An Improvement of Vegetation Height Estimation Using Multi-baseline Polarimetric Interferometric SAR Data

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Abstract—This paper proposes a method for improving the estimation accuracy of vegetation height using multi-baseline Polarimetric Interferometric Synthetic Aperture Radar (Pol-InSAR) data. Single-baseline Pol-InSAR technique has been applied to retrieve the vegetation parameters based on the random volume over ground (RVoG) model. There are two main error sources which might decrease the estimation accuracy. One is the non-volumetric decorrelation, such as thermal noise decorrelation, temporal decorrelation, etc. The other is the ground ambiguity and ideal assumption that volume-only coherence can be acquired in at least one polarization. This assumption may fail when vegetation is thick, dense, or the penetration of electromagnetic wave is weak. This paper proposes a method to solve both the abovementioned two problems at the same time based on the use of multi-baseline Pol-InSAR data. Firstly, the two main error sources are analyzed and an inversion model for representing them is constructed based on the RVoG model. With the constructed model, inversion procedure for estimating vegetation height using the multi-baseline Pol-InSAR data is presented. The performance of this new method is validated using simulated data, and the ratio between baselines and their effects on the estimation performance are also presented.

1. INTRODUCTION

Polarimetric Interferometric Synthetic Aperture Radar (Pol-InSAR) technique \cite{1} is a combination of SAR polarimetry and SAR interferometry and has been demonstrated its success in the estimation of vegetation parameters (height, extinction, underlying terrain) based on the Random Volume over Ground (RVoG) model \cite{2–4}.

Pol-InSAR vegetation height estimation is based on the use of volume decorrelation. Any non-volumetric decorrelation, such as thermal noise decorrelation, temporal decorrelation, etc., might decrease the accuracy of the estimated height. Regarding temporal decorrelation, it has been introduced to compensate its effect on the inversion performance by fixing one of the model parameters (extinction coefficient) \cite{5} or via a dual-baseline Pol-InSAR inversion procedure \cite{6}.

The inversion of RVoG model using single-baseline Pol-InSAR data, assumes that in at least one of the observed polarization channels (usually the cross-polarized HV channel), the effective ground to volume ratio is small. However, in some cases when vegetation is thick, dense, or the penetration of the electromagnetic wave is weak, the assumption fails. To solve this problem, an inversion procedure, which is based on the use of dual-baseline Pol-InSAR data, was proposed and validated \cite{7, 8}.

The two problems in the inversion of RVoG model were solved respectively. This paper discusses the feasibility to solve them at the same time based on the use of multi-baseline Pol-InSAR data. In Section 2, the error sources are analyzed and a revised inversion model for representing them is constructed based on the RVoG model. Section 3 describes the inversion procedure of the revised model. The performance of this new method is validated using simulated data, and the ratio between each baseline length and their effect on the estimation accuracy are also discussed in Section 4.

2. RVOG MODEL FOR VEGETATION HEIGHT ESTIMATION

2.1. RVoG Model

RVoG model is probably the most successful inversion model for the estimation of vegetation height using Pol-InSAR data. It is a two-layer model composed by a vegetation layer (trunks, branches, leaves or needles) and a ground layer. The vegetation layer is modeled as a layer of given thickness
\( h_V \) and random orientation homogeneous volume medium with wave extinction \( \sigma \) and can be expressed by

\[
\sigma_{ve}(z) = \exp \left[ -\frac{2 \sigma}{\cos \theta} (h_V - z) \right], \quad 0 \leq z \leq h_V.
\]  

(1)

The complex coherence of the random volume is related to the Fourier transform of \( \sigma_{ve} \):

\[
\tilde{\gamma}_V = \frac{1}{h_V} \int_0^{h_V} e^{i\kappa z'} \exp \left( \frac{2 \sigma z'}{\cos \theta} \right) dz'
\]

\[
= \frac{p}{p_1} \cdot \frac{\exp (p_1 h_V) - 1}{\exp (p h_V) - 1}, \quad \text{where} \quad \begin{cases} p = \frac{2 \sigma}{\cos \theta} \\ p_1 = p + i\kappa_z \\ \kappa_z = \kappa \Delta \theta / \sin \theta \end{cases}.
\]

(2)

\( \theta \) is the incidence angle, \( \kappa_z \) is vertical wavenumber, \( \kappa = 4\pi/\lambda \) for alternate-transmit mode (\( \kappa = 2\pi/\lambda \) for single-transmit mode) and the look angle difference \( \Delta \theta \) between the two antennas separated by the baseline. This random volume is located above a impenetrable ground scatterer. Considering both the volume and ground contribution, the total complex coherence can be expressed by

\[
\tilde{\gamma} (\vec{w}) = e^{i\phi_0} \cdot \tilde{\gamma}_V + \mu (\vec{w}) = \frac{\mu_G (\vec{w})}{\mu_V (\vec{w})} \exp \left( -\frac{2 \sigma h_V}{\cos \theta} \right).
\]

(3)

where \( \mu (\vec{w}) \) is the effective ground to volume ratio, \( \mu_G \) is the scattered return from the ground seen through the vegetation and \( \mu_V \) is the direct volume scattering return [3].

