Forest height estimation methods using polarimetric SAR interferometry

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Abstract: Forest height extraction with polarimetric SAR interferometry (POLInSAR) is a hot research field of imaging SAR remote sensing. Several available forest height inversion methods using POLInSAR data were validated and compared with repeat pass E-SAR datasets and the corresponding ground measured forest stand height through the analysis of the Random Volume over Ground (RVoG) scattering model. After analyzing the experiment results in the view of physical mechanisms, we developed an integrated inversion method combining interferometric coherence optimization and compensation of non-volumetric scattering decorrelation. Validation result shows that the general performance of the developed forest height inversion method is superior to the others.

Key words: POLInSAR, polarimetric interferometric coherence optimization, RVoG, forest height, non-volumetric scattering decorrelation

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1 INTRODUCTION

The forest height is an important forest resource information parameter and usually used in biomass estimation model. Forest height extraction with polarimetric SAR interferometry (POLInSAR) is a hot research field of imaging SAR remote sensing. SAR interferometry is a well-established SAR technique to estimate the vertical location of the effective scattering center in each resolution cell through the phase difference in images acquired from spatially separated antennas. Scattering polarimetry is sensitive to the shape, orientation and dielectric properties of scatterers. POLInSAR based on the coherent combination of radar interferometry and polarimetry allows us to overcome the severe limitations of both techniques when taken alone and is becoming an important technique for forest parameters extraction (Wu et al., 2007). Cloude et al. (2003) have proposed the three-stages inversion algorithm which is based on a coherent mixture model of a random volume over ground describing the relation of forest height and polarimetric interferometric coherence. A two-component polarimetric interferometric model is presented for improvement of vegetation parameter retrieval using the Nelder–Mead simplex optimal method. It combines scattering model based polarimetric decomposition technique and RVoG based POLInSAR forest parameters inversion model (Neumman et al., 2009). Hajnsek et al. (2009) discussed the effect of some factors, such as temporal decorrelation and topography etc., to forest height inversion accuracy using P-, L- and X-band airborne POLInSAR data of Indonesia’s tropical forests.

The error sources of POLInSAR forest height inversion has been qualitatively analyzed using SIR-C/X SAR L-band repeat pass POLInSAR data and the corresponding optical image acquired in Hetian of Xinjiang (Chen et al., 2007). Six forest tree height inversion methods of POLInSAR were validated using repeat pass E-SAR datasets and the corresponding ground measured forest stand height (Chen et al., 2008). Utilizing the differences among the powers of backward scattering signal and scattering centers with different scattering mechanism in the same resolving unit, some scholars proposed TLS-ESPRIT algorithm to extract dominant scattering center phases for forest tree height inversion. The method can improve computational efficiency, but the capability for improving inversion accuracy is limited (Yang et al., 2007; Zhou et al., 2008). In order to
improve the accuracy of forest tree height estimation, Li et al. (2005) and Chen et al. (2008) carried out relevant research work trying to increase the utilization of baseline or frequency information in observation space.

After analyzing the experiment results of several available forest height inversion methods in the view of physical mechanisms, a RVoG model based inversion model combining coherent amplitude with phase information is developed in this paper, where the Phase Diversity (PD) interferometric coherence optimization method (Tabb et al., 2002) is used to obtain the surface and volume scattering phase. In order to investigate better inversion methods, the performance of the proposed method is compared with the other available methods using repeat pass E-SAR L band POLInSAR data and the corresponding ground measured forest stand height.

2 TEST SITES AND DATA SETS

Repeat pass POLInSAR data of the test site Traunstein in Germany acquired by the E-SAR L-band SAR sensor of DLR in 2003 is used for the study. The flight altitude is about 3000m above ground; the horizontal spatial baseline is 5m and the temporal baseline is 20min. The incidence angle increases from 25° in near range to 60° in far range. The data were processed for 1.5m range resolution and 3.0m resolution in azimuth.

