Research on Forest Height Inversion Algorithm of Three-Stage Full-Polarization SAR Data Based on Improved Coherence Coefficient

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Abstract. Polariometric SAR interference technology (PolInSAR) has a wide range of applications in the extraction of forest height. At present, some commonly used tree height inversion algorithms, such as ESPRIT algorithm and DEM difference method, seriously underestimate the forest tree height. In this paper, in the process of traditional three-stage algorithm, the extraction of the coherence coefficient is improved, and the improved coherence coefficient is more accurate, thus greatly improving the accuracy of three-stage algorithm tree height inversion results. By highly inverting the 25 m data generated by the PolSARPro simulation software, it is found that the height before the improvement of the coherence coefficient is 18.2 m, and the improved height is 23.7 m.

Introduction

Vegetation height is a very important parameter in ecological environment construction and modern management of forest resources. Polarization Interferometric SAR (PolInSAR) is a combination of Polariometric SAR (PolSAR) and Interferometric SAR (InSAR). It has the characteristics of obtaining the scatterer texture structure information from polarization SAR and the vertical height of the scatterer obtained by interferometric SAR. In recent years, the use of SAR technology for vegetation inversion has become a new development direction. It has been shown that PolInSAR is not only sensitive to the spatial distribution but also sensitive to the shape and direction of vegetation scatterers [1-4], which provides a possibility for the inversion of vegetation height. Compared with the traditional interferometric synthetic aperture radar technology, the polarization interferometric SAR improves the inversion accuracy of vegetation height by separating the different scattering phase centers and interference phases of the vegetation body, which is of great significance for the study of vegetation height inversion [5-6].

At present, the most commonly used model for PolInSAR scatterer parameter estimation is the RVOG model, which was proposed by Treuhaft in 2000 [7]. In 2003, Cloud proposed a three-stage vegetation inversion method based on RVOG ground random scattering model, including least squares fitting in the complex plane, vegetation maximum deviation removal, vegetation heigh, and vegetation extinction coefficient estimation [8]. In 2005, Yu et al. proposed a scattering model and ESPRIT joint inversion algorithm, which reduces the scattering model parameters to only two parameters of the extinction coefficient and vegetation height [9]. In 2006, Cloud proposed Polarization Coherence Tomography (PCT) algorithm, which can invert the vertical structure distribution of vegetation, and further expands the theory and method of polarization interferometric SAR application [10]. Then multi-baseline tomography (SAR) is also applied to the inversion of forest tree height to achieve high-precision acquisition of backscattered power information in the vertical direction of the forest [11], and the tree height inversion effect is also obtained. improve. In 2016, Guo et al. used the single-baseline reduced polarization interference coherence coefficient to perform the straight line fitting of the coherent region, established the sub-forest terrain phase discrimination criterion, estimated the volume scattering decoherence coefficient, and obtained the terrain and forest average height [12].
However, when the traditional three-stage algorithm estimates the volume coherence coefficient, it is considered that there is no surface scattering component in the volume coherence coefficient, but this is inconsistent with the actual situation, so the volume coherence coefficient cannot be accurately estimated. This paper simulates the forest vegetation by PolSARpro software simulation data. The improvement of the coherence coefficient estimation method can more accurately estimate the volume coherence coefficient and improve the tree height inversion accuracy of the vegetation area.

Tree Height Inversion Classic Model

RVOG Model

The two-layer coherent model of vegetation is to simplify the geometrical structure parameters of the vegetation and the scatterers of each component into the vegetation layer of thickness \( h_v \) and the combination with the surface layer. Vegetation layer with random direction has the same attenuation and absorption effect on all polarization electromagnetic waves, that is, the extinction coefficient is the same and the polarization state of electromagnetic waves does not change. In the Random-volume-over-ground (RVOG) model, the observed coherence is given by the mixing formula, as shown in equation (1).

\[
\hat{\gamma}(w) = e^{i\phi_w} \frac{\hat{\gamma}_v + \mu(w)}{1 + \mu(w)} = e^{i\phi_w} \left( \hat{\gamma} + \frac{\mu(w)}{1 + \mu(w)} (1 - \hat{\gamma}_v) \right) \\
= e^{i\phi_w} \left( \hat{\gamma}_v + L(w)(1 - \hat{\gamma}_v) \right) \quad 0 \leq L(w) \leq 1
\]

where \( w \) is unitary vector associating polarization, \( \phi_w \) is the ground phase, \( \mu(w) \) is ground-to-volume scattering ratio, and \( \hat{\gamma}_v \) is the volume decorrelation coefficient. The expression \( \hat{\gamma}_v \) is,

\[
\hat{\gamma}_v = \frac{2\sigma}{\cos \theta_v (e^{i2\pi k \lambda \cos \theta_v} - 1)} \int_0^h e^{i2\pi k z} e^{i2\pi \gamma z} \cos \theta_v dz
\]

where \( \sigma \) is the extinction coefficient, \( \theta_v \) is the SAR angle of incidence, which varies with the range direction, \( h_v \) is the tree height, \( k_z \) is the effective vertical interferometric wavenumber, defined as

\[
k_z = \frac{4\pi B}{\lambda R \sin \theta_v}
\]

where \( B \) is the perpendicular spatial baseline, \( \lambda \) is the wavelength, and \( R \) is the slant range.