2.2. Revised Model Accounting for the Errors and Its Inversion

Pol-InSAR vegetation height estimation is based on the use of volume decorrelation. Any non-volumetric decorrelation, such as thermal noise decorrelation, temporal decorrelation, quantization and coregistration decorrelation, etc., might affect the estimation accuracy of height. Figure 1(a) shows a geometric interpretation of this type of error. The volume-only coherence point is affected by decorrelation (\( \gamma_D \)) and shifts toward the origin along the radius. In order to improve the estimation accuracy, it has to shift the observed volume-only coherence point away from the origin. This type of error can be represented in the RVoG model by a decorrelation item (\( \gamma_D \))

\[
\tilde{\gamma} = e^{i\phi_0} \cdot \frac{\gamma_D \tilde{\gamma}_V + \mu}{1 + \mu}
\]

(4)

The other error source is ground ambiguity and it is due to the ideal assumption that volume-only coherence can be acquired in at least one polarization. This assumption may fail when vegetation is thick, dense, or penetration of electromagnetic wave is weak. Figure 1(b) shows a geometric interpretation of this type of error. The volume-only coherence point lies outside of the observed area. In order to estimate accurate vegetation height, it has to shift the observed volume-only coherence point away from the ground coherence point and along the coherence line. In order to account for the error, it is necessary to insert one item (\( \Delta \mu \)) accounting for the coherence shifting.

\[
\tilde{\gamma} = e^{i\phi_0} \cdot \frac{\gamma_D \tilde{\gamma}_V + \mu + \Delta \mu}{1 + \mu}
\]

(5)

Figure 1: Geometric interpretation of two types of RVoG model inversion errors.
Now considering both the two types of errors, namely combining (4) and (5), it yields to the revised model which represents for both the abovementioned errors
\[
\tilde{\gamma} = e^{i\phi_0} \cdot \gamma_D \tilde{\gamma}_V + \left[ \mu + \Delta\mu \right] \frac{1}{1 + \left[ \mu + \Delta\mu \right]} \quad (6)
\]

3. INVERSION PROCEDURE OF THE REVISED MODEL

The revised new model expressed in (6) consists of six parameters \((\phi_0, h_v, \sigma, \mu, \Delta\mu, \gamma_D)\). Increasing one independent polarization channel will provide two more observables and one more model parameter \((\mu)\). Fully Pol-InSAR data provide six observables, but the number of unknowns becomes eight. Dual-baseline Pol-InSAR data provide six more observables, but the number of unknowns increases by six as well. Since the number of increased observables with increasing number of baselines is equal to that of increased unknowns, it is useless to increase the number of baselines except making some realistic assumptions.

In the case of single-pass Pol-InSAR operating mode and short revisit interval, the decorrelations during the two baseline acquisition could be assumed identical. Furthermore, by assuming the same \(\Delta\mu\), the number of unknowns reduces to twelve, which is equal to the number of dual-baseline Pol-InSAR observables. Now the inversion of the revised model based on dual-baseline Pol-InSAR data could proceed. Figure 2 shows illustrations of the inversion procedure and the major steps are as follows

i. Find out the ground phase \(\phi_{01}, \phi_{02}\) for each baseline. It is the intersection between the coherence line and the unit cycle of the complex plane. This step is identical with that in the inversion of the RVoG model [4].

ii. Shift the phase of each observed coherence by \(\exp(-\phi_{01}), \exp(-\phi_{02})\) so as to have the same zero ground phase.

iii. Stepping the non-volumetric decorrelation level \(\gamma_D\) from 1 to 0 using suitable hits and ground to volume ratio \(\mu\) from \(-40\,\text{dB} \) (relates to no ground ambiguity) to 0 dB using suitable hits, calculate volume-only coherence \(\tilde{\gamma}_V\) of the first baseline \(\kappa_{z1}\).

iv. Based on the volume-only coherence \(\tilde{\gamma}_V\) of the first baseline, calculate the corresponding height \(h_v\) and extinction \(\sigma\) using LUT and then calculate volume-only coherence \(\tilde{\gamma}_V\) of the second baseline \(\kappa_{z2}\).

v. Using the above the non-volumetric decorrelation level and ground to volume ratio, the observed coherence \(\tilde{\gamma}\) of the second baseline is calculated using (3).

vi. If the calculated coherence is equal to the observed coherence of the second baseline, we then set the above vegetation height as the output.