The study area is mainly covered by agricultural fields, pasture, forests and some urban area in the western part of it, where the city of Traunstein is located. The topography is flat with elevation varying from 600 to 650m. The dominant tree species of this site is composed of spruce, beech and fir. The mean dominant height of forest stand ($h_v$) means the mean height of the 100 highest trees per hectare) of 20 validation stands is estimated by means of detailed forest inventory. These validation stands are characterized by mixed mountainous forests with individual tree height up to 40m and a mean biomass level up to 450 t/hm².

Fig. 1 shows the Pauli-basis E-SAR L-band image for the Traunstein scene in RGB color combination. It can be seen that the forest regions appear green to white color indicating that volume scattering possess a comparably strong HV/VH response. There are also some double bounce scattering phenomena around the forest stand borders by the trunk-ground interaction.

In Fig.2, the average coherence amplitude and phase in HH, HV, VV and HH-VV polarization channel is plotted respectively against the ground measured upper canopy height of the 20 validation stands (Fig.1). As shown in Fig.2 (b), the difference of the mean coherence phase among the polarization channels is small. It can be seen from Fig.2 (a) that the coherence amplitude of each polarization channel is obviously more sensitive to forest height, but the difference between polarization channels is small. From these, we can see that a variety of scattering mechanisms and factors contribute to the polarization coherence. So, forest height inversion methods only based on the separation of scattering mechanisms have bigger forest height estimation error. In order to improve the inversion accuracy, some models and methods were proposed in recent years. In the paper, the performance of these forest height inversion algorithms are quantitatively discussed and evaluated using the POLInSAR dataset and some ground truth data in forest stand scale. The flow chart of this study is shown in Fig.3.

3 INVERSION METHOD WITHOUT ASSUMING STRUCTURE FUNCTION

This method was first proposed by Cloude and Papathanassiou (1998) as DEM differencing approach, but it is better to name it as DSM differencing approach. Without assuming a forest vertical structure reflectivity function, the method simply define forest height as a phase difference between interferogram of the polarization channel dominated by “pure” volume scattering from the forest canopy top and that of the polarization channel dominated by “pure” surface scattering from the ground surface. Forest height is obtained through the phase difference divided by the effective wave number as Eq. (1).

$$h_v = \frac{\arg(\gamma_{wv}) - \arg(\gamma_{wv})}{k_z},$$

where $k_z = \frac{4\pi\Delta\theta}{\lambda \sin \theta}$

where $k_z$ is the effective wave number, $\theta$ is the angle of incidence and $\Delta\theta$ is the apparent angular separation of the baseline from the scattering point, $\gamma_{wv}$ is complex coherence corresponding “pure” volume scattering mechanism for the top forest canopy, $\gamma_{wv}$ is complex coherence corresponding to “pure” surface scattering mechanism for the under-canopy ground surface. HV polarization is selected to obtain $\gamma_{wv}$, while cohe-
herence of HH-VV polarization is considered as $\gamma_w$. Average tree height inverted from Eq. (1) is plotted against ground measured average forest height in Fig. 4(a). The performance is shown in Table 1. The forest height was significantly underestimated because the difference between coherence phase of HV and HH-VV is small. So, we naturally think of using the polarization interferometric coherence optimization algorithm to determine $\gamma_w$ and $\gamma_w$, and we want to know whether it is more advantageous to the separation of interferometric coherence phase centers of different scattering mechanism. Average forest height for each stands are obtained using DEM difference method with $\gamma_w$ and $\gamma_w$ defined by the PD polarimetric interferometric coherence optimization algorithm (Eq. (8) – (11) in Section 5), and the scatter diagram against ground measured average tree height is shown as Fig. 4 (b). Although the square of correlation coefficient $R^2$ increased (Table 1), the tree height is still seriously underestimated. The results indicate the capability for PD interferometric coherence optimization algorithm to extract coherent component of “pure” volume scattering and “pure” surface scattering mechanism is limited.

