A novel coherence optimization algorithm for forest height inversion using single-baseline PolInSAR images

Thieu Huu Cuong[1], Pham Minh Nghia[2*], Phan Huy Anh[3]

[1]Telecommunications Faculty, Telecommunications University;
[2]Faculty of Radio-Electronics Engineering, Le Quy Don Technical University;
[3]Electronic Institute, Academy of Military Science and Technology.
*Corresponding author: nghiapm2018@mta.edu.vn

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ABSTRACT

Forest height is one of the influential information for managing forest cover and is also one of the criteria to evaluate the growth of organisms in the forest ecosystem. This paper suggests a novel coherence optimization algorithm to increase the accuracy of forest height estimation using the L-band PolInSAR images. First, the ground phase and coherence line are determined based on the mean of the coherence set. Then, the proposed algorithm is developed by adding more forced conditions to determine the volume-only coefficient coherence optimization. Finally, the forest height and extinction coefficient can be extracted by comparing the volume-only optimal coherence coefficient with the values in the look-up table. The effectiveness of the proposed method was evaluated with PolInSAR simulated and spaceborne data. Experimental results show that the proposed method has improved the accuracy of estimated forest height by more than 0.9m compared with the forest height retrieval algorithm by Tayebe.

Keywords: Polarimetric Interferometry Synthetic Aperture Radar (PolInSAR); Forest height; Ground phase.

1. INTRODUCTION

The PolInSAR technique has been intensively researched for more than two decades and has proven to be an effective tool for forest resource monitoring and control. Currently, there are many scientists interested in researching this field and they have proposed many new methods based on the 3-stage inversion algorithm [1-3] to improve the accuracy of estimated forest heights from PolInSAR data. For instance, Papathanassiou and Cloude [4] examined the application of the single baseline PolInSAR data to measure the volume thickness over a forest area. In their study, a straightforward forest height estimation method was introduced based on the phase difference corresponding to particular polarization bases and the surface and volume-only polarization basis. However, the proposed method underestimated the forest height due to its assumption about the surface- and volume-only polarization basis [4-7]. In 2022, the forest height retrieval based on the dual PolInSAR images [7] was proposed by Tayebe. This method uses a large number of polarization channels for ground phase determination and assumes that the optimal volume coherence factor has only a volume scattering component ($\mu(\omega)=0$). Because of these two disadvantages, the Tayebe method forest height estimation efficiency is not highly reliable and does not accurately reflect the scattering process in the actual forest environment.

In this paper, we attempt to develop a novel inversion method for forest height estimation, in which the mean of the coherence set is applied. In this framework, a new geometrical method is introduced to find the ground phase and coherence line. On the other hand, a vertically varying extinction RVoG model is applied to construct the look-up-table (LUT) of volume-only coherence, which considers the forest vertical heterogeneity. In order to modify the accuracy of forest height estimation, the main of this paper is to find the ground phase accurately and the upper interferometry phase center between all observed polarization states. Therefore, an optimization technique that enhances the reliability of forest parameter inversion by improvement the accuracy of ground phase and volume coherence is proposed in this paper.

2. MODEL-BASED FOREST HEIGHT INVERSION METHODS USING POLINSAR IMAGES

2.1. Complex polarimetric interferometry coherence (CPI)

A monostatic, fully polarimetric interferometry system is measured for each element in the scene from two slightly different viewing angles. In general, the CPI coherence can be expressed as [8].

$$\tilde{\gamma}(\vec{\omega}) = \frac{\vec{\omega}_1^H \Omega \vec{\omega}_2}{\sqrt{\left(\vec{\omega}_1^H T_{11} \vec{\omega}_1\right)\left(\vec{\omega}_2^H T_{22} \vec{\omega}_2\right)}} = \frac{\vec{\omega}^H \Omega \vec{\omega}}{\vec{\omega}^H T \vec{\omega}} \tag{1}$$

where, $\vec{\omega}_1 = \vec{\omega}_2 = \vec{\omega}$ is a unitary vector of each polarization channel. The superscript "*H*" denotes complex conjugation and transposition. By using the modified normalized coherence matrix, the Eq. (1) can be represented as follows:

$$\tilde{\gamma}(\vec{\upsilon}) = \left|\tilde{\gamma}(\vec{\upsilon})\right| e^{j\phi} = \vec{\upsilon}^H \Pi \vec{\upsilon}, \quad \vec{\upsilon}^H \vec{\upsilon} = 1 \tag{2}$$

In which $\Pi = T^{-1/2} \Omega T^{-1/2}$, the modified normalized coherence matrix, $\vec{\upsilon} = \sqrt{T}\vec{\omega} \big/ \vec{\omega}^H \sqrt{T}\vec{\omega}$ denotes the normalized polarization vector.

