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An improved volume coherence optimization method for forest height estimation using PolInSAR images

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***Abstract*—Forest height is one of the most important forest vertical structure parameter for many forest management and monitoring activities. One of the most widely used methods for forest height estimation using the PolInSAR image, which is the three-stage inversion process. In this method, the complex coherence value of the HV channel is used for forest height estimation. Therefore, the estimated forest height is usually lower than the actual forest height. Moreover, when determining the ground-phase coefficient, this method used a lot of channel coherence coefficients, which increased the amount of calculation complexity. The proposed method in this paper, we determined the optimum volume coherence coefficient of the system by comparing the polarization channels and using the optimal complex unitary vector. The experimental results show that the accuracy of forest height is significantly improved by the proposed method.**

***Index Terms*—PolInSAR, the forest height, the three-stage inversion algorithm.**

I. Introduction

Nowadays, Polarimetric Synthetic Aperture Radar Interferometry (PolInSAR) is one of the most advanced and promising remote sensing technologies for forest management, monitoring, and surveillance.In recent years, some researchers have introduced a great number of methods to estimate forest height using the PolInSAR image. Including some methods based on calculating the phase difference between the interfering images [1, 2]. One of the most popular and widely methods used today is the three-state inversion algorithm, which is introduced by Cloude and Papathanassiou in 2003 [3]. In this method, the authors combined waveform scattering and Random Volume over Ground-model (RVoG) [6]. However, the forest height estimated by this algorithm is not accurate due to the wave attenuation in the environment. Therefore, it creates ambiguity volume decorrelation region and might cause errors in the volume coherence coefficient determination $\tilde{\gamma}_v$. In order to improve accuracy for ground phase estimation, the three-stage algorithm must use from eight to twelve coherence coefficients of polarimetric channels. At the same time, the two-phase coefficients Φ_0 and Φ_1 both run on the unit circle. This makes the complexity of the calculation of the whole system much increased. In this paper, we attempted to develop the proposed method to forest height estimation from the L-band PolInSAR images. In the proposed method, we use the cancellation of scattering mechanisms to ground phase estimation [7], specifically the volume scattering mechanisms discarded to find the ground phase. The results of this method have the same accuracy as other algorithms but the complexity of the calculation is significantly decreased. After that, we construct the coherence line in the complex unit cycle, which goes through 2 points Φ_0 and γ_{HV}. Then, we find the optimal volume coherence coefficient by combining two methods, which are introduced by Fu Wenxue [8] and Tayebe Managhebi [9]. This combination not only increases the accuracy for volume coherence selection in an unambiguity region on the coherence line but also improved the disadvantages of the three-stage inversion algorithm for estimation of the forest height and wave extinction coefficient. In addition, the proposed method employs the range of the wave extinction coefficient [4] to construct a LUT table for each pixel. Finally, by comparing the coefficients $\tilde{\gamma}_v$ and γ_v in the LUT table to determine the estimated forest height. The effectiveness of the proposed method is assessed through simulation results from the PolSARProSim software.

II. THE THREE-STAGE INVERSION ALGORITHM

A. The PolInSAR system

For backscattering in the reversible environment, the Pauli scattering vector of each PolSAR system is performed as:

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$$\vec{K}_i = \frac{1}{\sqrt{2}} \left[\begin{array}{ccc} S^i_{HH} + S^i_{VV} & S^i_{HH} - S^i_{VV} & 2S^i_{HV} \end{array} \right]^T \tag{1}$$

Where, $S_{p,q}\,(p,\, q = \{h,\, v\})$ are complex scattering coefficients and $i = 1, 2$ expression for the two PolSAR systems. Data received from the PolInSAR system is the regular expression by the (6 × 6) complex coherence matrix and defined as (2)

$$[\mathrm{T}_6] = \left\langle \left[\begin{array}{c} k_1 \\ k_2 \end{array} \right] \left[\begin{array}{cc} k_1^H & k_2^H \end{array} \right] \right\rangle = \left[\begin{array}{cc} [\mathrm{T}_{11}] & [\Omega_{12}] \\ [\Omega_{12}^H] & [\mathrm{T}_{22}] \end{array} \right] \tag{2}$$

Where T_{11} and T_{22} are Hermitian polarization coherence matrices describing the polarization properties of the target obtained from each individual PolSAR images, $[\Omega_{12}]$ is a non-Hermitian complex matrix which contains the both polarimetric and interferometric information. The superscript "H" denotes the complex conjugate transposition.

