Modified Three-stage algorithm for forest height estimation using Polarimetric SAR Interferometry Image

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Abstract— **Estimation of the forest height using Polarimetric SAR interferometry (PolInSAR) images is one of the most promising applications in the field of active microwave remote sensing. The three-stage inversion process has been one of the methods most by used with PolInSAR image for forest height retrieval. However, the method tends to underestimate the forest height due to attenuations of the electromagnetic waves in the ground medium. This paper proposes a modified three-stage method to improve the accuracy of forest height estimation and reduce the computational complexity based on combination of cancellation of scattering mechanism and complex coherence coefficient optimization. Experimental results show that the proposed algorithm significantly improves the accuracy of forest heights.**

Keywords: PolInSAR, the forest height, cancellation of scattering mechanisms.

I. INTRODUCTION

Nowadays, to meet the need of forest management and investigation, PolInSAR is one of the most advanced active microwaves remote sensing system. The system is based on the combination of the advantages of Synthetic Aperture Radar Polarimetric (PolSAR) and Synthetic Aperture Radar Interferometry (InSAR). The target height can be extracted from the difference phase in the interferogram of PolInSAR system [1, 2]. One of the most widely used PolInSAR image for forest high estimation is three-stage inversion method [3], which is implemented by combining of the wave scattering models [4-6] and the Random Volume over Ground (RVoG) model [7]. However, this method requires multiple parameter least-square estimation, which is complicated and often becomes ill-conditioned. Furthermore, the estimation by using three-stage inversion process leads to an ambiguity zone in indicating complex coherence coefficient of HV channel. Therefore, forest height estimation of three-stage inversion process is sometimes not trustworthy. In addition, the efficiency of the three-stage algorithm has been examined with dual-polarization data [9]. The performance of the three-stage inversion method can also be improved by combining with the coherence optimization [13, 14]. Despite the good performance of the original three-stage inversion method in forest height estimation, the effects of the signal penetration in the determination of forest parameters need to further investigated.

In order to overcome these shortcomings, this paper presents a method to enhance the accuracy in both ground phase and forest height estimation and reduce computing time of the system. The proposed method is implemented in three stages. Firstly, ground phase is estimated by using cancellation of scattering mechanism [8]. Secondly, to remove ambiguity in choosing HV channel complex coherence coefficient, two channels HH and HV are used to improve accuracy when calculating the volume coherence coefficient ($\hat{\gamma}_{\text{est,v}}$) [9]. Finally, the forest height is estimated by comparing coefficient $\hat{\gamma}_{\text{est,v}}$ to coefficient $\hat{\gamma}_{\text{v}}$ in Look Up Table (LUT), which is generated by a function of the wave attenuation coefficient σ and the forest height h_v . The proposed method not only decreases computational complexity but also preserves the accuracy of topographic phase. The results show that the accuracy of the forest height estimation was essentially enhanced compared with three-stage inversion method.

The organization of this paper is as follow. The three-stage inversion process is mentioned in section II, following by the proposed method in section III. Section IV discusses the experimental results of proposed method with simulated data. Finally, the conclusion and future work are draw in section V.

II. THREE-STAGE INVERSION PROCESS FOR POLINSAR

A. PolInSAR system

In the fully polarimetric interferometric SAR system, [S1] and [S2] are the scattering matrices for the two acquisitions and the vectorized form can be represented by the Pauli scattering vectors k_1 and k_2, respectively [10]

$$[S_1]=\begin{bmatrix} S_{HH}^1 & S_{HV}^1 \\ S_{VH}^1 & S_{VV}^1 \end{bmatrix} \qquad [S_2]=\begin{bmatrix} S_{HH}^2 & S_{HV}^2 \\ S_{VH}^2 & S_{VV}^2 \end{bmatrix} \tag{1}$$

$$[\mathrm{k}_1]=\begin{bmatrix} S_{HH}^1+S_{VV}^1 & S_{HH}^1-S_{VV}^1 & 2S_{HV}^1 \end{bmatrix}^T \tag{2}$$

$$[\mathrm{k}_2]=\begin{bmatrix} S_{HH}^2+S_{VV}^2 & S_{HH}^2-S_{VV}^2 & 2S_{HV}^2 \end{bmatrix}^T \tag{3}$$