![Fig. 2] Scatter diagram of different polarization interferometric coherence vs. forest height
(a) Coherence amplitude; (b) Coherence phase

![Fig. 3] Flow chart of this study

![Fig. 4] Scatter diagram of average forest height inversed by DEM difference method with ground measured average forest height.
(a) Taking interferometric coherence of HV as $\gamma_w$, and that of HH-VV as $\gamma_w$; (b) $\gamma_w$ and $\gamma_w$ were defined by the PD polarimetric interferometric coherence optimization algorithm
Table 1 Comparison of inversion results

<table>
<thead>
<tr>
<th>Inversion Method used, polarization for $\gamma_v$ and $\gamma_w$</th>
<th>Average deviation/m</th>
<th>The squared correlation coefficient ($R^2$)</th>
<th>The root mean square error (RMSE)/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEM difference method, HV and HH-VV polarization</td>
<td>$-24.895$</td>
<td>$0.170$</td>
<td>$25.663$</td>
</tr>
<tr>
<td>DEM difference method, polarization defined by the PD optimizer</td>
<td>$-21.988$</td>
<td>$0.503$</td>
<td>$22.633$</td>
</tr>
<tr>
<td>SINC method, HV polarization</td>
<td>$15.874$</td>
<td>$0.766$</td>
<td>$16.420$</td>
</tr>
<tr>
<td>SINC method, HV polarization, non-volumetric decorrelation factor</td>
<td>$11.878$</td>
<td>$0.849$</td>
<td>$12.923$</td>
</tr>
<tr>
<td>Three stages method</td>
<td>$8.324$</td>
<td>$0.839$</td>
<td>$8.758$</td>
</tr>
<tr>
<td>The hybrid inversion method, HV and HH-VV polarization</td>
<td>$-0.181$</td>
<td>$0.286$</td>
<td>$6.288$</td>
</tr>
<tr>
<td>The hybrid inversion method, HV and HH-VV polarization, non-volumetric decorrelation factor</td>
<td>$-2.535$</td>
<td>$0.509$</td>
<td>$5.741$</td>
</tr>
<tr>
<td>the new hybrid inversion method, polarization defined by the PD optimizer</td>
<td>$3.434$</td>
<td>$0.678$</td>
<td>$5.206$</td>
</tr>
<tr>
<td>the new hybrid inversion method, polarization defined by the PD optimizer, non-volumetric decorrelation factor</td>
<td>$0.927$</td>
<td>$0.809$</td>
<td>$3.343$</td>
</tr>
</tbody>
</table>

4 INVERSION METHOD WITH ASSUMING STRUCTURE FUNCTION

4.1 Random volume scattering model

The RVoG model is simplified as random volume (RV) model when the ratio of effective surface to volume scattering is assumed to be zero. The corresponding coherence function is shown as Eq. (2),

$$
\gamma_c = \exp\left(\frac{2\alpha z}{\cos \theta}\right) \cdot \exp(jk_0 z) dz
$$

where the vertical structure function is assumed to be an exponent function; $\alpha$ is the mean extinction coefficient, $\phi_0$ is the ground phase. Without considering the surface phase, $\gamma_c$ is determined by two parameters, namely the height of the vegetation and its mean extinction coefficient. The relationship between the coherence amplitude, phase and the height, mean extinction coefficient is shown in Fig. 5. It can be seen from Fig. 5 (a) that coherence amplitude is prone to saturate when mean extinction coefficient is high, but the coherence phase is not saturated. In this case, it is a good way to use phase information for forest height inversion. When coherent phase is kept fixed, possible forest height can vary with the coherent amplitude because of the extinction coefficient difference. RV model becomes SINC function when extinction coefficient equals zero and coherence quickly decreased as the forest height increases. From Fig. 5, it can be seen that in case of equal forest height, when coherent amplitude is high, surface scattering contribution is dominant due to the terrain surface scattering or the strong forest canopy attenuation, which may be distinguished by coherence phase information: it will comes from strong attenuation caused by dense vegetation if the coherence phase value is high; otherwise it will comes from the ground surface under sparse vegetation.

Adding the effect of surface scattering on the coherence in the RV model, we get the RVoG model. Some inversion methods based on the RVoG model and its simplified forms will be discussed in detail as follows.