The complex polarimetric interferometry coherence of the PolInSAR system is described by a polarization function of the two images as follow:

$$\tilde{\gamma}\left(\vec{\omega}_1, \vec{\omega}_2\right) = \frac{\vec{\omega}_1^H \Omega \vec{\omega}_2}{\sqrt{\vec{\omega}_1^H T_{11} \vec{\omega}_1 \vec{\omega}_2^H T_{22} \vec{\omega}_2}} = \frac{\vec{\omega}^H \Omega \vec{\omega}}{\vec{\omega}^H T \vec{\omega}} \tag{3}$$

Where $\vec{\omega}_1 = \vec{\omega}_2 = \vec{\omega}$ is the complex unitary vector of each polarizable channel and $T = (T_{11} + T_{22})/2$.

B. The three-stage inversion algorithm

Three-stage inversion process was first proposed by Cloude and Papathanassiou in 2003, which uses random volume over ground (RVoG) model to retrieve forest height and ground topography with PolInSAR data. This method is divided into 3 stages:

Firstly, the authors find the most a straight line, which intersects the unit circle at two points γ_0 and γ_1. From that determines the ground phase of the observed area by comparing the distance from the complex coherence coefficient of the HV channel to the two intersections. According to [3], the point at which the distance is larger, that point corresponds to the ground phase. Secondly, in order to eliminates the surface roughness, the authors perform multiply the volume coherence coefficients with the amount of the ground phase just found. Finally, the authors construct a look-up table (LUT) for interferometric coherence coefficients, corresponding to the forest height h_v and the extinction coefficient σ, according to the Eq.4

$$\gamma_v = \frac{2\sigma}{\cos\theta_0 (e^{\frac{2\sigma z}{\cos\theta_0}} - 1)} \int_0^{h_v} e^{jk_z z} e^{\frac{2\sigma z}{\cos\theta_0}} dz \tag{4}$$

By comparing the complex coherence values of the HV channel with the LUT, we can estimate the forest height h_v and the mean extinction coefficient σ.

III. FOREST HEIGHT ESTIMATION USING THE PROPOSED METHOD

A. Ground phase estimation by cancellation of scattering mechanism

In order to reduce the computational steps for determining the actual ground phase of the system, the researchers based on Random Volume over Ground (RVoG). Here, polarimetric coherence matrix $[T]$ and polarimetric interferometric coherence matrix $[\Omega]$, which are represented by the ground scattering matrices $[Ts]$ and volume scattering matrices $[Tv]$ as Eq.5

$$\begin{array}{l} [\mathrm{T}] = f_v.[\mathrm{T}_v] + f_g.[\mathrm{T}_g] \\ [\Omega] = e^{j\phi_v}.f_v.[\mathrm{T}_v] + e^{j\phi_g}.f_g.[\mathrm{T}_g] \end{array} \tag{5}$$

Where f_v and f_g correspond to the scattering power coefficient of ground and volume scattering. So, Eq.4 can be expressed as Eq.6

$$\gamma(\omega_1, \omega_2) = \frac{\omega_1^H (e^{j\phi_v} f_v T_v + e^{j\phi_g} f_g T_g) \omega_2}{\sqrt{\omega_1^H (f_v T_v + f_g T_g) \omega_1 . \omega_2^H (f_v T_v + f_g T_g) \omega_2}} \tag{6}$$

To get the surface scattering component from Eq.6 (Carlos Lopez) assumption to the volume scattering component when multiplying with the complex vector lines ω_1 and ω_2 are zero. When the volume coherence coefficient only depends on the surface scattering component. The ground phase component is defined by Eq.7

$$\phi_0 = \arg\left\{\Omega_{12}(1,2) T(2,1)\right\} \tag{7}$$

Where $i,\ j = 1, 2$ are rows and columns of the matrices Ω_{12} and T. By this way time for defining the ground phase which was significantly decreased compared with the three-stage inversion process.