Where superscript 1 and 2 represent the acquisitions from two ends of the baseline. The 6x6 coherence matrix [T6] is the main observation in PolInSAR, and defined as

$$[\mathrm{T}_6]=\left\langle \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} [k_1^{*\mathrm{T}} \quad k_2^{*T}] \right\rangle = \begin{bmatrix} [\mathrm{T}_{11}] & [\Omega_{12}] \\ [\Omega_{12}^*] & [\mathrm{T}_{22}] \end{bmatrix} \tag{4}$$

In Eq. (4), $[T_{11}]$ and $[T_{22}]$ are the 3x3 Hermitian coherence matrices for the two acquisitions and describe the polarimetric properties of each acquisition. $[\Omega_{12}]$ is a 3x3 non-Hermitian complex matrix which contains both polarimetric and interferometric information.

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

$$\tilde{\gamma}(\omega_1,\omega_2)=\frac{\left|\left\langle \omega_1^{*T}[\Omega_{12}]\omega_2\right\rangle\right|}{\sqrt{\left\langle \omega_1^{*T}[T_{11}]\omega_1\right\rangle\left\langle \omega_2^{*T}[T_{22}]\omega_2\right\rangle}} \tag{5}$$

Where ω_1 , ω_2 are unitary complex vectors of polarization channel.

B. Three-stage inversion process for PolInSAR

The three-stage inversion process was first proposed by Cloude and Papathanassiou in 2003, which based on the random volume over ground (RVoG) model to retrieve forest height and ground topography with PolInSAR data. The implementation of the three-stage inversion process is summarized as following [11].

1. Stage 1: Least squares line fit

The first stage is to find the best-fit straight line inside the unit circle of interferometric complex coherence. In that, the authors used a total least squares line fit to the real and imaginary components of the data and then use the line parameter estimation to secure the intersection points. Alternatively, a faster least squares line fit in the real and imaginary parts can secure an estimation of the minimum error solution. This process requires some care in complex coherence because the complex coherences may be afflicted with certain variance and errors [11].

2. Stage 2: Vegetation bias removal

In this stage, one of the two phases as the underlying ground topographic phase for each pixel is chosen. It is the intersection of the unit circle with the estimated line in stage 1, and the distance from it to complex polarimetric interferometric coherence HV is the greatest. The extracted ground phase was expected to come from a smooth topography without abrupt changes. Therefore, smoothing the ground phase can compensate for the uncertain line fitting and help the ground phase decision. An accurate ground phase determination is the most sensible point of the three-stage inversion process.

3. Stage 3: Height and extinction estimation

In order to estimate the two remaining parameters, height and extinction, the author used the estimation of ground phase ϕ_0 to find the intersection point between the coherence line and the curve corresponding to the height/extinction variations.

Firstly, the volume coherence $\hat{\gamma}_{hv}$ is estimated by using obtained ground phase ϕ_0 in stage 2. Secondly, from the baseline data, the wavenumber k_z can be determined and then the LUT for $\hat{\gamma}_v$ is pre-calculated as a function of h_v and σ according to the Eq. (6)

$$\hat{\gamma}_v=\frac{2\sigma}{\cos\theta_0(e^{\frac{2\sigma z}{\cos\theta_0}}-1)}\int_0^{h_v} e^{jk_z z}e^{\frac{2\sigma z}{\cos\theta_0}}dz \tag{6}$$

In Eq. (6), the polarimetric interferometric volume only coherence associated with a mean extinction coefficient σ ranging from 0 to 2 dB/m and the forest height ranging from 0 to 2π height ambiguity ($h_v\in(0,2\pi/k_z)$). Finally, by comparing $\hat{\gamma}_{hv}$ with the LUT, the height and extinction are estimated without the need for iterative optimization algorithms.

C. Limitations of the three-stage inversion process

As can be seen, the three-stage inversion process is simple and most widely used. However, the accuracy of ground phase estimation is not relatively high, and there is still an ambiguity zone of ground phase estimation. Therefore, the estimation accuracy of forest height and extinction is not reliable. In this process, to increase accuracy in ground phase estimation, many complex coherence coefficients have to be used, this leads to increased computational complexity. Otherwise, to reduce the calculated time, it means less complex coherence coefficients are used, the accuracy in ground phase estimation will decrease.

