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Optimal Polarization Channel Method for Estimating Forest Height From PolInSAR Images

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Abstract— **This paper proposes a method of optimizing polarization channels to improve accuracy in forest parameter retrieval using PolInSAR images. The forest parameters extracted by the proposed method are implemented through three stages. The topographic phase and the range of mean extinction coefficients can be determined in the first two stages by searching optimal polarization channels. The forest height is retrieved in the final stage based on the determination of a complex coherence coefficient for direct scattering component from canopy layer. The effectiveness of the proposed method was assessed with simulation data from PolSARprosim 5.2 software. Experimental results show that the proposed method has improved the accuracy of the estimated forest height compared to the Tayebe's Method by roughly 6.85%.**

Keywords-PolInSAR, forest height estimation, 3-stage, optimal polarization chanel, ground phase estimation.

I. INTRODUCTION

Forests are always considered as a valuable resource of every country, it not only stores a large amount of woods but also plays an important role in preventing natural phenomena such as natural disasters, floods, landslides [1]. In recent years, many countries have prioritized the development and application of remote sensing radar technology in monitoring and managing forest ecosystems. PolInSAR is one of the remote sensing radar systems, which not only has the ability to identify scattering mechanisms in the natural environment based on different polarization signals but also has the ability to determine the vertical structure of the forest through polarized interferential coefficient [2, 3]. Consequently, PolInSAR has always been considered one of the outstanding inventions of mankind in the field of remote sensing in forest resource management.

Over the past two decades, many methods have been developed for estimating forest parameters using PolInSAR images. Most of them were developed based on two main research directions: (1) based on the PolInSAR decomposition technique, and (2) based on 2-layer scattering model. Among the former mentioned techniques, there are some typical works such as Berman [4], Nghia P. M [5]. The efficiency of these methods depends greatly on whether or not the parameters of the matrix interferometric polarimetric are used up. Another prioritized direction is to develop forest height inversion methods based on the two-layer RVoG model [6]. This model describes the scattering process of ultra-high frequency waves in a natural environment like a volume of random oriented scattering objects placed on flat ground. Based on this model, the three-stage inversion method was first proposed by Cloude in 2003 [7]. This method is widely used for estimating forest height over a long period due to its simplicity of implementation as well as its processing time. However, the effectiveness of this method in some case is not high due to the incorrect selection of the extinction coefficient. To overcome these shortcomings, Tayebe suggested an improved 3-stage inversion algorithm for estimating forest height using PolInSAR data (Tayebe's method) [8]. Tayebe's method focuses primarily on improving the determination of the mean extinction coefficient. Based on the relationship between frequency and the penetration's depth of radar signals in the natural environment, Tayebe has built a possible range of effective extinction coefficient. This method has greatly enhanced the efficiency of estimating forest height compared to the classical 3-stage method. Although there have been certain efficient, this method still has many problems such as: (1) the terrain phase has low reliability because it still uses the line fit method through several complex interference factors of polarized channels; (2) Tayebe still use HV polarization channel as a pure ideal polarization channel for scattering from the canopy. However, in practice, it is difficult to find a polarizing channel without the contribution of the scattering component from the ground. As a result, the reliability of the Tabeye method sometimes becomes irrelevant and unreliable especially in complex forested areas.

From the above analysis, this paper proposes a method of optimizing polarization channels to improve the efficiency of estimating forest parameters using PolInSAR images. First, we propose a method of optimizing the polarization channel to increase the accuracy and reliability of the topographic phase estimation without increasing the complexity in the calculation. Then, a useful range of wave absorption coefficients based on Taybe's geometric structure is applied. Finally, a global optimization method is proposed to find the complex coherence coefficient in which it has the least contribution of other scattering components, and from which we can restore the forest height. The method has improved the efficiency of estimating forest parameters compared to previous methods in the following main points: (1) Improve the accuracy of surface phase , (2) minimize calculation time as well as improve the accuracy of forest height estimation, (3) there is no need to assume that a polarization channel with $m\left(\vec{\omega}\right)=0$ exists.

II. RANDOM VOLUME OVER GROUND MODEL (RVOG) AND TAYBE'S METHOD

A. *Random Volume over Ground Model*

The RVoG model is a basic forest model proposed by Trehauft in 2000 [6]. This model assumes that the vertical structure of the forest is composed of two separate layers, the canopy layer and the ground layer. In which the canopy layer is modelled as a homogeneous random scattering volume with a fixed mean extinction coefficient. Then, decorrelation coefficient of RVoG model can be presented as:

$$\tilde{\gamma}^{RVoG}=e^{j\phi_0}\frac{\tilde{\gamma}_v(h_v\sigma)+m\left(\vec{\omega}\right)}{1+m\left(\vec{\omega}\right)} \tag{1}$$