Fig. 5 Change of interferometric coherence with forest height and extinction
(a) Coherence amplitude; (b) Coherence amplitude and phase
4.2 Inversion algorithm with constant structure function

The method is based on single-layer model with one constant structure function assuming the scattering is only from a random volume. For forest height inversion, only the amplitude information is considered, while the phase and the surface backscattering are completely ignored. A polarization channel with expected low surface to volume scattering ratio (HV to HV coherence, for example) is always subjectively selected as volume coherence during the inversion. The algorithm is sensitive to forest stands with strong canopy structure variations. Big forest height estimation error is possible due to serious vertical structure variations in the canopy. Furthermore, if we set the mean extinction as zero, the model becomes a “SINC” function (Eq.(3)).

$$\gamma_v = \lim_{a \to \infty} \left\{ \frac{\exp(j\phi_0)}{\int_0^h \exp(2az/cos\theta) \cdot \exp(jk_zdz)} \right\}$$

$$\gamma_v = \exp(j\phi_0) \sin\left(\frac{1}{k_z}h\right)$$

Coherence of HV to HV is also selected as $\gamma$, and the forest heights of the 20 validation stands are inversed using Eq.(3). Scatter plot of the estimated forest height with the ground measured is shown in Fig.6 (a). The correlation with the ground-measured heights is good ($R^2 = 0.766$ as shown in Table 1), but the forest heights are overestimated for each validation stand. From Fig.5 (a), it can be seen that the forest height should be underestimated for the same coherence amplitude. So the overestimated problem observed may be caused by the contribution of non-volumetric related decorrelation, which should be compensated before inversion process.

For measuring vegetation through repeat-pass interferometry, there are volume decorrelation and non-volumetric related decorrelation sources (range, temporal or system decorrelation). In the RVoG-model (Eq.(6) in Section 4.3), range- and system-decorrelation affect all coherences equally and temporal decorrelation affects only the volume-coherence as shown in Eq.(4) (Mette, 2007).

$$\gamma = \gamma_{\text{range}} \gamma_{\text{system}} + \gamma_{\text{temporal}} + \mu(1 - \gamma_{\text{temporal}})$$

$$\gamma = \gamma_{v} \gamma_{d}$$

Coherence of HV to HV polarization that was corrected through incorporating the average decorrelation factor into Eq.(5) to compensate all the non-volumetric decorrelation, is considered as $\gamma_v$. Then forest heights are estimated from Eq.(3) and the average height for each validation stand is computed. The inversion results are shown as scatter plot of Fig.6 (b). It is evident that the overestimated problem is solved in some degree by this way.

4.3 Inversion algorithm with extinction and ground contribution

Assuming an exponential structure function and taking the contribution of surface scattering into consideration, the RVoG model can be expressed as Eq.(6) for forest height inversion,

$$\tilde{\gamma}(w) = \exp(j\phi_0) \left[ \tilde{\gamma}_{v} + \frac{\mu(w)}{1 + \mu(w)} (1 - \tilde{\gamma}_{v}) \right]$$
where $\mu(w)$ denotes the ground-to-volume scattering ratio being of polarization dependent. It can be seen from Eq.(6) that the complex coherence follows a straight line in the coherence unit circle which intersects the circle at two points. One of the two points corresponds to the underlying topography phase, so this point is called the true ground phase point; the "pure" volume coherence will be furthest away in distance from the true ground phase point along the line. According to this principle, Cloude and Papathanassiou (2003) developed the three-stages inversion method as the following:

1. Using least squared error regression algorithm to fit one line to the real and imaginary components of the data, a pair of points on the unit circle that defines a line and minimizes the mean squared error (MSE) between the line and the set of coherence points are found out.

2. Determine one of the pair points as the ground phase point using ranking order algorithm.

3. Then, after removing the effect of surface scattering and ground topography on coherence, forest height and corresponding extinction coefficient can be estimated using one 2D look-up table (LUT).

Scatter diagram of estimated average forest height by three-stages method with ground measured average forest height is shown in Fig.7. Although the $R^2$ value is high, the root mean squared error (RMSE) is relative big (RMSE=8.758) and the overestimated problem is still existed.