III. MODIFIED THREE-STAGE ALGORITHM FOR FOREST HEIGHT ESTIMATION

A. Ground phase estimation by cancellation of scattering mechanism

For the Random Volume over Ground (RVoG) model, the polarimetric coherence matrices and polarimetric interferometric coherence matrix are decomposed into the two scattering mechanisms corresponding to ground and volume scattering.

$$\begin{aligned}[\mathrm{T}]&=f_v.[\mathrm{T}_v]+f_g.[\mathrm{T}_g]\\ [\Omega]&=e^{j\phi_v}.f_v.[\mathrm{T}_v]+e^{j\phi_g}.f_g.[\mathrm{T}_g]\end{aligned} \tag{7}$$

Where f_g and f_v represent the scattering power coefficient of ground and volume scattering, respectively. $[T_v]$ and $[T_g]$ are expressed as

$$[\mathrm{T}_v]=\begin{bmatrix}1&0&0\\0&\eta&0\\0&0&\eta\end{bmatrix}\qquad [\mathrm{T}_g]=\begin{bmatrix}1&t_{12}&0\\t_{12}^*&t_{22}&0\\0&0&t_{33}\end{bmatrix} \tag{8}$$

Where the parameter η accounts for the mean particle shape, ranging from η = 0 in case of spheres to η = 0.5 in case of dipole-like particles.

Then, the complex coherence coefficient in Eq. (5) is rewritten as follows

$$\gamma(\omega_1,\omega_2)=\frac{\omega_1^H(e^{j\phi_v}f_vT_v+e^{j\phi_g}f_gT_g)\omega_2}{\sqrt{\omega_1^H(f_vT_v+f_gT_g)\omega_1.\omega_2^H(f_vT_v+f_gT_g)\omega_2}} \quad (9)$$

The purpose of this method is to select the unitary complex vectors ω_1 , ω_2 , therefore the volume scattering component can be removed.

Meanwhile, the combination of the restriction conditions in [6] produces the ground phase ϕ_0 as follows

$$\phi_0=\frac{1}{2}\arg\{\Omega_{12}(1,2)\Omega_{12}(2,1)\} \quad (10)$$

The Eq. (10) introduce an additional phase wrapping of ϕ_0 which may be avoided if $T_{11}(2,1)$ is used instead of $\Omega_{12}(2,1)$

$$\Omega_{12}(1,2)\,T_{11}(2,1)=e^{j\phi_0}e^{-2\frac{2\sigma h_v}{\cos\theta_0}}m_g^2\left|t_{12}\right|^2 \quad (11)$$

Finally, the ground phase is computed as follow

$$\phi_0=\arg\{\Omega_{12}(1,2)\,T_{11}(2,1)\} \quad (12)$$

In proposed method, ground phase is determined quickly by Eq. (12). While three-stage inversion process requires many complex coherence coefficients and many computational steps to produce ground phase. So, the computational complexity of the system is reduced by using cancellation of scattering mechanism.

B. Remove surface roughness

In this stage, the surface roughness (or the changing ground phase) is removed by multiplying the coefficient $e^{-j\phi_0}$ with the complex coherence coefficients, as reported in [3]. The exclusive difference is that the ground phase was determined in stage A and the surface phase elimination was proceeded from the beginning of complex coherence coefficients computation.

C. Estimate the forest height

Firstly, the complex coherence coefficients γ_{hh}, γ_{hv} for the two channels HH and HV are determined as

$$\gamma=e^{-j\phi_0}\frac{E\{S_1S_2^*\}}{\sqrt{E\{|S_1|^2\}E\{|S_2|^2\}}} \quad (13)$$