B. The coherence optimation

In the proposed algorithm, the first stage is to determine the first optimal volume complex coherence coefficient by comparing the complex coherence coefficient values of the HV and HH channels. According to [6], the estimated complex coherence coefficient values of HH and HV channels are calculated by Eq.8

$$\begin{array}{l} \gamma_{est(hh)} = e^{j\phi_0} \left[\gamma_v - L(HH)(1 - \gamma_v) \right] \\ \gamma_{est(hv)} = e^{j\phi_0} \left[\gamma_v - L(HV)(1 - \gamma_v) \right] \end{array} \tag{8}$$

Then, the L(HH) and L(HV) are varied in the range (0,1), and the values of the complex coherence $\gamma_{est(hh)}$

and $\gamma_{est(hv)}$ lie in the coherence line. The complex coherence line is determined by two points in the complex unit circle (the ground phase point and the HV channel complex coherence point). The optimum volume complex coherence coefficient is determined by the sum of the error distances between the estimated coefficients and the complex coherence coefficients of the HV, HH channels according to Eq.9 and Eq.10

$$\begin{aligned} d_1 &= \left|\gamma_{hh} - \gamma_{est(hh)}\right| \\ d_2 &= \left|\gamma_{hv} - \gamma_{est(hv)}\right| \end{aligned} \tag{9}$$

$$\min\left(\sum_{i=1}^{2} d_i\right) \tag{10}$$

The second stage is the determination of the second optimal volume complex coherence coefficient according to [9]. From Eq.6, the complex unitary vector ω is calculated as

$$\omega = \left[\begin{array}{ccc} \cos\alpha & \sin\alpha\cos\beta e^{j\varepsilon} & \sin\alpha\sin\beta e^{j\psi} \end{array}\right]^T \tag{11}$$

After that, we build a look-up table for the volume only coherence coefficients by varying the $\alpha,\ \beta$ in the range (0, $\pi/2$) and the $\varepsilon,\ \psi$ in the range ($-\pi$, π). The phase of the volume complex coherence coefficients can be determined by Eq.12

$$\phi_C = \arg(\gamma(\omega)) = \arg(\omega^H \Omega_{12} \omega) \tag{12}$$

Combined with the two conditions below to find the second optimal volume complex coherence coefficient value corresponding to the optimum phase angle ϕ_C.

The first condition:

$$\arg(\gamma_{HV}) \le \phi_C \le \phi_1 \tag{13}$$

For ϕ_1 is the second intersection of the straight line passing through the point ϕ_0 and the HV channel complex coherence coefficient.

The second condition:

$$\max\left|\phi_C - \arg(\gamma_{HV})\right| \tag{14}$$

At the end of the second stage, compared two optimal volume complex coherence coefficient values together to find the volume complex coherence coefficient of the system. This decision is based on the distance from the two points to the ground phase of the system. Points that are farther (or larger) are considered volume complex coherence coefficient of the system. The third stage is the LUT table construction according to the ratio between the HV channel complex coherence coefficients with two intersections ϕ_1 and ϕ_0 according to [4]. The extinction coefficient σ is calculated as

$$D.I = \frac{A.L}{V.L} \tag{15}$$

Where $D.I$ is the distance proportional coefficient, $A.L$ and $V.L$ are the distances from the HV channel complex coherence coefficient to ϕ_1 and ϕ_0 respectively. From this, the extinction coefficient σ is assigned as in Table I [4].

TABLE I
MEAN EXTINCTION LIMITS BASED ON DISTANCE RATIO INDEX VARIATION.

Index Range	Extinction Coefficient Range σ
0 – 0.4	0.6 – 1
0.4 – 0.65	0.3 – 0.6
Larger than 0.65	0 – 0.3

After that, we use the Eq.6 to build a look-up table for each pixel. Finally, we compare the volume complex coherence coefficients found in the second stage with the LUT table to determine the forest height and the corresponding extinction coefficient.

