci lie always on a line for any value of γ_{TV} - as indicated by the dotted red line for the case where $\gamma_{TV}=0.5$. By varying γ_{TV} the line itself is rotated about the line-circle intersection point.

The one end of the sensible line segment is given by $\tilde{\gamma}(\vec{w}_{m=0}) = \exp(i\varphi_0)\ \gamma_{TV}\tilde{\gamma}_V$. In the extreme case of total temporal decorrelation, i.e. $\gamma_{TV}=0$, this point falls into the origin of the complex plane, while in the other extreme case of no temporal decorrelation it is given by the "volume-only" point $\tilde{\gamma}(\vec{w}_{m=0}) = \exp(i\varphi_0)\ \tilde{\gamma}_V$. The other end of the sensible line segment lies – unaffected by γ_{TV} - on the unit circle at $\tilde{\gamma}(\vec{w}_{m=\infty}) = \exp(i\varphi_0)$. This is an important cognition as it implies an unbiased estimation of the underlying topography in the presence of γ_{TV}. In the following, the model as stated in Eq. 3 will be refered in the following as the ***Random Volume over Ground with Volume Temporal Decorrelation (RVoG+VTD)*** model.

III. Inversion of the RVoG+VTD model

The inversion of the RVoG model in the presence of γ_{TV} leads to an overestimation of the volume (e.g. forest) height due to the underestimation of the true "volume-only" coherence values. To obtain useful parameter estimates temporal decorrelation has to be accounted and compensated. While in the general temporal decorrelation scenario all attempts to deal with this problem end up in a highly underestimated problem, in the case of RVoG+VTD, the fact that the temporal decorrelation coefficient γ_{TV} is scalar and affects only the volume makes the inversion in terms of a single baseline fully polarimetric configuration a challenge.

Facing this, the first steps of a possible inversion scheme are the same as for the inversion of the RVoG model:

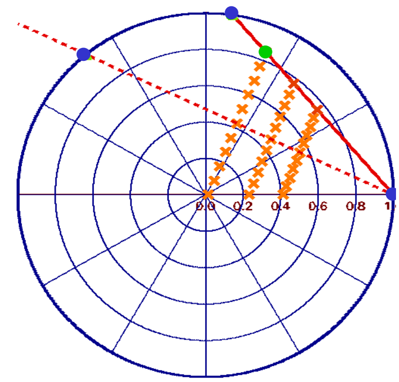

Figure 1. Geometrical Interpretation of the RVoG+VTD Model.

1. Perform a total least-squares line fit through the loci of the complex interferometric coherences at different polarisations on the complex plane.

2. Find the two line–circle intersection points and choose the one that corresponds to the "ground-only" point. Estimate from this point the phase φ_0 related to the underlying topography.

3. Identify the "volume-only" point as the optimum coherence point – or its projection onto the LS-line - that is furthest away from the "ground-only" intersection point.

This latest point corresponds – under the assumption of zero ground scattering - to the "volume-only" point affected by temporal decorrelation $\tilde{\gamma} = |\tilde{\gamma}|\exp(i\varphi_V) = \exp(i\varphi_0)\ \gamma_{TV}\tilde{\gamma}_V$ (indicated in Fig. 2 left by the green point). The next step is to compensate the effect of γ_{TV} in order to obtain the true "volume-only" point $\exp(i\varphi_0)\ \tilde{\gamma}_V$. According to the RVoG+VTD model, this can be performed by shifting in the complex plane the estimated "volume-only" point radially to higher coherence values. However, the problem is that there is no knowledge about how much the estimated "volume-only" point has to be shifted. As a consequence, all points on the radial line segment beyond $\exp(i\varphi_0)\ \gamma_{TV}\tilde{\gamma}_V$ up to the unit circle - indicated by orange crosses in Fig. 2 - become possible $\exp(i\varphi_0)\ \tilde{\gamma}_V$ points. Each of them leads to a different possible extinction / height solution pair.

Probably the simplest way to overcome this ambiguity is to set the extinction value to a fixed value. Then, starting from the evaluated "ground-only" point on the unit circle and increasing volume height and plotting the loci of the corresponding coherence values - obtained from the RVoG model - for the given geometry, and the fixed extinction value a curve can be drawn on the unit circle that intersects the ambiguous line segment at a given point (see Fig. 2). This point is the $\tilde{\gamma}_V$ point corresponding to the fixed extinction value.

4. Fix the extinction value, $\sigma=\sigma_0$ and estimate the $\exp(i\varphi_0)\ \tilde{\gamma}_V(h_V, \sigma=\sigma_0)$ point.

