RECENT ADVANCES ON INSAR TEMPORAL DECORRELATION: THEORY AND OBSERVATIONS USING UAVSAR

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ABSTRACT

We review our recent advances in understanding the role of temporal decorrelation in SAR interferometry and polarimetric SAR interferometry. We developed a physical model of temporal decorrelation based on Gaussian-statistic motion that varies along the vertical direction in forest canopies. Temporal decorrelation depends on structural parameters such as forest height, is sensitive to polarization and affects coherence amplitude and phase. A model of temporal-volume decorrelation valid for arbitrary spatial baseline is discussed. We tested the inversion of this model to estimate forest height from model simulations supported by JPL/UAVSAR data and lidar LVIS data. We found a general good agreement between forest height estimated from radar data and forest height estimated from lidar data.

1. INTRODUCTION

Synthetic aperture radar (SAR) interferometry is a mature technique applied to measure Earth's surface deformations, such as those caused by volcanoes, earthquakes and ice flows [1]. The role of SAR interferometry to measure forest parameters became important with the development of a technique named *polarimetric SAR interferometry* [2]. Polarimetric SAR interferometry can be regarded as the conventional SAR interferometry with interferograms generated for arbitrary choice of transmit and receive wave polarizations. A peculiar aspect of polarimetric SAR interferometry is the use of *physical models* to extract the desired biophysical parameter from set of polarimetric interferograms.

Physical models relate the complex interferometric coherence to biophysical parameters. For instance, the random volume over ground model (RVoG) [3] predicts the value of *volume coherence* given canopy height, ground topographic phase, mean wave extinction in the canopy and ratio between ground backscatter and canopy backscatter. This ratio is referred to as *ground-to-volume ratio* and can change with wave polarization by several dBs over forests.

Polarimetric and interferometric SAR data consist of a set of 8 SLCs (4 polarimetric channels for each interferometric pass), which can be reduced to 6 SLCs assuming reciprocity of the medium (HV=VH). In practice, the user forms only 9 interferograms (3×3 SLCs), being able to generate interferograms for arbitrary transmit/receive polarizations using combinations of these 9 interferograms. Optimization procedures can be used to find interferograms with desired characteristics (e.g., higher coherence amplitude, lower coherence phase, etc.). Model parameters, such as canopy height, are estimated from polarimetric interferograms and optimized interferograms using model-based inversion procedures [3].

To ensure a robust estimation of model parameters, model predictions must match coherence observations. A model of volume coherence such as the RVoG model can be used for single-pass (i.e. tandem) interferometry only. In repeat-pass interferometry, the effects of dynamic changes occurring in the forest significantly change the volume coherence and needed to be accounted for. In this paper, we review three important models of polarimetric-interferometric coherence measured over forest, respectively associated with volume decorrelation (cf. 2), temporal decorrelation (cf. 3) and temporal-volume decorrelation (cf. 4).

2. VOLUME DECORRELATION MODEL

In SAR interferometry and polarimetric SAR interferometry, forests can be modeled as two-layer scenarios, constituted by a penetrable vertical distribution of scattering elements and an underlying dielectric surface. The RVoG model is an example of two-layer models [2].

In the RVoG model, the canopy layer is constituted by a uniform distribution of randomly-oriented scattering elements. The structure function associated with this layer is an exponential function characterized by an arbitrary wave extinction coefficient. The interferometric coherence of the RVoG model may be written as

$$\gamma_{gv} = e^{j\varphi_g}\,\frac{\mu + \gamma_v e^{-j\varphi_g}}{\mu + 1} \tag{1}$$

where μ is the ground-to-volume scattering ratio, φ_g is the interferometric phase associated with the ground surface, and γ_v is the interferometric coherence of the canopy layer only (without ground surface)

$$\gamma_v = e^{j\varphi_g} \frac{p_1 \left(e^{p_2 h_v} - 1\right)}{p_2 \left(e^{p_1 h_v} - 1\right)} \tag{2}$$

where

$$p_1 = \frac{2\kappa_e}{\cos\theta}, \qquad p_2 = p_1 + jk_z. \tag{3}$$

In (2) and (3), h_v indicates the canopy height, θ is the look angle of the interferometer, κ_e is the mean extinction coefficient and k_z is interferometric vertical wavenumber. The RVoG coherence is sensitive to polarization through the ground-to-volume ratio. Coherence values associated with different values of ground-to-volume ratio are aligned along a line segment in the complex plane. The line model has been largely validated and used for forest height estimation from polarimetric-interferometric data [4, 5]

Using models of volume decorrelation in repeat-pass interferometry may lead to large errors if temporal decorrelation is not properly compensated. In a recent work [6], we proposed to account for temporal decorrelation by modeling the effects of temporal changes as described below.

