THE EFFECTS OF TEMPORAL AND TOPOGRAPHIC DECORRELATION ON FOREST HEIGHT RETRIEVAL USING AIRBORNE REPEAT-PASS L-BAND POLARIMETRIC SAR INTERFEROMETRY

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ABSTRACT

We have explored the effects of temporal baseline and terrain slope on forest height estimation using L-band repeat-pass polarimetric-interferometric synthetic aperture radar (PolInSAR). Data were collected using NASA's Uninhabited Aerial Vehicle Synthetic Aperture Radar instrument over a study area exhibiting high slope topography in the Laurentides Wildlife Reserve of Québec, Canada. We used lidar-derived canopy height and terrain slope maps to quantify the decorrelation effects, in both magnitude and phase, that distort the observed coherences compared to the random volume over ground forest model. We derived forest height maps for a number of different temporal baselines using both fixed model parameters and model parameters that varied with slope, and compared the results. Further work is necessary to develop improved slope correction methods, and to see if slope corrections derived from lidar data for this study area can be applied to other study areas, or generalized to a theoretical model.

***Index Terms*—** radar, polarimetric SAR interferometry, forest height, temporal decorrelation, topography

1. INTRODUCTION

The capability of polarimetric-interferometric synthetic aperture radar (PolInSAR) for the estimation of forest canopy heights is well established. Cloude and Papathanassiou [1] proposed a three-stage inversion process through which the random volume over ground (RVoG) model could be used to estimate forest height from single-baseline PolInSAR data.

For single-pass PolInSAR data without temporal effects, generally the largest source of decorrelation in forested areas is volumetric decorrelation due to the height distribution of scatterers within the forest canopy [1]. However, for repeat-pass PolInSAR data, significant decorrelation can also result from temporal processes such as wind-induced canopy motion, or dielectric changes due to rainfall [2, 3]. Most studies using PolInSAR for forest height estimation have focused on relatively flat study areas, but non-zero terrain slope can also have an effect on the observed complex coherences, increasing the errors in the forest height estimates if not accounted for.

To study the effects of both temporal and terrain slope induced decorrelation, we have looked at Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) data of the Réserve Faunique des Laurentides, in Québec, Canada. Repeat-pass PolInSAR data were collected by the UAVSAR for two flight lines on three separate days: August 5, August 7, and August 14 of 2009. This yielded three single-baseline PolInSAR datasets with 45 minute temporal baselines. As well, we can form pairs of the August 5-7 (2-day), August 7-14 (7-day), and August 5-14 (9-day) acquisitions. Each temporal baseline provides a different look at the effects of temporal decorrelation on the resulting canopy height estimates. A previous study [4] focused on zero spatial baseline data of this area in order to study the temporal coherence directly. Here, we use data from two flight lines separated by an approximately 65 m spatial baseline, so that the observed coherence will contain the combination of volumetric, temporal, and other decorrelation effects.

For this paper, we focus on a small subset of the UAVSAR scene coincident with lidar data. We used the lidar canopy height resampled to 30 m spatial resolution as a reference for the PolInSAR canopy heights, and also used the lidar ground DEM to calculate the terrain slope. The lidar canopy heights in this area had an average of 6.9 m and a max of 21 m. The area of interest covers approximately 100 km^2, has a look angle range of 58–$65°$, and a k_z range of 0.107–0.158 rad/m. The area has ground elevations ranging from 750 to 1000 m, with terrain slopes as high as 70 degrees.

2. METHODS

We calculated the 6 by 6 covariance matrix for each image pair, performed multilooking using a 12 by 3 rectangular window (yielding pixel spacing of 7.2m in azimuth and 4.8m in slant range), then performed non-local means speckle filtering as implemented in the NL-SAR toolbox [5]. We masked out pixels with HV σ^0 less than -30 dB, or with HV σ^0 dy-

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Michael Denbina is a fellow with the NASA Postdoctoral Program. © 2016. California Institute of Technology. Government sponsorship acknowledged.