### 4.4 Hybrid inversion method based on fusion of the coherence amplitude and phase information

From the above we can see that forest height estimated just from the phase information (DEM difference method) is underestimated. It is very difficult to find polarizations with phase centers exactly at the top and bottom of the vegetation layer, since polarization is "contaminated" by the volume scattering. Although coherence optimization is useful to the effective estimation of ground phase, the phase of the volume only scattering channel can lie anywhere between half-way and the top of the canopy layer, and hence in general this will lead to underestimated forest height (Fig. 4(b)). The simplified inversion algorithm based only on coherence amplitude information, even taking into account the impact of non-volumetric decorrelation, still overestimates the forest height (Fig. 6(b)). Therefore, it is possible to get improved inversion results by combining the two methods (Cloude, 2006). The hybrid inversion method is shown as Eq. (7).

$$h_s = \frac{\arg(\tilde{\gamma}_{w_s}) - \hat{\phi}_0}{k_z} + \varepsilon \frac{2 \sin c^{-1}(\hat{\gamma}_{w_s})}{k_z}$$

where,

$$\hat{\phi}_0 = \arg(\tilde{\gamma}_{w_s} - \tilde{\gamma}_{w_s} (1 - L_{w_s})), 0 \leq L_{w_s} \leq 1$$

$$AE^2_{w_s} + BL_{w_s} + C = 0 \Rightarrow L_{w_s} = \frac{-B - \sqrt{B^2 - 4AC}}{2A}$$

$$A = |\tilde{\gamma}_{w_s}|^2 - 1$$

$$B = 2 \text{Re}(\tilde{\gamma}_{w_s} - \tilde{\gamma}_{w_s})\tilde{\gamma}_{w_s}^*$$

$$C = |\tilde{\gamma}_{w_s} \tilde{-\gamma}_{w_s}|^2$$

The idea of the method is that as the phase centre separation increases, the effective volume depth decreases (as the structure function becomes more localized near the top of the layer), hence the level of volume decorrelation will decrease. SINC coherence function is used to make up the phenomenon of "compression" at the top of vegetation which is always happens with phase only inversion method. $\varepsilon$ can be taken different value due to different structure function. There are two important special cases: Firstly, the medium has a uniform structure function (extinction is zero), then the first term will give half the height or $\frac{1}{2}k_z h_s$, and we can know from Eq.(3) that the second term will also obtain half the true height and yield $\frac{1}{2}k_z h_s$, therefore $\varepsilon$ is set as 1/2; Secondly, to the opposite extreme of infinite extinction, the structure function in the volume channel is localized near the top of the layer, then the first term will give $k_z h_s$ and the second term will approach zero, this means $\varepsilon=0$ is the correct choice. So the inversion method will provide a reasonable estimate for arbitrary structure functions between these two extremes and $E$ value is proposed to be 0.4 as a suitable compromise for height estimation in varying forest density and structure environments (Cloude, 2006).

Coherence of HV to HV is considered as $\gamma_{w_s}$, coherence of HH-VV to HH-VV is used as $\gamma_{w_s}$, are inputted to Eq.(7) and scatter plot is shown in Fig.8(a). $R^2$ is low. Even using the average decorrelation factor by the same way in section 4.2, $R^2$ is still low, and that indicate the two polarization channels selected from the physical mechanism point is not dominant by "pure" volume scattering and surface scattering respectively, with phase centers are furthest between.

![Fig. 7 Scatter diagram of estimated average forest height by three-stages method with ground measured average tree height](image-url)
5 IMPROVEMENT OF HYBRID INVERSION METHOD

The increasing phase center separation by interferometric coherence optimization method is useful for choosing polarization channels dominated by “pure” volume scattering and surface scattering respectively. In this study, Phase Diversity (PD) interferometric coherence optimization method is used for the purpose, which is based on maximization of the separation of the phase center of the POLInSAR coherence.