With ϕ_0 denotes the terrain phase and $m\left(\vec{\omega}\right)$ is the value of the power ratio of the surface scattering component to the scattering component from the canopy. k_z is the vertical wavenumber and $\tilde{\gamma}_v\left(h_v,\sigma\right)$ is complex interference coherence coefficients of scattering components directly from the canopy that can be expressed as below:

$$\tilde{\gamma}_v\left(h_v,\sigma\right)=\frac{2\sigma}{2\sigma+jk_z\cos\theta}\cdot\frac{\exp\left(\dfrac{2\sigma h_v}{\cos\theta}+jk_zh_v\right)-1}{\exp\left(\dfrac{2\sigma h_v}{\cos\theta}-1\right)} \tag{2}$$

B. *Tayebe's Method [8]*

Tayebe found that the radar absorption coefficient in the natural environment is a function that depends on many factors such as signal frequency, tree density, tree height, tree type, etc. Therfore, this factor greatly affects the accuracy of forest parameter extraction. Based on the principle of scattering electromagnetic waves in a natural environment, the wave extinction coefficient is inversely proportional to the depth of wave penetration vertically. According to this, Tayebe conducted experiments on several tree species and gave an effective range of values for the mean extinction coefficient. In Tayebe's method, the surface phase is determined similarly to the classical 3-state algorithm in the first two stages. In the final stage, the HV polar channel is used for forest height retrieval based on the assumption that no contribution of any scattering component in the HV channel. In this section, we only mention the highlights of Tayebe's method, which is the determination of the effective mean extinction coefficient range. Based on the relative position of the HV coherence coefficient on the coherence line in the complex plane, Tayebe suggested a new geometric structure index to determine the mean extinction coefficient, as shown in the first figure 1 that is expressed as:

$$DI=\frac{AL}{VL} \tag{3}$$

Wherein, DI is the index of the distance ratio, AL is the length of the line segment in the ambiguity region and VL is the length of the line segment in the visible area. From Fig. 1, the Tabye's geometric index has two extremely: (1) when $AL=0$ the ultra-high frequency waves only interact at the top of the tree and so the wave extinction coefficient will have the greatest value ($\sigma\approx\sigma_{\max}$). (2) when $VL=0$ the electromagnetic wave penetrates down to the surface and therefore the wave extinction number approximates zero ($\sigma\approx 0$). Based on this geometric structure, Tayebe constructed a table of possible values for the mean extinction coefficient, as shown in TABLE I

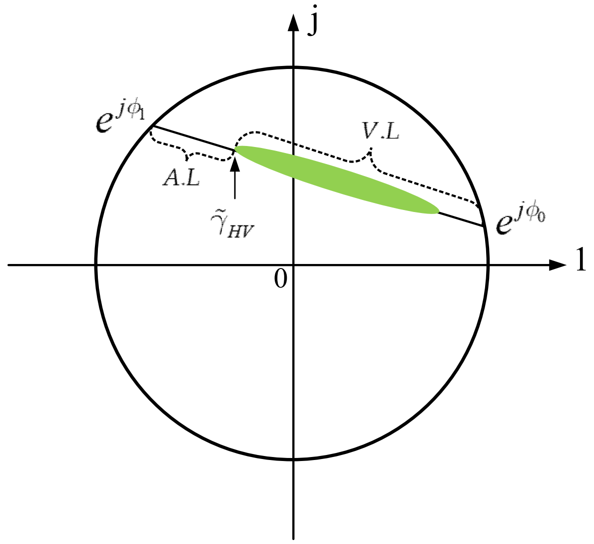


Fig 1. Unit circle on the complex plane of the Tayebe's Method

TABLE I. MEAN EXTINCTION LIMITS BASED ON *DI*

DI	**σ range (dB/m)**
0 ÷ 0.4	0.6 ÷ 1
0.4 ÷ 0.65	0.3 ÷ 0.6
≥ 0.65	0 ÷ 0.3

In the final stage, based on the geometric index in each pixel, Tayebe selected a corresponded range of mean extinction coefficients and built a predicted model for the scattering components from the canopy according to the formula (2). By comparing the forecasted model and interference coherence factor of the HV channel, they can completely extracted the forest height.

III. METHODOLOGY

A. Surface phase estimation based on polarization state optimization

The accuracy and stability in topographic phase estimation play a decisive role in the effectiveness of forest parameter inversion algorithms using remote sensing radar images. There are several methods for estimating this phase, of which TLS is the most commonly used method. The accuracy of the surface phase estimated by the TLS method depends greatly on the number of polarization channels used and often results in a problem in the lack of optimal conditions. In order to improve the accuracy of the topographic phase estimation, we suggested the use optimization method for polarization channel. To accomplish this purpose, we searched for two optimal polarization channels corresponding to surface scattering and volume scattering components based on a comprehensive search of optimal polarization vectors. In PolInSAR systems, the complex interference coherence factor is expressed as follows:

$$\tilde{\gamma}(\vec{\omega}) = \frac{\vec{\omega}_1^H \cdot \Omega_{\text{int}} \cdot \vec{\omega}_2 \cdot}{\sqrt{\left(\vec{\omega}_1^H \cdot T_M \cdot \vec{\omega}_1\right)\left(\vec{\omega}_2^H \cdot T_S \cdot \vec{\omega}_2\right)}} = \frac{\vec{\omega}^H \cdot \Omega_{\text{int}} \cdot \vec{\omega}}{\vec{\omega}^H \cdot T_A \cdot \vec{\omega}} \quad (4)$$