C. Forest height estimation

The proposed method is divided into three steps:

Step 1: From the input data, create 2 coherence matrices [T] and [Ω]. Next, determine the coefficient γ of HH, HV channels. Then estimation of ground phase ϕ_0 based on the combination of cancellation of scattering mechanism and determine the ϕ_1.

Step 2: Remove surface roughness of HH, HV channels.

Step 3: Determine the first optimal volume complex coherence coefficient by comparing the complex coherence coefficient values of the HV and HH channels. Next, determine the second optimal volume complex coherence coefficient based on the unitary complex vector ω . Then comparing the two optimal volume complex coherence coefficients together to find the optimal volume complex coherence coefficient of the system. After that build LUT table based on the extinction coefficients are determined by the ratio of the distance from the complex coherence coefficients of the HV channel with two intersections ϕ_0 and ϕ_1. Finally, the estimation of forest height h_v and wave extinction coefficient σ by comparing the optimal volume complex coherence coefficient of the system with the LUT table.

We repeat three above steps for each pixel in the image. The proposed method is summarized in Fig.1

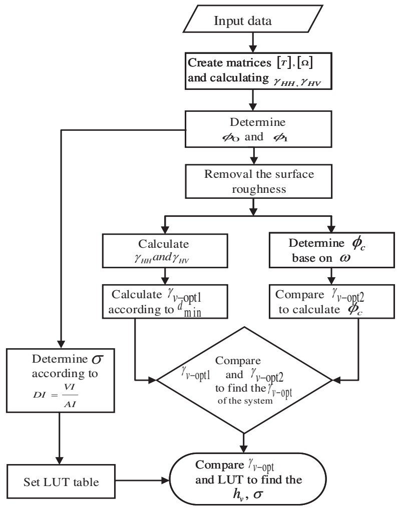

Fig. 1. Flowchart of the proposed method.

IV. EXPERIMENTAL RESULTS

The effectiveness of the proposed method is evaluated with simulation results generated from the PolSARProSim software [5]. Simulation data received from the L-band PolInSAR system at 1.3 GHz and with 10m horizontal and 1m vertical baseline. The forest survey area is 2.8274 Ha with a density of 800 trees/Ha. Which has an average tree height of 18m in relatively flat terrain. Fig.2 shows the Pauli colour image of the forest survey area with dimensions of 155 x 233 pixels.

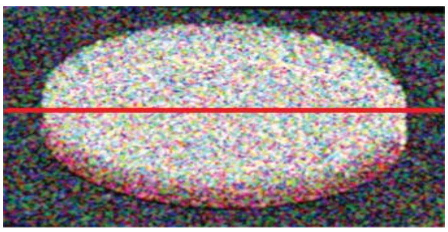

Fig. 2. Pauli color image

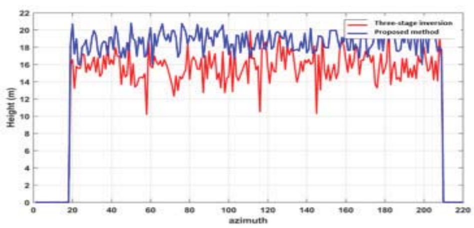

Fig. 3. Forest height result comparison.

Fig.3 is a graph comparing the estimated forest height from the proposed method on the green line with the three-stage inversion process on the red line. The forest height of the proposed algorithm has a higher accuracy than the three-stage inversion process. The forest survey area has the actual height of 18m, the three-stage inversion process and the proposed algorithm had average heights of 15.8917m and 18.4316m, and mean errors of 2.1083m and 0.4316m, respectively.

TABLE II
FOREST PARAMETERS ARE ESTIMATED FROM TWO ALGORITHMS.