The basic idea of PD method is to find the eigenvectors ($\Omega$) that maximize the cotangent of the phase of the complex coherence ($\gamma$).

$$\cot(\gamma) = \frac{\text{Re}\{\gamma\}}{\text{Im}\{\gamma\}} = \frac{w^T (\Omega_{12} + \Omega_{12}^*) w}{w^T [-j(\Omega_{12} - \Omega_{12}^*)] w}$$

where $\Omega_{12} = \Omega_{21}^*$, $\Omega_{12}$ and $\Omega_{12}^*$ are the elements of the matrix $T$ (Eq.(10)), contains polarimetric and interferometric information.

$$\gamma = \frac{w^T \Omega_{12} w}{w^T T w}$$

(11)

where $k = \pm 1$ if the measurement of the two ends of spatial baseline respectively.

Figure 8 shows the scatter diagram of estimated average forest height by the hybrid inversion method with ground measured average forest height.

(a) Without non-volumetric decorrelation compensation; (b) With non-volumetric decorrelation compensation.

Figure 9 shows the scatter diagram of estimated average forest height by the new hybrid inversion method with ground measured average forest height.

(a) Without non-volumetric decorrelation compensation; (b) With non-volumetric decorrelation compensation.

The optimum coherence values obtained from Eq.(11) using the two eigenvector are considered as $\gamma_w$ and $\gamma_s$, respectively, and inputted to Eq.(7). Thus forest heights estimated for 20 validation stands is used to plot against ground measured average forest height in Fig. 9(a). It can be seen that the general performance of the method is good (Table 1), but the overestimated problem still exists in some degree. By taking into account the impact of non-volumetric decorrelation, the general performance has been further improved.
The forest height inversion performance of the methods involved in the paper was summarized in Table 1. DEM difference method is the worst with largest RMSE and lowest $R^2$. $\gamma_w$ and $\gamma_w^2$ determined by PD interferometric coherence optimization method was used in DEM method to improve $R^2$ to 0.503. Instead of using coherence of HV and HH-VV, if the optimum coherence values obtained by PD is used in the hybrid inversion method based on fusion of the coherence amplitude and phase information, the RMSE can be reduced from 6.288m to 5.206m and $R^2$ is improved from 0.286 to 0.678, which indicates PD can separate effectively the phase center of coherence. Further considering the compensation of non-volumetric decorrelation, the RMSE is reduced to 3.343m, which is the smallest of all the methods, while $R^2$ is increased to 0.809.

It is shown in Fig.10 that forest height profile along the azimuth direction (a straight line of column 278 in the image shown in Fig.1) of three inversion algorithms involved in the paper. It can be seen that the inversion method developed in the paper (corresponding to the green line) can significantly improve the performance of inversion.

6 CONCLUSIONS

Several available forest height inversion methods for POLInSAR data were investigated and compared using repeat pass E-SAR L band polarimetric SAR interferometry data and the corresponding ground measured forest stand height. The results show that: (1) the overestimated problem for forest height caused by non-volumetric decorrelation can be solved in some degree by taking into account the average decorrelation factor $\gamma$. (2) PD interferometric coherence optimization method can separate effectively the phase center of coherence for different scattering mechanism, and can be used for improving the inversion performance in the DEM difference method and the hybrid inversion method. (3) Although the hybrid inversion method is simple, however it considers comprehensively the underestimated and overestimated problem associated with inversion method based only on the coherent phase or the amplitude respectively, higher accuracy for forest height estimation can be obtained if some ground true information available. The paper proposed one improved inversion method by incorporating interferometric coherence optimization and compensation of non-volumetric decorrelation into the hybrid inversion method, the validation result shows that the general performance of this method is superior to the others.

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1. [内容]
2. [内容]
3. [内容]
4. [内容]

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2

SAR 增强（DLR）和 ESAR 交付 SAR 产品 L、H、V 域观察。3km，5m，20min

- 25°，60°
- 1.5m，3m

600—650 m，20

- 100
- 40m，450t/hm²

SAR PAULI RGB

1，PAULI

HV

(a)

(b)

1

PAULI

20

HH HV VV HH-VV

(b)

2

(a)

DEMS (Cloude & Papathanasssiou, 1998)