5. Estimate from the estimated $\exp(i\varphi_0)\ \tilde{\gamma}_V(h_V, \sigma=\sigma_0)$ value the volume height h_V.

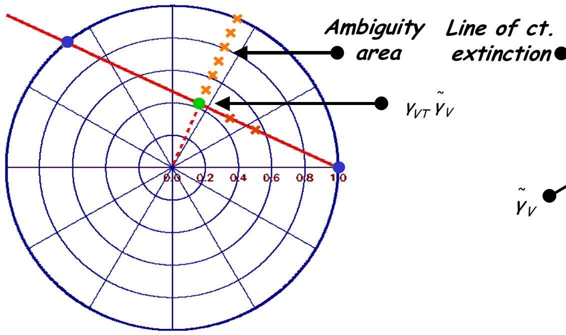

Figure 2. Geometrical Interpretation of the RVoG + VTD Model Inversion

This way it is possible to obtain unique volume height h_V estimates in the presence of temporal decorrelation effects. The price to be paid for this is the physical reduction of the scattering model by the loss of the extinction coefficient and the resulting reduced estimation accuracy of volume height h_V compared to the single-pass estimation scenario. The loss in estimation accuracy depends primarily on how good the guess of the extinction value σ_0 is.

In the case where it is assumed that $\sigma = 0$, the volume height can be derived directly from the phase difference between the "volume-only" and the "ground-only" points as:

$$h_V = \frac{2\Delta\varphi}{\kappa_Z} \quad \text{where} \quad \Delta\varphi = \varphi_V - \varphi_0 \qquad \text{-5)}$$

This underlines the fact that in the RVoG+VTD model the interferometric phases are the essential observables. The reason for this is that while the absolute coherence values are affected by the presence of γ_{TV} the location of the effective phase center and thus the interferometric phases are not. However, the estimation accuracy suffers under the increased phase variation due to the lower coherence values.

IV. EXPERIMENTAL INVERSION RESULTS

In this section, the inversion performance of the proposed RVoG+VTD inversion scheme is validated using the experimental SIR-C L-/C-band Kudara data sets (2-days repeat-pass time). The L-band data are inverted under the assumption of no temporal decorrelation using the RVoG model and the obtained height estimates are then used as reference.

In Fig. 3 on the top, a L-band height profile is shown. The height profile obtained from the inversion of the C-band data without accounting for temporal decorrelation (i.e. by using the RVoG model) is shown in the middle of Fig. 3. The overestimation of forest height as a consequence of the degradation of the interferometric coherence due to temporal decorrelation becomes obvious. While the L-band height profile shows a forest height of about 20 meters the corresponding values for the C-band heights lies at 33m, and 30m, respectively. To compensate this overestimation, the C-band data are – in a second step - inverted by using the RVoG+VTD scenario. For this the extinction coefficient is chosen to be 0.4 dB/m. This value was chosen from the height/extinction information from the L-band data inversion. This information is in a standard repeat–pass scenario not available. The obtained heights - with a mean value of about 20m - are shown in Fig. 3 (bottom) and demonstrate the potential of the proposed approach to deal with temporal decorrelation effects.

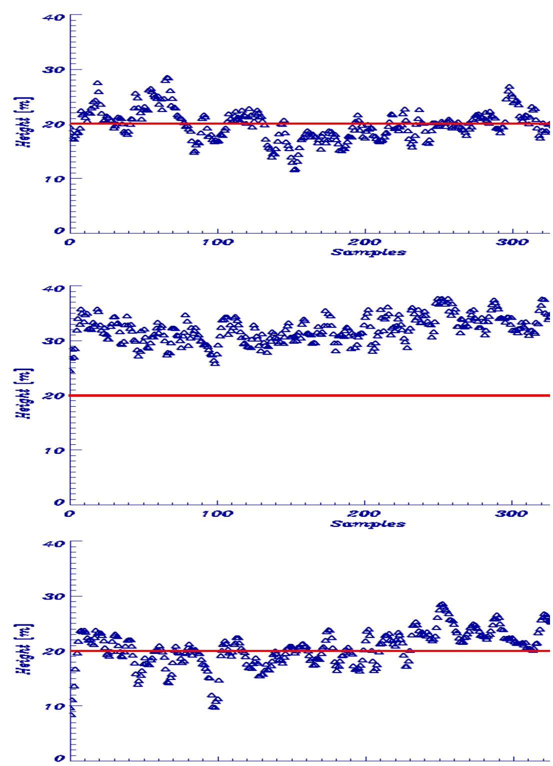

Figure 3. Inverted Height Profiles. Top: L-band (RVoG), Middle: C-band (RVoG), Bottom: C-band (RVoG+VTD)

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