Parameters	Real value	Three-stage inversion algorithm	Proposed algorithm
$h_v\,[m]$	18	15.8917	18.4316
$\phi_0\,[rad]$	- 0.0148	- 0.004	- 0.008
$\sigma\,[dB/m]$	0.2	0.1221	0.2474
RMSE	0	2.0459	1.1260

In table II, it showed results comparing the estimated forest parameters from the proposed method and the three-state inversion algorithm. The ground phase estimated by using proposed method is lower than its by three-stage inversion process but time consuming reduces significantly. Besides, the proposed method gives the extinction coefficient σ of 0.2474 which is relatively accurate compared to the three-state inversion algorithm of 0.1221. Another parameter to prove the proposed method is more accurate than the three-state inversion algorithm is the mean error value of the system. In Table II, it is clear that the mean error value of the proposed method is 1.1260, which is lower and closer to the actual value of the system.

According to [3], the modified three-state inversion algorithm has introduced a look-up table. It includes the distance value between the volume complex coherence coefficient γ_v and the HV channel complex coherence coefficient corresponding to the extinction coefficient σ, and the forest height of the area observed in Table II. In the paper, we compare the volume complex coherence coefficients γ_v, and the distance value between γ_v and γ_{HV} of algorithms together to improve the correctness of the proposed method. Table III shows that the forest height estimated by the proposed method is more accurate than the height estimated by other algorithms.

Tree height in the entire surveyed forest is estimated from the proposed method as shown in Fig.4. In this figure, we can see that the forest height is approximately 18m. Except that at some pixels, which are estimated higher than the actual forest height, but most

TABLE III
VOLUME COHERENCE VALUE OF FOUR ALGORITHMS.

Algorithm	Volume coherence coefficient γ_v	Distance between γ_v and γ_{HV}	Forest height hv(m)
Three-stage inversion	-0.2154 - 0.0060i	0.1992	$\sim$ 15.7
Three - stage inversion value optimization γ_v	0.0640 + 0.0008i	0.0486	$\sim$ 18.6
Extended three - stage inversion	0.0274 + 0.0029i	0.0115	$\sim$ 19
Proposed method	-0.0177 + 0.0008i	0.0547	$\sim$ 18.4

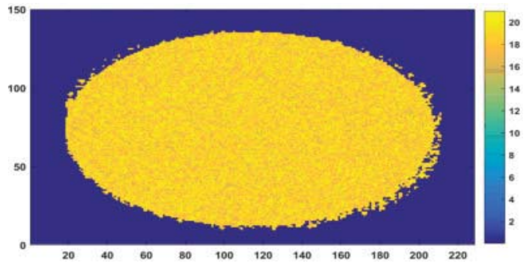

Fig. 4. 2-D Forest height is estimated by the proposed method.

of the forest heights at these sites are less than 21m. Such as that, the proposed method gives a relatively accurate result with small errors.

In order to further evaluate the effectiveness of the proposed method, we have taken randomly assigned 200 pixels according to the azimuth in the surveyed area. The main forest parameters estimated by the proposed method in the 200 surveyed pixels are shown in Fig.5.

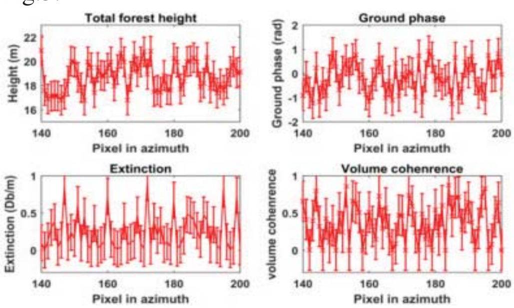

Fig. 5. Estimation of parameters for the test area.

Fig.5 shows graphs of values and standard deviations of forest parameters determined by the proposed method. In Fig.5 (a), we found that the forest height varies from 17m to 21m. However, they are concentrated mainly around the height of 18m. The ground phase changes in the range of -1 to 1. In Fig.5 (b), it shows that the extinction coefficient varies from 0.1 to 0.5, and around 0.2 (Fig.5 (c)). Moreover, the volume complex coherence coefficient varies from 0 to 0.8 in Fig.5 (d).

V. CONCLUSION

In the paper, we propose a new method for improving the accuracy of forest height estimates using the PolInSAR images. The proposed method base on the combination of cancellation of scattering mechanisms and volume complex coherence coefficient estimation. The experimental results show that the proposed method not only produces better results but also reduces the complexity of the calculation compared to the classical three-stage algorithm.

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