2.2. Varying extinction RVoG model (VE-RVoG)

According to the RVoG model [8], the CPI coherence of the scattering mechanism can be written as.

$$\tilde{\gamma}(\vec{\omega}) = e^{j\phi_0}\left(\tilde{\gamma}_{0v} + \frac{\mu(\vec{\omega})}{1+\mu(\vec{\omega})}\left(1-\tilde{\gamma}_{0v}\right)\right) \tag{3}$$

where ϕ_0 denotes the ground phase, $\mu(\vec{\omega})$ is the ground-to-volume scattering ratio, and $\tilde{\gamma}_{0v}$ is the CPI coherence of the canopy layer.

In the RVoG model [8], the extinction of microwave at the tree top layer is set equal to zero, and then, it is supposed to increase with depth in the forest medium from a given offset value. Therefore, the extinction coefficient σ varies linearly in the vertical direction with a factor α.

$$\sigma(z) = \alpha z, \qquad \textit{with } \alpha > 0 \tag{4}$$

The volume-only coherence associated with a varying extinction can be determined as [8]:

$$\tilde{\gamma}_{0v} = e^{-\frac{\cos\theta k_z^2}{8\alpha}+jk_z h_v} \frac{erf\left(\frac{j\cos\theta k_z+4\alpha h_v}{2\sqrt{2\alpha\cos\theta}}\right)-erf\left(\frac{jk_z}{2}\sqrt{\frac{\cos\theta}{2\alpha}}\right)}{erf\left(\sqrt{\frac{2\alpha}{\cos\theta}}h_v\right)} \tag{5}$$

where $erf\left(\bullet\right)$ denoted Gaussian error function. k_z and σ are the vertical wavenumber and mean extinction coefficient, respectively. The angle θ is the incidence angle of the SAR system. The forest height is estimated by comparing the $\tilde{\gamma}_{0v}$ with $\tilde{\gamma}_{HV}$.

3. FOREST HEIGHT INVERSION BASED ON MEAN OF COHERENCE SET

3.1. Ground phase and coherence line estimation

In this paper, the ground topography phase is retrieved by using the mean of the mean coherence set [9]. In the general case, using equal projection vectors, the single scattering mechanism coherence set.

$$\Gamma_{SSM} = \left\{\vec{\upsilon}^H \Pi \vec{\vartheta} : \vec{\upsilon} \in \mathbb{C}, \vec{\upsilon}^H \vec{\upsilon} = 1\right\} \tag{6}$$

Under the numerical range theory, the numerical range of Π square matrix in Eq. (2) can be considered as a coherence set region [7, 9]. Since, the coherence region shape of PolInSAR data is defined as a hull convex of the points in a complex plane, which corresponds to the eigenvalues of Π matrix. We demonstrate that the Π matrix has three complex eigenvalues λ_1, λ_2 and λ_3. By establishing a line through two points λ_1 and λ_3 on the complex plane, and then we can completely determine the ground phase as Eq.(7).

$$\phi_0 = \arg\left\{\lambda_1 - \lambda_3\left(1-\mathrm{K}\right)\right\} \tag{7}$$

The factor K can be determined as follow.

$$A_0\mathrm{K}^2 + A_1\mathrm{K} + A_2 = 0 \rightarrow \mathrm{K} = \frac{-A_1 - \sqrt{A_1^2 - 4A_0A_2}}{2A_0} \tag{8}$$

Where: $A_0 = \left|\lambda_3\right|^2 - 1; A_1 = 2\,\mathrm{Re}\left\{\left(\lambda_1 - \lambda_3\right)\lambda_3^*\right\}; A_2 = \left|\lambda_1 - \lambda_3\right|^2$ (9)