Three-stage Algorithm

The inversion of equation (1) involves observing complex coherence in different polarizations and then minimizing the difference between model prediction and observation in the least squares sense. In most of the previous studies, it was considered a six-dimensional optimization problem using a standard iterative process. Due to the nonlinearity of the optimization problem, the resulting solution depends to a large extent on the choice of the initial value. Poor initial values may result in unstable parameter estimates [13-14]. Thus, Cloud inverts vegetation parameters through three separate stages.

It can be seen from (1) that the complex correlation is a straight line on the complex plane, and there are two intersection points between the straight line and the circle, as shown in Fig. 1. The line intersects the circle at two points. One of them is the potential ground phase (as shown by point Q in Fig 1). The other is the wrong solution and must be rejected by the inversion process. In fact, when \( \mu = 0 \), we think it is the case of random volume scattering, and when \( \mu \) tends to infinity, we think it is the surface scattering situation. The length of the line visible in the data may be only a small part of the PQ, and neither P nor Q can be directly observed. The visible length depends on the baseline, operating frequency, and vegetation density. At the same time, this line can be extrapolated to achieve parameter estimation.
Stage 1: Least squares line fit

The first stage is to find the best-fit straight line inside the unit circle of interferometric coherence, and delineating two intersections of the line and circle. The polarization interference matrix is obtained by vectorization of the scattering matrix of the master-slave image, calculate the coherence coefficient and the optimal coherence coefficient $\gamma_{\text{opt1}}$, $\gamma_{\text{opt2}}$, $\gamma_{\text{opt3}}$ of different polarization channels in the polarization interference matrix.

Stage 2: Vegetation bias removal

In the second stage we must choose one of the pair $\psi_1$, $\psi_2$ as the underlying ground topographic phase for each pixel. The surface phase is determined by the position of the HV and HH+VV or HH-VV polarization coherence coefficients on the fitted line on the complex plane. The closest to the HH+VV or HH-VV polarization coherence coefficient is the surface phase. Usually, it is considered that there is no ground component in the HV channel, so the HV coherent channel is farthest from the true phase point Q. Assuming that the two intersection points are $k_1$ and $k_2$, $\gamma_{k_1}$ and $\gamma_{k_2}$ are complex coherence coefficients corresponding to two points, which can be determined by the following formula:

$$
\begin{align*}
\phi_0 &= \arg(\gamma_{k_1}), \quad |\gamma_{hv} - \gamma_{k_1}| > |\gamma_{hv} - \gamma_{k_2}| \\
\phi_0 &= \arg(\gamma_{k_2}), \quad \text{other}
\end{align*}
$$

Stage 3: Height and extinction estimation

To estimate the remaining two parameters, height and extinction, the estimate of ground phase $\phi$ and (2) are used to find the intersection between the coherence line and the curve corresponding to the height/extinction change. The vegetation height and extinction coefficient are estimated by the following:

$$
\mu(w) = \frac{\hat{\gamma}_v - \hat{\gamma}(w)}{\hat{\gamma}(w) - e^{i\phi_0}}
$$

Figure 1. Distribution of complex coherence coefficients in the complex plane.

Figure 2. Relative location of polarization states along the coherence line.
principle of mean square error minimization, as shown in equation (5), where $h_v$, $\sigma$ represents the vegetation height and extinction coefficient respectively, and equation (5) is a two-bit search problem. According to the above three steps. Inversion is used to find the tree height.

$$\min_{h_v, \sigma} D(h_v, \sigma, \omega_{h_v}) = \left\| \nu(w_{HV}) - e^{ih_v \gamma} \right\|$$

(5)

**Improved Three-Stage Algorithm**

Usually, when performing vegetation height inversion, it is considered that $\mu(w) = 0$ in the HV channel, that is, only the body scattering of vegetation exists in the HV channel. In practice, the HV channel also has some surface scattering. If the surface scattering is not considered, the volume scattered coherence coefficient $\gamma$, $\exp(i\phi_v)$ causes a certain error in the actual vegetation height inversion.