In the proposed method, the optimal coherence coefficients γ_{opt1}, γ_{opt2}, γ_{opt3} of the PolInSAR system are used instead of the complex coherence coefficients γ_{vv}, γ_{hh+vv}, γ_{hh-vv} for the channels VV, HH + VV, HH – VV. This is to improve accuracy of determining the best-fit straight line corresponding to the complex coherence coefficients. These optimal coherence coefficients can be obtained from the matrix K, which is expressed as

$$[K]=[T_{22}]^{-1}[\Omega_{12}]^*[T_{11}]^{-1}[\Omega_{12}] \quad (14)$$

The matrix K has three real nonnegative eigenvalues λ_i (i=1,2,3) with $1 \geq \lambda_1 \geq \lambda_2 \geq \lambda_3 \geq 0$. The optimum interferometric coherence values are then given by the square root of the corresponding eigenvalues.

$$\gamma_{opt(i)}=\sqrt{\lambda_i} \quad (15)$$

From Eq. (15) the best-fit straight line corresponding to the complex coherence coefficients γ_{hh}, γ_{hv}, γ_{opt1}, γ_{opt2}, γ_{opt3} is found out. Using the volume coherence coefficient optimization method [9], the two estimate matching coefficients $\gamma_{est(hh)}$, $\gamma_{est(hv)}$ for the two channels HH and HV can be ascertained

$$\begin{aligned}\gamma_{est(hh)}&=e^{j\phi_0}\left[\gamma_v-L(\mathrm{HH})(1-\gamma_v)\right]\\ \gamma_{est(hv)}&=e^{j\phi_0}\left[\gamma_v-L(\mathrm{HV})(1-\gamma_v)\right]\end{aligned} \quad (16)$$

Where γ_v takes turns the values on the best-fit straight line for the complex coherence coefficients as determined in step 3, corresponding to the values of *L(HH)* and *L(HV)* within the limits from 0 to 1. Next, the error between estimated coherence coefficients $\gamma_{est(hh)}$, $\gamma_{est(hv)}$ and complex coherence coefficients γ_{hh}, γ_{hv} is calculated

$$\begin{aligned}d_1&=\left|\gamma_{hh}-\gamma_{est(hh)}\right|\\ d_2&=\left|\gamma_{hv}-\gamma_{est(hv)}\right|\end{aligned} \quad (17)$$

The optimization of the volume coherence coefficient can be done by calculating the sum of the errors for d_1 and d_2 in pairs. The smallest error is the optimal volume coherence coefficient as

$$\min\left(\sum_{i=1}^{2}d_i\right) \quad (18)$$

Finally, comparing γ_{v_opt} with γ_v in the LUT table, we can obtained the forest height.

IV. EXPERIMENTAL RESULT

In this section, the proof of the algorithm concept proposed in section III is addressed. For such a purpose we have employed simulated data from PolSARproSim software [12]. The proposed approach is tested with a simulated RVoG scenario, *Hedge,* in the PolSARproSim software. The simulated data is implemented at 1.3 GHz and at 22.5-degree angle of incidence from 3 km altitude with 10 m horizontal and 1 m vertical baseline. The height of the stand is 18 m, the forest stand occupies a 2.8274 Ha area and stand density is 800 stem/Ha. Fig. 1 shows Pauli image on RGB coding of the RVoG stand, with 155 rows and 233 columns in azimuth and the red line indicates the transection analyzed in this section.

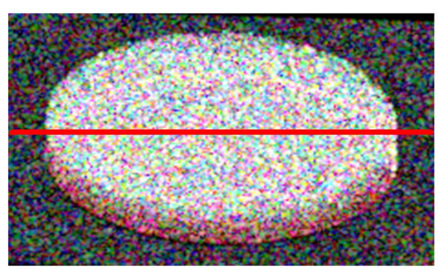

Fig. 1 Pauli image on RGB coding of the RVoG stand

Figure 2 is a plot of the forest height estimation of the proposed method compared with the three-stage inversion process in the azimuth transect line (the red line in Fig .1). Comparing with 18m actual tree height, the three-stage inversion processing method and the proposed method produces mean of 15.0988m and 17.3610m, and mean errors of 2.9012m and 0.639m, respectively. Table 1 indicates that the average forest height and the wave extinction factor of the proposed algorithm are 17.3610m and 0.2158 (dB/m), respectively, they are closer to the real value of the simulated data. The ground phase estimated by using proposed method is lower than its by three-stage inversion process but time consuming reduces significantly. It is reasonable that the three-stage method used greater than eight lexicographic coherence to improve the accuracy of ground phase estimation. On other hand, this method requires that the vertical structure and temporal decorrelation is neglected and the minimum ground-to-volume scattering ration needs to be lower than -10dB to secure around 10% accuracy [3]. Therefore, in the three-stage inversion process, the estimation of forest height and extinction are not reliable, while the estimation of ground phase is time consuming and reliable.