The topographic phase detected by the polarization state optimization method has overcome the disadvantages in determining the phase of the previous three-stage inversion algorithm. In [7], Tayebe used the line fit method to determine the surface phase. Although simple and easy to implement, the line fit method results in inaccurate surface phase estimation. In addition, this method often uses many polarized channels to draw assumed lines on the complex plane for the process of determining surface phases. Therefore, the time to determine the soil phase of this method is very large. In contrast, the proposed method uses only two polarizing channels to draw a line through the complex unit circle (CUC) at two points and determine the terrain phase according to conditions (7). Thus, the surface phase estimated by the proposed method has not only improved the accuracy but also reduced the calculation time.

In order to increase the accurate forest height inversion, the combination of adaptive and least square methods is proposed to determine the coherence line in the complex plane. First, the straight line passing through $e^{j\phi_0}$ is constructed, where $\beta\left(\beta\in[0\div\pi]\right)$ is the angle between the vertical axis and the straight line. Then, three eigenvalues of the Π matrix, and $\tilde{\gamma}_{HV}$ are used to fit the coherence line in the CUC by varying β for its entire range. The best fit of the coherence line is determined under optimization criteria as (10).

$$\min_{0\le\beta\le\pi}\left\|\sum_{i=1}^{4}\frac{1}{1+\tan^2\beta}\left(\mathrm{Im}\left(\tilde{\gamma}_i\right)-C-\mathrm{Real}\left(\tilde{\gamma}_i\right).\tan\beta\right)\right\| \tag{10}$$

The coherence line intersects the CUC at the second point, which is defined as $e^{j\phi_1}$. The phase will use to estimate the forest height more accurately.

3.2. Volume-only coherence optimization

In practically, the HV channel not only is affected by ground scattering components but also is a mixture of other scattering mechanisms, such as scattering from tree trunks or double bounce scattering mechanisms. That means the HV phase center is not the upper phase center between all observed coherence. In order, to avoid the disadvantage in previous methods of 3-stage inversion [6, 7], we propose an optimization procedure to find the upper phase center more accurately as well as reduce the time implementation. There, the comprehensive search method by mean coherence set is applied to find the best volume coherence phase. In this paper, we will search all coherence phases by finding possible complex unitary vector $\vec{\omega}$. As a result, we introduce a free phase parameter into a modified normalized matrix Π [9].

$$\Gamma=\frac{\Pi e^{j\phi}+\Pi^{*T}e^{-j\phi}}{2} \tag{11}$$

For each value $\phi\ \left\{\phi\in[-\pi\div\pi]\right\}$, we perform analysis on eigenvalues and eigenvectors for the matrix $\Gamma\left(\phi_k\right)$. Then, we found an eigenvector $\nu_{\max}^{k}$, which corresponds to the maximum eigenvalue $\left|\lambda_{\max}^{k}\right|$ of matrix $\Gamma\left(\phi_k\right)$. The complex unitary vector can be extracted as.

$$\vec{\omega}^k=T^{1/2}\nu_{\max}^{k} \tag{12}$$

By replacing the $\vec{\omega}^k$ into Eq. (1), we can achieve the general expression for the complex interferometry coherence coefficient for each polarized channel.

$$\tilde{\gamma}\left(\vec{\omega}^k\right)=\frac{\left(\vec{\omega}^k\right)^{*T}\cdot\Omega\cdot\vec{\omega}^k}{\left(\vec{\omega}^k\right)^{*T}\cdot T\cdot\vec{\omega}^k} \tag{13}$$

And then, we can consider the argument of the complex coherence coefficient $\tilde{\gamma}\left(\vec{\omega}^k\right)$ as a function of the free phase ϕ. Since we obtained a coherence phase set of all polarization channels.

$$\phi^{k}{}_{pol}=\arg\left(\tilde{\gamma}\left(\vec{\omega}^k\right)\right)=\arg\left(\left(\vec{\omega}^k\right)^{*T}\cdot\Omega\cdot\vec{\omega}^k\right) \tag{14}$$

After that, we search all the complex coherence coefficients on the ambiguous segment of the coherence line, which satisfy the following condition.