It can be seen from the literature [15] that the coherence coefficient $\gamma$ (0<$\gamma$<1) of interference between two images is:

$$\gamma = \frac{|\langle \mu, \mu^H \rangle |}{\sqrt{\langle \mu, \mu^H \rangle \langle \mu, \mu^H \rangle}} = \frac{|\omega^H \Omega_{12, 1} \omega_1|}{\sqrt{(\omega^H T_{11} \omega_1)(\omega^H T_{22} \omega_2)}}$$

(6)

The $T_{11}$ and $T_{22}$ contain radar system for target polarization information, they are all semi-positive definite Hermitian matrix, and $\Omega_{12}$ is a 3 × 3 polarization interference matrix, it also contains the ground targets of polarization information and the interference between different polarization channels.

Since $T_{11}$ and $T_{22}$ are approximately equal, Equation (6) can be changed to:

$$\hat{\gamma} = \frac{\langle \omega^H \Omega_{12, 1} \omega \rangle}{\langle \omega^H ((T_{11} + T_{22})/2 \omega \rangle}$$

(7)

Therefore, the real part of $\hat{\gamma}$ can be obtained as:

$$\text{Re}(\hat{\gamma}) = \frac{\langle \omega^H ((\Omega_{12} + \Omega_{12}^H)/2 \omega \rangle}{\langle \omega^H ((T_{11} + T_{22})/2 \omega \rangle}$$

(8)

At this time, the $\text{Re}(\gamma, \exp(i\phi_v))$ corresponding to the boundary point on the corresponding coherent line is:

$$\text{Re}(\gamma) = \frac{\langle \omega^H ((e^{i\phi_v} \Omega_{12} + e^{-i\phi_v} \Omega_{12}^H)/2 \omega \rangle}{\langle \omega^H ((T_{11} + T_{22})/2 \omega \rangle}$$

(9)

By using the Langeland multiplier method, a Lagrangian complex equation $L$ can be obtained to obtain:

$$L = \omega^H ((e^{i\phi_v} \Omega_{12} + e^{-i\phi_v} \Omega_{12}^H)/2 \omega + \lambda(\omega^H ((\Omega_{12} + \Omega_{12}^H)/2 \omega - C))$$

(10)

$$\frac{\partial L}{\partial \omega^H} = 0$$

(11)

$$((e^{i\phi_v} \Omega_{12} + e^{-i\phi_v} \Omega_{12}^H)/2 \omega + \lambda((\Omega_{12} + \Omega_{12}^H)/2 \omega = 0$$

(12)

At this time, a maximum value and a minimum value of $w$ can be obtained, that is, a scattering mechanism corresponding to the boundary point of the coherent line, and the coherence coefficient of the corresponding boundary point can be obtained:
\[
\hat{\gamma}_1 = \frac{\omega_{\text{max}}^H \Omega_{\text{max}} \omega_{\text{max}}}{\omega_{\text{max}}^H (T_1 + T_2)/2 \omega_{\text{max}}}, \quad \hat{\gamma}_2 = \frac{\omega_{\text{min}}^H \Omega_{\text{min}} \omega_{\text{min}}}{\omega_{\text{min}}^H (T_1 + T_2)/2 \omega_{\text{min}}} \tag{13}
\]

Finally, the required volume coherence point can be judged by the formula (4).

**Simulation Results and Analysis**

In order to verify the improved algorithm, the forest simulation data was generated by PolSARPro simulation software. The parameters were: center frequency 1.3GHz, platform height 3km, horizontal baseline 10m, vertical baseline 1m, forest distribution density 500stem/Ha, tree height 25m. As shown in Table 1. Fig. 1 is a simulation of the vegetation area. Table 1. PolSARPro Simulation data parameters, Fig. 2 shows the Pauli decomposition image of the simulated data with 103 pixels in range and 99 in azimuth.

| Parameter          | Center frequency (GHz) | Platform height (m) | Horizontal baseline (m) | Vertical baseline (m) | Density (stem/Ha) |
|--------------------|------------------------|---------------------|-------------------------|-----------------------|-------------------|
|                    | 1.3                    | 3000                | 10                      | 1                     | 500               |

Table 1. SAR simulation data parameters.

Fig. 3. Simulated vegetation map.  
Fig. 4. RGB diagram of Pauli-based synthesis.  
Fig. 5. Vegetation area mask.