3. TEMPORAL DECORRELATION MODEL

Temporal decorrelation of two-layer scattering scenarios can be effectively modeled by a vertical-varying function that accounts for modification of scattering properties of the layers [7, 6]. The temporal function can be derived assuming temporal changes to be caused by Gaussian-statistic motion of the scatterers with motion variance linearly increasing from the bottom to the top of canopy. The structure function can be assumed to be the same as the RVoG structure function. The model of polarimetric-interferometric temporal coherence may be written as [6]

$$\gamma_{t_{gv}} = \frac{\mu\,\gamma_{t_g} + \gamma_{t_v}}{\mu + 1} \tag{4}$$

where μ is the ground-to-volume ratio, γ_{t_g} is the ground-level temporal coherence

$$\gamma_{t_g} = \exp\left[-\frac{1}{2}\left(\frac{4\pi}{\lambda}\right)^2 \sigma_g^2\right], \tag{5}$$

and γ_{t_v} is the temporal coherence associated with the canopy layer

$$\gamma_{t_v} = \gamma_{t_g} \frac{p_1 \left[e^{(p_1+p_3)h_v} - 1\right]}{(p_1+p_3)\left(e^{p_1 h_v} - 1\right)}\,, \tag{6}$$

with

$$p_3 = -\frac{\Delta\sigma^2}{2h_r}\left(\frac{4\pi}{\lambda}\right)^2. \tag{7}$$

The parameter $\Delta\sigma^2$ is the *differential motion variance*

$$\Delta\sigma^2 = \sigma_v^2 - \sigma_g^2\,, \tag{8}$$

where σ_g and σ_v are the motion standard deviations of the scattering elements at ground-level and of the canopy at reference height h_r. The differential motion variance along the vertical direction is a key parameter of our temporal decorrelation model. If $\Delta\sigma^2 = 0$, then (4) reduces to the temporal decorrelation model proposed by Zebker and Villasenor in 1992 [8].

The temporal decorrelation model (4) and the differential motion have been validated using JPL/UAVSAR data acquired with zero spatial baseline and 45 minutes temporal baseline [6]. From (4), we can see that temporal decorrelation depends on structural parameters, such as canopy height, and changes with wave polarization through the ground-to-volume ratio.

The model (4) has been derived in the case of zero spatial baseline data ($k_z = 0$). In this case, the differential motion leads to real-valued temporal decorrelation. In the case of arbitrary spatial baseline (cf. Sec. 4), we now show that the differential motion affects both the amplitude and phase of the volume coherence.

4. TEMPORAL-VOLUME DECORRELATION MODEL

The coherence observed by an interferometer with arbitrary spatial and temporal baseline contains a mixture of temporal and volume effects. A temporal-volume coherence model can be derived starting from the differential Gaussian-statistic motion and the RVoG structure function [9, 10]. A closed-form expression of our temporal-volume coherence model may be written as

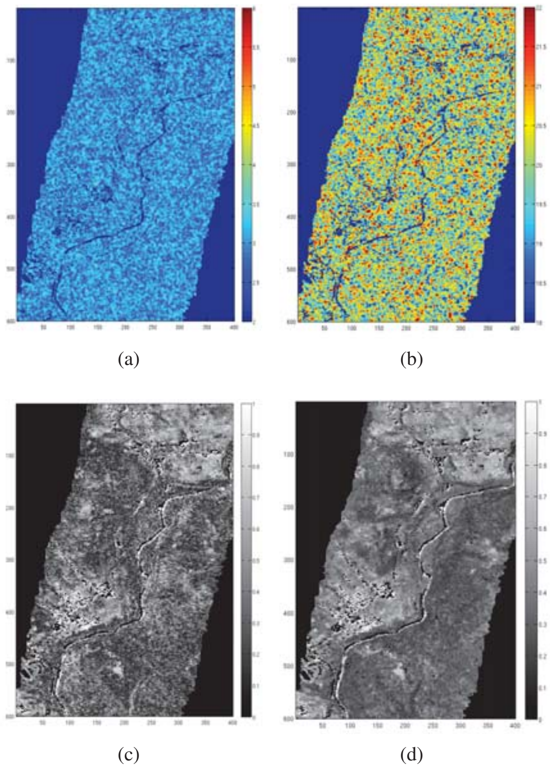
$$\gamma = e^{j\varphi_g} \frac{\mu\,\gamma_{t_g} + \gamma_{vt}\, e^{-j\varphi_g}}{\mu + 1} \tag{9}$$

where γ_{vt} is the temporal-volume decorrelation of the canopy layer only

$$\gamma_{vt} = e^{j\varphi_g}\,\gamma_{t_g} \frac{p_1 \left[e^{(p_2+p_3)h_v} - 1\right]}{(p_2+p_3)\left(e^{p_1 h_v} - 1\right)}. \tag{10}$$

Note that γ_{vt} is complex-valued and represents the temporal-volume decorrelation of the canopy layer at arbitrary spatial baseline. This term is different than γ_{t_v} shown in (6), which is real-valued and denotes the temporal decorrelation only. Eq. (9) is not obtained from the product of (4) and (1). The non-separability of temporal and volume decorrelation is a consequence of the differential motion in forest canopies.