namic range greater than 10 dB in the surrounding 3 by 3 neighborhood, in an attempt to mask out water areas and forest edges. We also masked out pixels with lidar tree heights less than 3 m. We then used the phase diversity coherence optimization procedure [6] to find two coherences, γ_{high} and γ_{low}, which represented the highest and lowest phase centres observed within the forest canopy. We estimated the ground phase, ϕ, using the standard RVoG line fit procedure [1], applied to the two coherences from the coherence optimization. The RVoG model is defined by the equations [1]:

$$\gamma_{rvog} = e^{j\phi} \frac{\mu + \gamma_v}{\mu + 1} \tag{1}$$

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

$$p_1 = \frac{2\kappa_e}{\cos(\theta)} \tag{3}$$

$$p_2 = p_1 + jk_z \tag{4}$$

γ_{rvog} is the RVoG modelled coherence, h_v is the vegetation height, ϕ is the ground phase, μ is the ground-to-volume ratio, κ_e is the wave extinction, θ is the incidence angle, and k_z is the vertical wavenumber.

2.1. Temporal Decorrelation

Recently, Lavalle et al. [3] proposed the random motion over ground (RMoG) model for dealing with temporal decorrelation effects resulting from random motion of the forest and ground scatterers. In the RMoG model the effects of the temporal decorrelation can be represented by a complex-valued temporal decorrelation factor, α_t, which acts as a multiplier on the theoretical single-pass coherence, γ_{rvog} (i.e., the coherence in the absence of temporal effects) [3]:

$$\gamma = \alpha_t \gamma_{rvog} \tag{5}$$

γ is the complex coherence observed by the radar. In the RMoG model, α_t is a function of the model parameters. Here, we have chosen to calculate a general decorrelation factor α empirically, in order to quantify the effects of not only the temporal decorrelation but also other decorrelation sources not accounted for by the RVoG model, such as decorrelation induced by the terrain slope, or potentially violations of the RVoG model assumptions. In this sense, α is a residual between the modelled coherences and the observations.

We used the lidar derived forest canopy heights as h_v, and fixed values of κ_e = 1.5 dB/m and $\mu = 0$ in order to calculate a theoretical value of γ_{rvog} for each pixel. The κ_e value of 1.5 dB/m was higher than we would expect to be the theoretical extinction value for this area at L-band, but we found that high extinction values tended to produce lower variance in α (and the estimated forest heights), and also that when using lower extinction values (e.g., 0.3 dB/m), there was a bias in the forest height estimates compared to the lidar data.

After the theoretical γ_{rvog} was calculated, we then calculated α as the ratio $\gamma_{high}/\gamma_{rvog}$. We can then compare the α values between the different temporal baselines, and examine α as a function of terrain slope or other parameters.

2.2. Topographic Decorrelation

In order to study the effects of terrain slope on the PolInSAR coherences and estimated canopy heights, we projected the lidar ground DEM into radar coordinates (azimuth and slant range). We estimated the gradient in the azimuth and slant range directions using the central differences of the ground DEM along each axis. Using the range slope, s_x, and the azimuth slope, s_y, we then calculated the overall terrain slope as $s = \sqrt{s_x^2 + s_y^2}$.

We analyzed the value of α as a function of range slope, azimuth slope, and overall terrain slope by taking the mean value of α within 1 degree slope bins. We only plot results for slope bins containing at least 500 pixels. In an attempt to separate the topographic and temporal effects on α, in the plots below of α vs. slope we normalize α by the α value for flat terrain, so that at zero slope, the plotted α equals unity. This allows a fairer comparison between the different temporal baselines.

3. RESULTS

The mean magnitude of α vs. the overall terrain slope, for each temporal baseline, is shown in Fig. 1. As expected, higher slopes generally exhibit lower α values (greater amounts of decorrelation), but this relationship varies somewhat between the different temporal baselines. In particular, we note that precipitation related effects in the August 7 data, as previously discussed by Simard et al. [4], result in lower α values for the image pairs that match the August 7 data with the other two dates. For this reason, we have excluded the August 5-7 and August 7-14 data from the rest of the plots, in order to focus on the higher coherence baselines.

The phase of α is also of interest, as it can cause significant errors in the estimated canopy height. The phase of α vs. the range and azimuth slopes is shown in Figs. 2 and 3, respectively. As well as a slope-dependent mean phase shift, the phase variance of α also increases with slope, likely due to the increased decorrelation. The best overall behavior for α seems to occur in the August 14 data, where the mean and variance of $\arg(\alpha)$ is flatter with respect to slope than on most of the other dates. Note that as $\arg(\alpha)$ increases this signifies that, if not compensated for, the forest height would be overestimated (i.e., k_z is positive). From these plots it is clear that both range and azimuth slopes have different but significant effects on the observed PolInSAR coherences.