$$\phi_2 = \max\left(\arg\left(\tilde{\gamma}_{HV}\right), \arg\left(\lambda_3\right)\right) \le \phi_{pol} \le \phi_1 \tag{15}$$

where λ_3 is the eigenvalue of Π matrix and ϕ_1 is the phase corresponding to $e^{j\phi_1}$ which is defined as above. Then the optimal phase center ϕ_{opt} is selected by maximizing $\left|\phi_{pol} - \phi_2\right|$. Therefore, ϕ_{opt} is the upper observed phase, which is generated from a complex unitary vector. Finally, the volume-only coherence $\tilde{\gamma}_{opt}$ can be extracted from equation (10) with the optimal complex unitary vector $\vec{\omega}_{opt}$. The order of steps of the proposed method is presented by the algorithm flowchart in Fig. 1.

The optimal volume coherence factor is determined based on the optimal loop method to improve the forest height estimation efficiency of the approached method. The way to find the optimal volume coefficients of the proposed method has been avoided assumption of the Tayebe method and also improved the efficiency of the estimated vegetation parameters. The effectiveness of the proposed method will be verified with simulation data in the next section.

4. EXPERIMENTAL RESULTS AND ANALYSIS

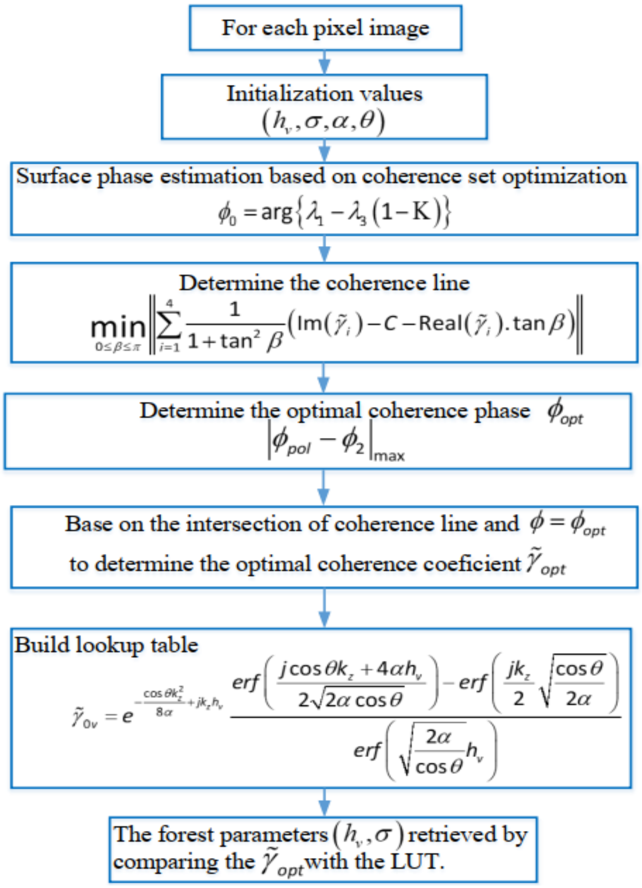


Figure 1. *Flowchart of the proposed algorithm.*

In this section, we use two different PolInSAR data types to demonstrate the effectiveness of the proposed method. The proposed method is first applied to simulated PolInSAR data, which is generated from PolSARProSim simulation software [10], to evaluate the effectiveness, stability, and reliability of its results. After that, based on the obtained results with simulated data, it is completely reliable to apply the proposed method to real data. Finally, we can make valid statements for the performance of the proposed methods from obtained results.

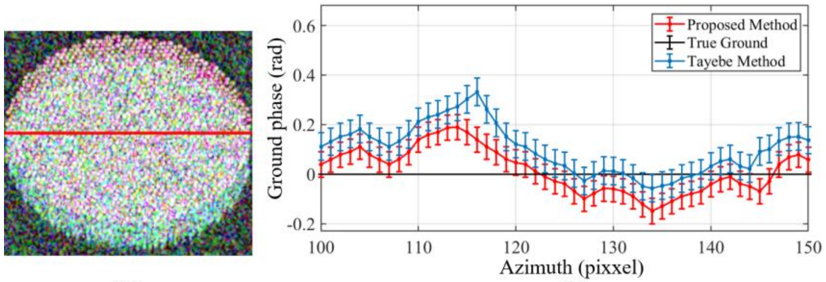
4.1. Simulated PolInSAR data

In this paper, simulated data of tested forest scenes is created from PolSARProSim 5.2 software [10]. The parameters of the simulated forest area are detailed and represented in table 1. To demonstrate the effectiveness of the proposed method, we will compare the proposed method with the Tayebe method [7] with different simulated forest scenarios. These forest regions will be changed in terms of the wavenumber coefficient. Through experimental results, it is possible to assess the reliability and stability of the proposed method.