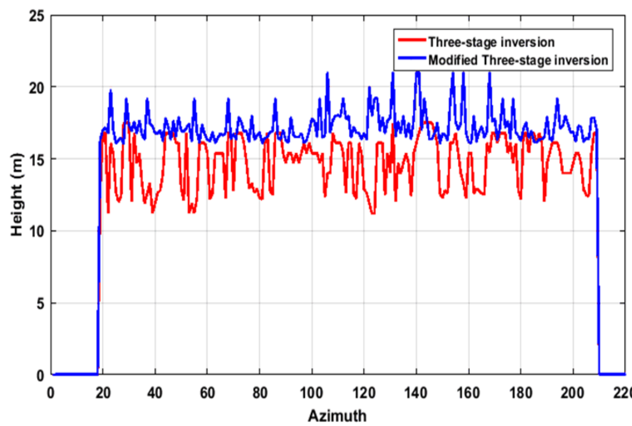

Fig. 2 Forest height result comparison

Table 1 Forest height estimation for two approaches

Parameters	True	Three-stage inversion	Proposed method
h_v [m]	18	15.0988	17.3610
ϕ_0 [rad]	-0.148	-0.1437	-0.1263
Average extinction $\sigma[dB/m]$	0.2	0. 3266	0.2158
Average error [m]	0	2.9012	0.6390
RMSE [m]	0	1.7402	1.1291

From Fig. 2 and Table 1, it is clear that the forest height and ground phase estimations by using proposed method are more accurate than those by using three-stage inversion method. The forest height estimation by using three-stage inversion process for whole scene is presented in Fig. 3. It is shown that three-stage inversion process delivers the forest height mostly around 15m, and the forest height ranges from 10m to 20m. On other hand, the result of proposed method is shown in Fig. 4. In this figure it is shown that the peak differential of the forest height is located approximately at 17.4m. The actual forest height are quite well retrieve, except some pixel are overestimated but almost of forest height in these pixels all less than 21m. However, these values are almost lower than the 2π height ambiguities, which about 25m. The real effectively forest height will be higher than these values so we can say that these results are acceptable. Likewise, the proposed method provides relative accuracy with small error, and is more accurate for vertical structural variations.

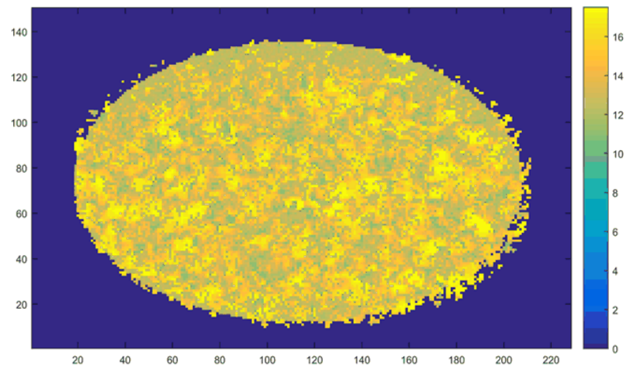

Fig. 3 Forest height estimation from the three-stage inversion method

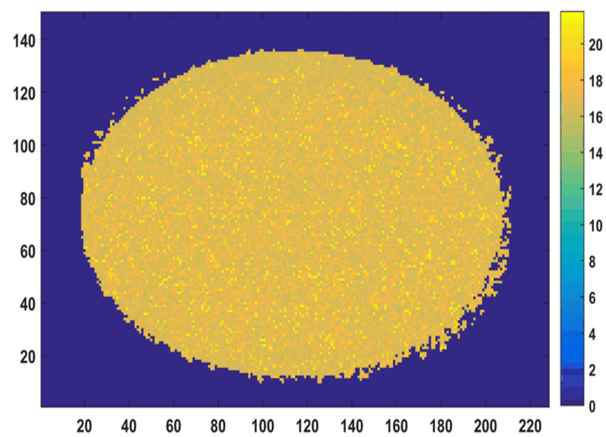

Fig. 4 Forest height estimation from the proposed method

Figure 5 shows a three-dimensional perspective view of the estimated height by the proposed approach for the whole scenario. It can be seen that estimation forest height is almost uniform and there is no sudden fluctuation in forest height.