One method that has been proposed to help compensate for the topographic effects is to use the local incidence angle (e.g., the look angle minus the range slope), rather than the

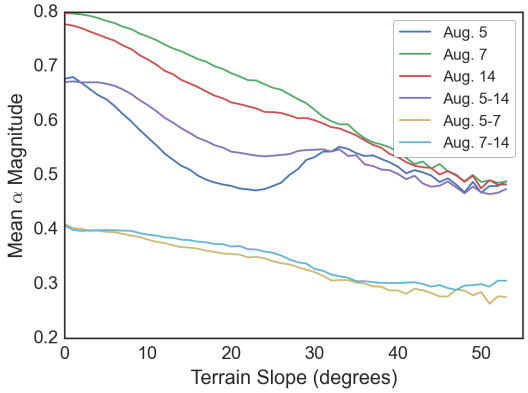

Fig. 1. Mean decorrelation factor magnitude vs. terrain slope, for each temporal baseline. α is averaged within each 1 degree slope bin, then the magnitude of the average is plotted.

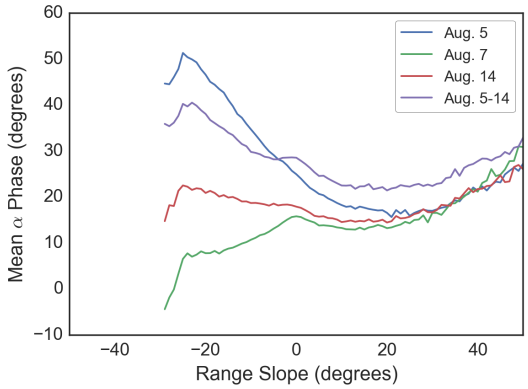

Fig. 2. Mean decorrelation factor phase vs. range slope. α is averaged within each 1 degree slope bin, then the phase of the average is plotted.

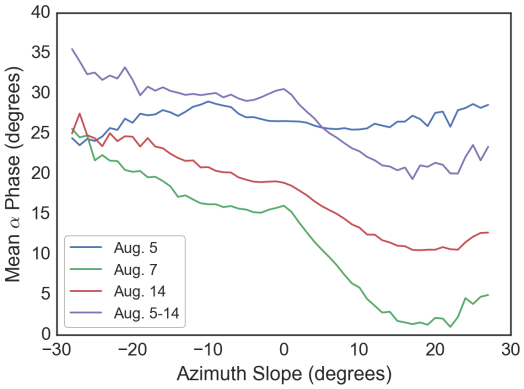

Fig. 3. Mean decorrelation factor phase vs. azimuth slope. α is averaged within each 1 degree slope bin, then the phase of the average is plotted.

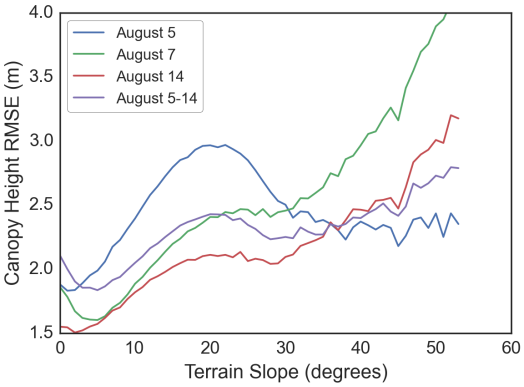

Fig. 4. The RMSE of the PolInSAR canopy height estimates vs. lidar canopy height, for each 1 degree slope bin, using a fixed α value.

look angle alone, when calculating p_1 in eqn. (3) [3]. This does slightly reduce the phase variance of α, and improved the accuracy of the height estimates, so we have used this correction for the results shown below. However, many effects of the topography remain, including both azimuth slope and residual range slope effects. Note as well that the local incidence angle should not be used when calculating k_z, as doing so increased the phase variance of α, and increased the forest height errors.

We estimated forest heights using a fixed α value equal to the mean for the area. For the August 14 data, which produced the most accurate canopy heights compared to the lidar, the fixed α was equal to $0.69e^{j0.32}$. When performing the model inversion we used the same fixed extinction and μ value as in the calculation of α above. We solved for h_v using a search procedure which calculated the RVoG model coherence, multiplied it by the fixed value of α, then compared it to the observed γ_{high}. The value of h_v was chosen that most closely matched the observed coherence. The resulting forest height maps were then smoothed using a 7 by 7 moving average.