Table 1. *Forest parameters of the simulation scenario.*

Altitude	**Vertical baseline**	**Central frequency**	**Horizontal baseline**
5000m	1.5 m	1.3 GHz	20m
Incidence angle	**Density**	**Tree species**	**Tree height**
30^0	800 stem/Ha	Hedge	18 m

Figure 2(a) shows a coding color Pauli image of the surveyed forest area that includes (179× 239) pixels. Fig. 2(b) depicts the estimated topography phase of two methods along 50pixels of the transection line in Fig. 2(a). From this figure, we can be seen that the estimated topography phase of the proposed method changes in the range [-0.15÷0.2] rad, and the average ground phase approximates 0.018 rad. Meanwhile, the estimated ground phase by total line fit square method fluctuates in the relatively wide range [-0.1÷0.35] rad and the average topography phase is about 0.063 rad. In this paper, 8 complex coherences are used to estimate the ground phase by using least square line fit, whereas the proposed method only calculates the eigenvalue of (3×3) matrix compared with the true ground phase (approximate 0.009 rad), the proposed approach provides the results more accurate and computation cost lower than the line fit method.



(a) (b)

Figure 2. *(a) Pauli photo of the observed area,*
(b) The estimated ground phases of two manners.

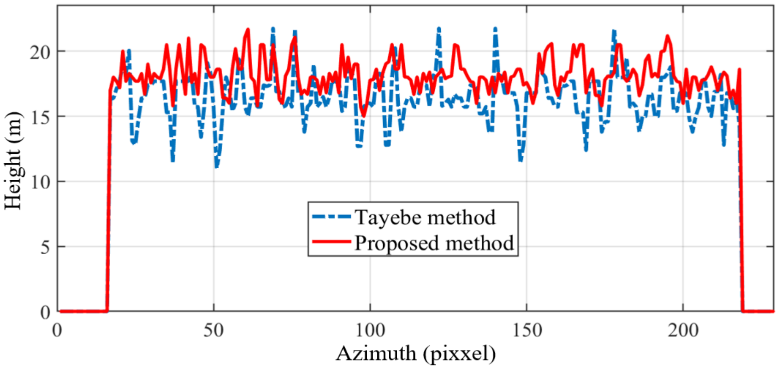


Figure 3. *Graph comparing forest height estimated by two methods.*

Figure 3 is a graph which is comparing forest height extraction of the proposed method with Tayebe method along the transection line in Fig. 1(a). In figure 3, the average value of the forest height estimated by the suggested method is approximately 17.5 m and usually ranges from 16 m to 19.5 m. Whereas, the average forest height predicted by Tayebe method is approximately 16.6 m and it varies widely between 12 m and 19 m.

Table 2. *Evaluated forest index from two processes.*

Parameters	**Factual values**	**Tayebe method [7]**	**Proposed method**
h_v [m]	18	16.556	17.449
ϕ_0 [rad]	0.009	0.063	0.018
σ [dB/m]	0.198	0.305	0.239
RMSE [m]	0	2.267	1.637
Accuracy [%]	100	91.38	96.93

On the other hand, table 2 shows the results of comparing the retrieved forest parameters by two methods. The survey forest area has an actual height of about 18 m and the forest height estimated by Tayebe method and the proposed method have average values of 16.556 m and 17.449 m, respectively. Thus, the precision of the forest height assessed by the proposed method is higher than Tayebe approach about 5.57%. Fig. 3 and table 2 show that the forest parameters estimated by the proposed method are more precise and reliable than using the Tayebe method.