To estimate the main forest parameters, the alternate transmit model is used. The parameter inversion process consists of the error function and the estimation of the physical parameters, including the forest height h_v, ground phase ϕ_0, extinction coefficient σ and volume coherence coefficient. Figure 6 demonstrates the parameter inversion performance in the pixels from 140^{th} to 200^{th} of the red line in Fig.1. In the paper, the graphs describe the value and the standard deviation of the estimated parameters. Fig. 6a illustrates the average forest height around 17m, and it ranges from 16m to 21m. The underlying topographic phase is around 0.25 rad and it is varied in ranges from 0 to 0.75 rad (Fig. 6b), with the average phase is 0.12 rad or 7 degrees. In Fig. 6.c, the extinction coefficient is around 0.2 dB/m, the highest point is 0.4 dB/m, and the volume extinction coefficient is from 0 to 2 dB/m of L band. Module of the volume coherence coefficient is around 0.2, and there are some pixels with the coherence coefficients γ_v is 0.8 corresponding to the forest height about 21m in Fig. 6d.

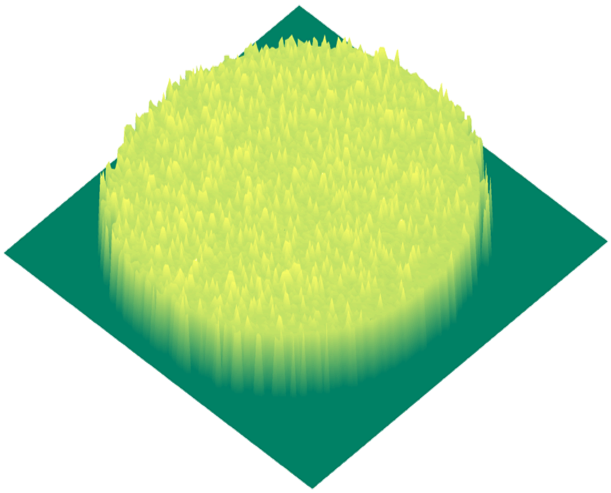

Fig. 5 3-D view of forest height

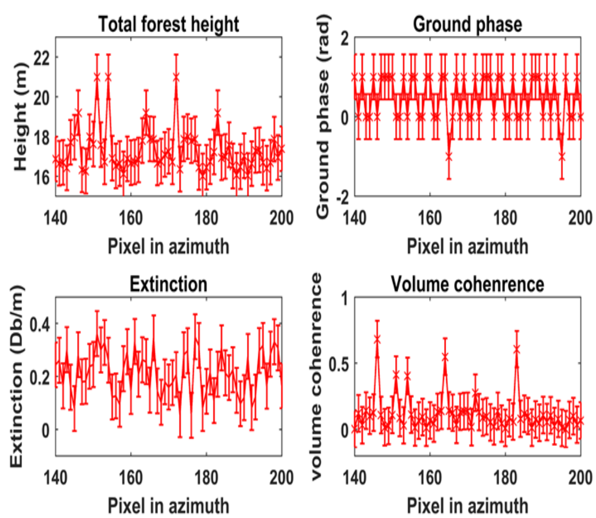

Fig. 6 Parameter estimation for test site area. (a) Forest height estimation, (b) ground phase estimation, (c) the volume extinction coefficient, and (d) the volume coherence coefficient.

V. CONCLUSION

The paper introduces a method to improve accuracy of forest height estimation. The identification is based on combination of removal of scattering mechanism and complex coherence coefficient computation. The proposed method not only overcomes the limitations of the three-stage inversion algorithm but also reduces the computational complexity of the whole system. The experimental result has shown that a more accuracy estimation for forest height appraisal can be obtained. Observational results indicate that vegetation parameters can be retrieved directly and accurately by the association of this approach.

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