A plot of canopy height RMSE vs. terrain slope for each baseline is shown in Fig. 4. The overall RMSE for the August 14 baseline was 1.99 m. For the August 5 baseline, the RMSE was 2.65 m. For the August 7 baseline, the RMSE was 2.09 m. For the August 5-14 baseline, the RMSE was 2.29 m. The August 5-7 and August 7-14 baselines yielded the largest estimation errors, with RMSE values of 2.97 m and 2.93 m, respectively. For each baseline we used the average α, which reduced the impact of decorrelation effects that were constant throughout the area. However, there is still a clear difference in height estimation error between the baselines, driven by differences in how α varies across the image, and as a function of the terrain.

In addition to a fixed α value, we also tested PolInSAR height inversion using a 2-D LUT of the mean α values for each combination of azimuth and range slope, in 1 degree

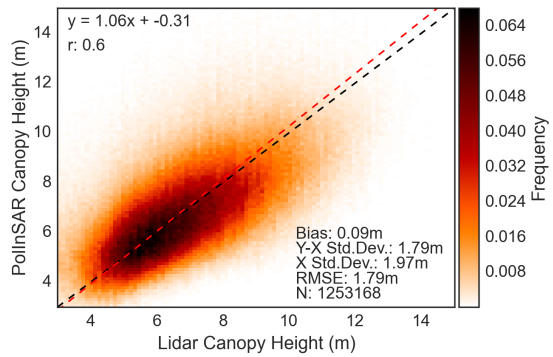

Fig. 5. Density plot of UAVSAR PolInSAR canopy height vs. lidar canopy height, for the August 14 baseline, using α values from a 2-D LUT of azimuth and range slope. The fitted line is shown in red, with the line $y = x$ shown in black. The r value shown is the Pearson's r calculated between the PolInSAR canopy heights and the fitted line.

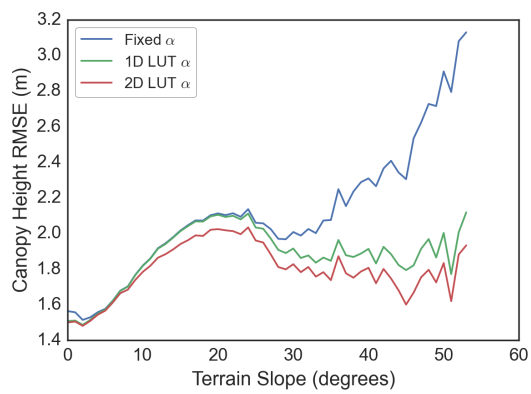

Fig. 6. The RMSE of the PolInSAR canopy height estimates vs. lidar canopy height for the August 14 baseline, comparing the fixed α and each LUT α method. The RMSE is calculated for each 1 degree slope bin.

bins. We also tested the use of a 1-D LUT containing mean α values as a function of the overall slope. For the August 14 baseline, a density plot of PolInSAR canopy heights using the 2-D LUT vs. the lidar is shown in Fig. 5. A plot of the canopy height RMSE vs. terrain slope comparing the fixed and LUT α results is shown in Fig. 6. The errors for high slope regions are reduced, though the RMSE still increases for negative slopes facing away from the radar, where the phase variance of α increases substantially.

4. CONCLUSIONS

Using repeat-pass UAVSAR PolInSAR data, we have investigated the effects of temporal decorrelation as well as decorrelation resulting from non-zero terrain slope. We quantified this effect using a complex-valued decorrelation factor parameter, as in the RMoG model [3], and plotted the value of this parameter as a function of terrain slope. In general, increasing terrain slope causes decorrelation that manifests in both a reduced coherence magnitude as well as a phase shift. Due to the reduced coherence magnitude, the phase variance is also increased. These coherence effects vary differently with both azimuth and range slope, and can cause significant errors for PolInSAR forest height retrieval in high slope regions if not accounted for.

Empirical corrections which model the coherence magnitude and phase shift as a function of slope can reduce the canopy height error, though large errors still remain for slopes facing away from the radar. Further work is necessary to see if the slope effects can be generalized and corrections can be applied across multiple study areas, or can be explained by a theoretical model.

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