4.2. Spaceborne PolInSAR data

In this section, we perform applying both methods to spaceborne PolInSAR data, which is acquired from the SIRC system. The data set used in this paper was taken from an image pair of the forest area at KUDARA, LAKE BAIKAL, RUSSIA. Fig. 4 depicts the Google image for the whole observation area, in which the test area is shown by the red rectangle. Figure 4b is the composite image of the evaluation patch on Pauli basis.

The surveyed region includes some objects such as forest areas, roads, and agricultural areas (violet area). One of the causes induces the error in forest height estimating that is the presence of temporal decorrelation in the PolInSAR data [4]. However, the magnitude of the interference correlation coefficient of the PolInSAR data is almost greater than 0.7 and the forest tree does not much change in a month. Based on the analysis of Papathanassious [4], we can ignore the effect of the temporal decorrelation when estimating forest height. After co-registering PolInSAR images, we selected a survey area with (500 x 500) pixels.

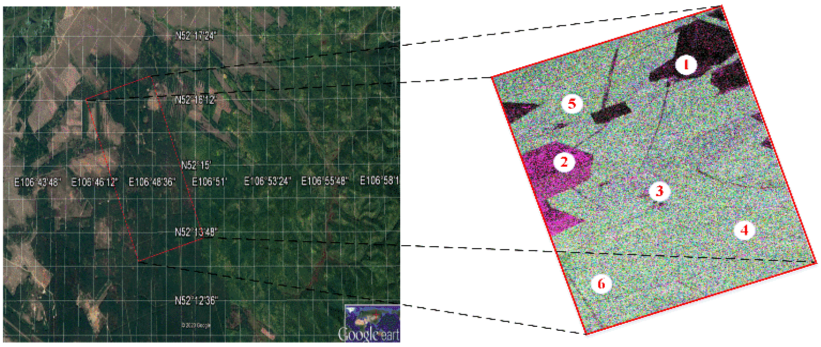
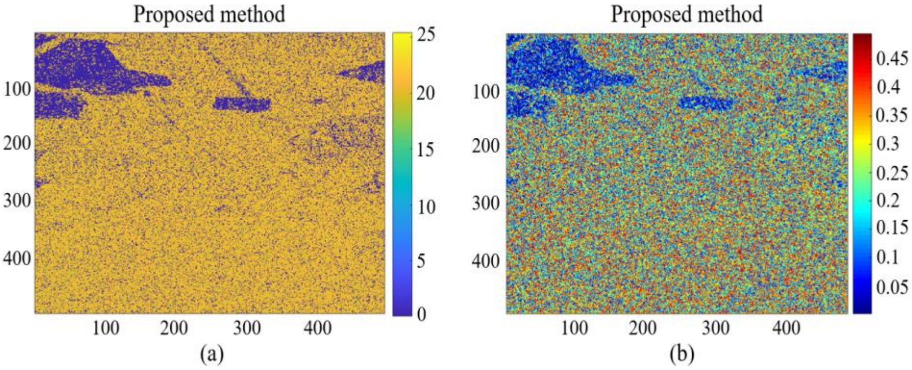


Figure 4. *(a) The optical image of the test site from Google Earth; (b) RGB Pauli image.*

For a general view of the effectiveness of the two methods, some forest parameters calculated from the two approaches are shown in table 3. In this table, the proposed approach gives the estimated height is 20.315 m. Concurrently, the height estimated by the Tayebe method is 19.286 m. In addition, the land phase and the extinction coefficients were extracted by the proposed method, and they both showed high accuracy and were close to the real value of the system compared to the parameters of the Tayebe manner. It can be seen that the proposed method has greatly enhanced the accuracy of forest parameter estimation based on the PolInSAR image.

Table 3. *The estimated forest parameters of the two methods.*

Parameters	h_v [m]	ϕ_0 [rad]	σ [dB/m]	RMSE [m]
Tayebe method	19.286	0.204	0.447	2.267
Proposed method	20.315	0.146	0.318	1.172



(a) (b)

Figure 5. *(a) Image depicting forest height extraction,*

(b) Image depicting the mean extinction.