3

DEM

DSM
无结构函数假设的反演法

基于相干相位的 DEM差分反演法

基于相干相位的 DEM差分反演法

基于相干相位的 DEM差分反演法

改进的相干相位-幅度综合反演法(极化相干优化和非体散射去相关补偿的综合反演方法)

基于结构函数假设的反演法

式 (1) \[ k_z = \frac{4\pi\Delta \theta}{2 \sin \theta} \]

式 (1)

表 1 反演结果比较

<table>
<thead>
<tr>
<th>DEM</th>
<th>HV</th>
<th>HH-VV</th>
<th>SINC</th>
<th>HUD</th>
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<tr>
<td>M/M</td>
<td>25.663</td>
<td>22.633</td>
<td>16.420</td>
<td>8.324</td>
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<td>RMSE/m</td>
<td>2.535</td>
<td>3.434</td>
<td>5.206</td>
<td>3.343</td>
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<tr>
<td>R²</td>
<td>0.678</td>
<td>0.766</td>
<td>0.849</td>
<td>0.839</td>
</tr>
<tr>
<td>R²</td>
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<td>0.839</td>
</tr>
</tbody>
</table>

图 1 反演结果比较

图 1 反演结果比较
4.1 RVoG (RV) (2)

\[
\gamma_v = \exp(j\phi_h) \frac{\int_0^h \exp(2\alpha z / \cos \theta) \exp(jk_z z) dz}{\int_0^h \exp(2\alpha z / \cos \theta) dz}
\]

4.2 (3)

\[
\gamma_v = \lim_{\alpha \to 0} \left\{ \exp(j\phi_h) \frac{\int_0^h \exp(2\alpha z / \cos \theta) \exp(jk_z z) dz}{\int_0^h \exp(2\alpha z / \cos \theta) dz} \right\}
\]

(3) SINC (4)

\[
\gamma = \gamma_{range} \gamma_{temporal} + \frac{\mu}{1 + \mu} (1 - \gamma_{temporal}) \gamma_v
\]
6. SINC

(a) RVoG (6) \( \gamma_0 \), \( \gamma_h \).

(b) E-SAR (6) \( \gamma_h \).

6.3. E-SAR

\( \gamma_h \) (Mette, 2006; Mette, 2007).

6.4. E-SAR

\( \gamma_h \) (Cloude, 2006).

4.4

4.4.2

(SINC)
\[
\hat{\phi}_0 = \arg[\tilde{\gamma}_{w_1} - \tilde{\gamma}_{w_1}^*(1 - L_{w_1})], 0 \leq L_{w_1} \leq 1
\]

\[
A\tilde{L}^2_{w_1} + BL_{w_1} + C = 0 \Rightarrow L_{w_1} = \frac{-B - \sqrt{B^2 - 4AC}}{2A}
\]

\[
A = |\tilde{\gamma}_{w_1}|^2 - 1
\]

\[
B = 2\Re((\tilde{\gamma}_{w_1} - \tilde{\gamma}_{w_1}^*)\tilde{\gamma}_{w_1}^*)
\]

\[
C = |\tilde{\gamma}_{w_1} - \tilde{\gamma}_{w_1}^*|^2
\]

\[
0.4\text{(Cloude, 2006)}
\]

\[
\hat{\phi}_0 = \arg[\tilde{\gamma}_{w_1} - \tilde{\gamma}_{w_1}^*(1 - L_{w_1})], 0 \leq L_{w_1} \leq 1
\]

\[
A\tilde{L}^2_{w_1} + BL_{w_1} + C = 0 \Rightarrow L_{w_1} = \frac{-B - \sqrt{B^2 - 4AC}}{2A}
\]

\[
A = |\tilde{\gamma}_{w_1}|^2 - 1
\]

\[
B = 2\Re((\tilde{\gamma}_{w_1} - \tilde{\gamma}_{w_1}^*)\tilde{\gamma}_{w_1}^*)
\]

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\]

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0.4\text{(Cloude, 2006)}
\]
9(a), 9(b), 0.9, 0.503, 0.678, RMSE 3.343m, 0.503, 0.809, RMSE 3.343m, 0.503, 0.809

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附中文参考文献