The decoherence of the vegetation coverage area is more serious than the simple surface. Therefore, in order to eliminate the influence of the flat phase, the image is masked, leaving only the middle circular vegetation area. In Fig. 5, the black area is the vegetation cover, and the white area is the flat land removed by the mask. In order to make the result representation more intuitive, the inversion height of the whole vegetation area is counted, and the statistical histogram is obtained, as shown in Fig. 6. The blue solid line in the figure is the height histogram of the improved algorithm, it can be seen that most pixels appear around 18m and 25m. The red dashed line in the figure is the height histogram of the traditional three-stage algorithm. It can be seen that the most concentrated pixels are between 13m-19m. By calculating the average height of vegetation areas in equation (14), it can be known that the average height calculated by the improved algorithm is 23.7m, with an error of 5.2% from the preset average tree height. The average height of the traditional three-stage algorithm is 18.2m, with an error of 27.2%. It can be seen that the vegetation height obtained by the algorithm after improving the coherence coefficient is closer to the preset tree height value. Fig 7 is the 3-d vegetation height result map generated by the improved algorithm.

\[
hv_{\text{average}} = \frac{1}{N} \sum_{i=1}^{N} hv
\tag{14}
\]
Figure 6. Comparison of height results.  
Figure 7. Tree height inversion results 3-D map.

Table 2. Comparison between the proposed approach and three-stage inversion method.

| Parameter            | Average height(m) | REMS(m) |
|----------------------|-------------------|---------|
| Proposed method      | 23.7              | 2.05    |
| Three-stage method   | 18.2              | 6.17    |

Conclusion

In the process of forest height inversion of fully polarized SAR data, in most cases, the body coherence coefficient is not included in the surface scattering component. After considering the surface scattering component, the calculation of the volume coherence coefficient is more accurate, compared with the traditional three-stage algorithm greatly improved the inversion accuracy of the vegetation height. The tree height inversion was performed on the vegetation area with an average height of 25 m, and the result was increased from 18.2 m to 23.7 m.

References

[1] Yi-rong Wu, Wen Hong, Yan-ping Wang. The Current Status and Implications of Polairmetric SAR Interferometry[J]. Journal of Electronics & Information Technology, 2013, 29(3): 43-47.
[2] Ting-wei Li, Dian-nong Lian, Ju-bo Zhu. A Review of Inversion of the Forest Height by Polairmetric Interferometric SAR[J]. Remote Sensing Information, 2009(3): 85-90.
[3] Huan-min Luo. Models and methods of Extracting Forest Structure Information by Polairmetric SAR Interferometry[D]. Chengdu: University of Electronic Science and Technology, 2011.
[4] Hai-qiang Fu, Chang-cheng Wang, Jian-jun Zhu, et al. A modified PolInSAR PCT method to invert vegetation vertical structure[J]. Engineering of Surveying and Mapping, 2014, 23(11): 56-66.
[5] Shun-jun Wei. Research on Height Estimation Method of Polarization Interferometric SAR Vegetation[D]. Chengdu: University of Electronic Science and Technology, 2009.
[6] Jong-Sen Lee, Eric Pottier. Polairmetric Radar Imaging: From Basics to Applications[M].Beijing: Electronic Industry Press, 2013.
[7] Treuhaft R N, Siqueira P R. Vertical Structure of Vegetated Land Surfaces from Interferometric and Polairmetric Radar[J]. Radio Science, 2000, 35(1):141-177.
[8] Cloud S.R., Pапathanassiou K. P. Three-stage Inversion Process for Polairmetric SAR Interferometry[J]. IEEE Proc. -Radar Sonar Navigation, 2003, 150(3):125-134.
[9] Da-yang Yu, Gui-wei Dong. Forest Height Inversion Based on Interferometric Polarimetric SAR Data[J]. Journal of Tsinghua University (Science and Technology), 2005, 45(3): 334-336.

[10] Cloud S. R. Polarization Coherence Tomography[J]. Radio Science, 2006, 41(4):1-27.

[11] Wen-mei Li, Er-xue Chen, Zeng-yuan Li. Multi-baseline interference tomography SAR extraction method for forest tree height[J]. Forest Research, 2014, 27(6): 815-821.

[12] Sheng-long Guo, Yang Li, Qiang Yin, et al. Forest vertical parameter inversion based on condensed polarization interferometric SAR data[J]. Journal of Electronics & Information Technology, 2016, 38(1): 71-79.

[13] Tabb, M., and Carande, R.: ‘Robust inversion of vegetation structure parameters from low-frequency, polarimetric interferometric SAR’. Proceedings of IEEE-IGARSS 2001, Sydney, Australia, July 2001.

[14] Ulbricht, A., Fabregas, X., And Sagues, L.: ‘Applying polarimetric interferometric methods to invert vegetation parameters from SAR data’. Proceedings of IEEE Int. Geosci. Remote Sens. Symp. (IGARSS), Sydney, Australia, 9-13 July 2001 (on CD).

[15] S. R. Cloude, K. P. Papathanassiou. Polarimetric SAR interferometry [J]. Geoscience and Remote Sensing, IEEE Transactions on, 1998, 36(5): 1551-1565.