4. SIMULATION ANALYSIS OF THE INVERSION PROCEDURE

In order to evaluate validity of the aforementioned inversion procedure, dual baseline Pol-InSAR data are firstly simulated with both error sources described in Section 2.2 [9]. The main steps are as follows

Figure 2: Illustrations of inversion procedure.
a) Calculate the observable $C_6$ of a pixel using the RVoG statistical model with errors

$$C_6 = \left[ \begin{array}{c} T_V + T_G \\ X^{\ast T} \\ T_V + T_G \end{array} \right] X$$

(7)

where $X = e^{i\phi} (\gamma_D \tilde{T}_V + T_G)$, $[T_V] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{bmatrix}$, $T_G = \begin{bmatrix} \mu_1 & 0 & 0 \\ 0 & \mu_2 & 0 \\ 0 & 0 & \mu_3 \end{bmatrix}$ $T_V$.

b) Compute $C^{1/2}$, where $C^{1/2}(C^{1/2})^T = C$.

c) Simulate a 6-component complex random vector $v$ from the Gaussian distribution $G(0, 0.5)$.

d) The simulated Pol-InSAR image is $g = C^{1/2}v$, where

$$g = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix}, \quad h_i = \begin{bmatrix} S_{HH} \\ \sqrt{2}S_{HV} \\ S_{VV} \end{bmatrix}, \quad i = 1, 2$$

Table 1 shows the simulation parameters which are typical forest at L band. To simulate the non-volumetric decorrelation, $\gamma_D$ is set to 0.8.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_V$</td>
<td>20 m</td>
<td>$\sigma$</td>
<td>0.3 dB</td>
</tr>
<tr>
<td>$\theta$</td>
<td>45°</td>
<td>$\varepsilon$</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mu_1$</td>
<td>-10 dB</td>
<td>$\mu_2$</td>
<td>-3 dB</td>
</tr>
<tr>
<td>$\mu_3$</td>
<td>0 dB</td>
<td>$\gamma_D$</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 2 shows the inversion results from simulated dual-baseline Pol-InSAR data using the procedure described in Section 3. In the case of single-baseline inversion, results of $\kappa_{z2}$ and $\kappa_{z3}$ are better than that of the others because they are much closer to the optimal baseline [10]. Vegetation heights estimated using dual-baseline data are much more accurate than those using single-baseline data. It should be noted that different combinations of baselines have different estimation accuracy, e.g., the combination of $\kappa_{z2}$ and $\kappa_{z3}$ provides the most accurate estimation results in this simulation analysis. Figure 3 shows the inversion results for different given heights and the advantages of using dual-baseline is obvious. Here we can also see that the combination of $\kappa_{z2}$ and $\kappa_{z4}$ provides better estimation results than that of $\kappa_{z1}$ and $\kappa_{z3}$.

<table>
<thead>
<tr>
<th>Inversion Method</th>
<th>Estimated Mean Value</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.-B. $\kappa_{z1}$ = 0.1</td>
<td>23.0552 m</td>
<td>3.1068</td>
</tr>
<tr>
<td>S.-B. $\kappa_{z2}$ = 0.15</td>
<td>23.3332 m</td>
<td>1.8202</td>
</tr>
<tr>
<td>S.-B. $\kappa_{z3}$ = 0.2</td>
<td>23.3840 m</td>
<td>1.8743</td>
</tr>
<tr>
<td>S.-B. $\kappa_{z4}$ = 0.3</td>
<td>23.4660 m</td>
<td>6.0923</td>
</tr>
<tr>
<td>D.-B. $\kappa_{z1}$ + $\kappa_{z2}$</td>
<td>20.7208 m</td>
<td>2.4365</td>
</tr>
<tr>
<td>D.-B. $\kappa_{z1}$ + $\kappa_{z3}$</td>
<td>20.5084 m</td>
<td>2.3178</td>
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<tr>
<td>D.-B. $\kappa_{z2}$ + $\kappa_{z3}$</td>
<td>19.7060 m</td>
<td>2.0423</td>
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<tr>
<td>D.-B. $\kappa_{z3}$ + $\kappa_{z4}$</td>
<td>19.7472 m</td>
<td>1.6903</td>
</tr>
<tr>
<td>D.-B. $\kappa_{z2}$ + $\kappa_{z4}$</td>
<td>19.9372 m</td>
<td>1.6852</td>
</tr>
</tbody>
</table>
5. CONCLUSION

This paper proposes a method to compensate the errors in the single-baseline Pol-InSAR RVoG inversion by using the multi-baseline Pol-InSAR data. Two error sources are modeled into the RVoG model and the inversion problem using multi-baseline Pol-InSAR data is analyzed. Inversion procedure of the revised RVoG model is described and validated using simulated Pol-InSAR data. The estimated heights from dual-baseline data are more close to the ideal height than just from single-baseline data. Different combinations of baselines have different estimation performance and the choice of baseline combination will be analyzed in the further work.

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REFERENCES