In order to compare the temporal-volume coherence with the volume coherence, we can define the *temporal factor* α_t such that $\gamma = \alpha_t \gamma_{gv}$. In general, the temporal factor is complex-valued, i.e. the differential motion affects both coherence amplitude and phase, and can be greater than



(a) (b)

(c) (d)

Figure 1: Maps of ground-level (a) and canopy-level (b) motion of scatterers generated to simulate the repeat-pass polarimetric-interferometric coherence. The temporal parameters have been estimated from zero-spatial baseline UAVSAR data [6]. (c) and (d) show the coherence amplitude simulated using model (9) with the minimum (c) and maximum (d) ground-to-volume ratio estimated from polarimetric UAVSAR data. Random noise has been added to the coherence to test the height estimation algorithm.

one.

One application of the model (9) is the estimation of forest height from repeat-pass polarimetric-interferometric data. As we assumed the ground-to-volume ratio to be constant between the acquisitions, the model is specially suitable for short or moderate temporal baselines. The model contains six real parameters: the topographic phase φ_g, the canopy height h_v, the extinction coefficient κ_e, the ground-to-volume ratio μ, the motion of scattering elements at ground-level σ_g and the motion of the scattering elements at canopy-level σ_v. The key idea is that σ_g and σ_v absorb the bulk of temporal changes, enabling more robust estimation of canopy height. Since the ground-to-volume ratio is the sole parameter that changes with polarization, and each polarimetric channels contributes with a complex coherence observation, a minimum set of 5 complex coherence samples measured at different polarimetric channels is needed to estimate forest height.

In this paper we show a first test of forest height estimation from model simulations supported by real JPL/UAVSAR and lidar LVIS data. Our objective here is limited to test the invertibility of the temporal-volume coherence model. We estimated the temporal parameters and the minimum/maximum ground-to-volume ratio from zero spatial baseline UAVSAR data [6]. Using forest height available from lidar data and model (9), we generated a set of polarimetric-interferometric coherence images free of platform motion errors and residual geometric and SNR decorrelation. The mean wave extinction was generated from a Gaussian distribution with 0.3 dB/m mean and 0.05 dB/m standard deviation. Random noise was also added to coherence maps. Fig. 1 shows the motion of the scattering elements of the ground (mean value is 3 mm) and of the canopy (mean value is 20 mm) used in the simulation. Maps of Coherence amplitude corresponding to minimum and maximum ground-to-volume ratio are also shown.

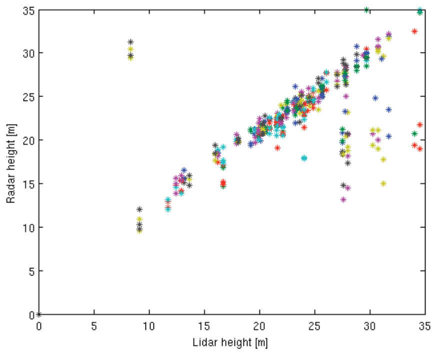


Figure 2: Forest height estimated from polarimetric-interferometric SAR data. Data have been generated using model (9) supported by real JPL/UAVSAR data acquired with zero spatial baseline and lidar LVIS data.

We tested the inversion of (9) using a non-linear constrained optimization approach. The constraints were set to include a wide range of physical values of model parameters (e.g., h_v was constrained between 0 m and 50 m, μ was constrained between -30 dB and 30 dB, etc.). The input to the inversion algorithm was a set of 5 coherence samples generated for different values of ground-to-volume ratio, taken uniformly spaced between the minimum and the maximum ground-to-volume ratio. We plotted the estimated forest height against the true forest height as shown in Fig. 2. There is a general good agreement between estimated and true forest height. Outliers are likely due to regions of low coherence (eg. the river) and can be easily masked before performing the inversion procedure.

5. CONCLUSION

Repeat-pass SAR interferometry supported by polarimetry can be used to estimate forest parameters. We have reviewed three important models of the polarimetric and interferometric coherence, namely a volume decorrelation model, a temporal decorrelation model, and a model of the temporal-volume decorrelation. The latter can be inverted and used to estimate forest height from polarimetric and interferometric SAR data. We used model simulations supported by real JPL/UAVSAR airborne data to illustrate the results. More experiments with real UAVSAR data are in progress.

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