Fig. 5 depicts the forest height and mean extinction extraction by using the proposed method. This figure also shows that the wave penetration coefficient across the observed forest area is very similar and proportional to the estimated forest height. This result accounts for the scattering process of wave radar in the natural forest. The forest height estimated by the method proposed in figure 5 (a) is concentrated at the altitude of 20 m, in agricultural lands and road areas for heights from 0 m to 5 m. In figure 5 (b), the wave penetration coefficient at the polar of two regions is very small, in the range (0-0.15) dB/m. The average value of forest height and the wave penetration coefficient of the proposed method are approximately 20 m. These values are relatively accurate and completely consistent with the actual value of the observation area.

Table 4. *Forest parameters extracted by two methods over six stands.*

Parameters	**Name of method**	**Patches**					
		I	**II**	**III**	**IV**	**V**	**VI**
h_v [m]	Proposed	3.824	0.253	17.952	20.594	20.651	19.052
	Tayebe	3.251	0.186	16.541	19.194	19.386	17.793
ϕ_0 [rad]	Proposed	0.078	0.047	0.146	0.152	0.125	0.137
	Tayebe	0.092	0.069	0.231	0.224	0.198	0.216
σ [dB/m]	Proposed	0.027	0.014	0.152	0.213	0.276	0.198
	Tayebe	0.032	0.019	0.172	0.264	0.317	0.232
RMSE [m]	Proposed	0.972	0.185	1.591	1.953	1.773	1.612
	Tayebe	1.392	0.457	2.582	2.846	2.715	2.497

Table 4 demonstrates the obvious differences in the estimated forest parameters across each region. In particular, area I is an agricultural area, and area II is bare land, so these areas give very low forest height. Areas III and VI are in uneven tree areas, so the average value of tree height in these areas is slightly lower 20 m than the average height of surveyed forest area. Areas IV and V are located in the tree areas with high and uniform density so the average height in these two areas is greater than 20.5 m. Other parameters also show the suitability of the calculation of the two methods. However, the forest parameters estimated by the proposed method give reliable results and are closer to the value of the surveyed forest than Tayebe's method.

5. CONCLUSIONS

A new method to retrieve the forest parameters by mean coherence set over forest area, which has heterogeneous vertical forest structure. In the proposed method, the terrain ground phase is extracted by combining the numerical range theory and adaptive method, while the comprehensive search method is used to extract the forest parameters. Additionally, the vertical varying extinction coefficient is used to determine the volume-only coherence, which makes the proposed method more appropriate for estimating forest parameters in larger forest areas. The proposed method achieved higher performance than the previous methods when using both simulated data and space-borne data. Experimental results are shown that the proposed method not only enhances the reliability and stability of forest parameter inversion but also truly reflects the scattering process of radar waves in a natural forest environment.

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TÓM TẮT

Một thuật toán tối ưu vùng tương can giao thoa mới cho chuyển đổi độ cao rừng từ ảnh ra đa tổng hợp mặt mở giao thoa phân cực một đường cơ sở

Chiều cao rừng là một trong những tham số quan trọng phục vụ công tác kiểm tra, quản lý độ che phủ của rừng và cũng là một trong những chỉ tiêu đánh giá mối quan hệ sinh trưởng của sinh vật trong hệ sinh thái rừng. Bài viết này đề xuất một phương pháp tối ưu vùng tương can giao thoa mới để tăng độ chính xác trong việc tính toán chiều cao rừng sử dụng dữ liệu PolInSAR băng tần L. Đầu tiên, pha địa hình và đường thẳng kết hợp được xác định dựa trên tập hợp kết hợp trung bình. Sau đó, phương pháp đề xuất xác định hệ số tương can giao thoa của tán cây bằng cách bổ sung thêm các điều kiện mới. Cuối cùng, chiều cao rừng và hệ số suy hao sóng được trích xuất bằng cách so sánh hệ số kết hợp khối tối ưu với các giá trị trong bảng tra cứu. Hiệu quả của phương pháp đề xuất được đánh giá với dữ liệu mô phỏng và dữ liệu thực nghiệm. Kết quả thực nghiệm cho thấy phương pháp đề xuất đã cải thiện độ chính xác ước lượng chiều cao rừng hơn 0.9 m so với thuật toán trích xuất độ cao rừng của Tayebe.

Từ khoá: Ra-đa tổng hợp mặt mở giao thoa phân cực; Chiều cao rừng; Pha bề mặt.