Where Ω_{int} is the cross-correlation matrix of two data acquisition of the PolInSAR system, T_M, T_S respectively are the coherence matrix of the master and slave PolSAR systems and $T_A = \left(T_M + T_S\right)/2$. $\vec{\omega}_1 = \vec{\omega}_2 = \vec{\omega}$ is a complex unitary vector that represents each polarization state of the electromagnetic wave. For the PolInSAR system under backscattering in the reciprocal environment, the complex unitary vector is expressed as follows:

$$\vec{\omega} = \begin{bmatrix} \cos\alpha & \cos\alpha \sin\beta . e^{j\phi_1} & \sin\alpha \sin\beta . e^{j\phi_2} \end{bmatrix}^T \quad (5)$$

Where α, β, ϕ_1 and ϕ_2 are real coefficients and their range of values are defined in Eq. (6).

$$\begin{cases} 0 \le \alpha \le \pi/2; & 0 \le \beta \le \pi/2 \\ 0 \le \phi_1 \le 2\pi; & 0 \le \phi_2 \le 2\pi \end{cases} \quad (6)$$

Based on some equations from (4) to (6), we develop a comprehensive search algorithm to determine complex interference coherence coefficients for surface and only volume scattering mechanism. So, now our algorithm becomes the problem of finding 4 optimal real values under a certain condition. In the proposed method, all complex interferometry coefficients are generated from complex unitary vectors, which is used to search the phase center of canopy and surface layer. By changing four real variables (α, β, ϕ_1 and ϕ_2) in its range, we can determine a set of interferential coherence coefficients according to (4). The unitary polarization vectors representing the scattering components directly from the canopy are determined under following conditions:

$$\arg\left(\tilde{\gamma}\left(\vec{\omega}_k\right)\right) > \arg\left(\tilde{\gamma}_{HV}\right) \quad (7)$$

Based on the theory of electromagnetic scattering, the factors $\tilde{\gamma}\left(\vec{\omega}_k\right)$ that meet the conditions (7) will be considered as interference coherence factors for direct scattering from the canopy and is called $\tilde{\gamma}_2\left(\vec{\omega}_2\right)$. Next, the factors $\tilde{\gamma}\left(\vec{\omega}_l\right)$ that satisfy the condition (8) will be considered as interference coherence factors exclusively for surface scattering, and is called $\tilde{\gamma}_1\left(\vec{\omega}_1\right)$.

$$\arg\left(\tilde{\gamma}_{HH-VV}\right) > \arg\left(\tilde{\gamma}_k\left(\vec{\omega}_l\right)\right) \quad (8)$$

Based on a set of coherence coefficients obtained through two conditions (7) and (8), we can determine an optimal pair of complex interferometry coherence factors ($\tilde{\gamma}_{1\_opt}\left(\vec{\omega}_1\right)$, $\tilde{\gamma}_{2\_opt}\left(\vec{\omega}_2\right)$) for surface and volume scattering components under following condition.

$$\max_{\alpha,\beta,\phi_1,\phi_2} \left\| \arg\left(\tilde{\gamma}_2\left(\vec{\omega}_2\right)\right) - \arg\left(\tilde{\gamma}_1\left(\vec{\omega}_1\right)\right) \right\| \quad (9)$$

In order to increase the accuracy and stability for the estimation of the terrain phase, we find a line that is most suitable on the complex plane based on 3 polar channels $\tilde{\gamma}_{HV}, \tilde{\gamma}_{1\_opt}\left(\vec{\omega}_{1\_opt}\right)$ and $\tilde{\gamma}_{2\_opt}\left(\vec{\omega}_{2\_opt}\right)$. This line will intersect the unit circle in the complex plane at 2 points, and one of these points will be the surface phase. This line will look like this:

$$y = \hat{\mathrm{M}}\, x + \hat{C} \quad (10)$$

Where

$$\hat{\mathrm{M}} = \frac{-a_1 \pm \sqrt{a_1^2 - 4 a_2 a_0}}{2 a_2}; \; \hat{C} = \overline{y} - \hat{\mathrm{M}}\, \overline{x} \quad (11)$$

With

$$\begin{aligned} &\overline{x} = \frac{1}{3}\sum_{i=1}^{3} \mathrm{Re}\left(\tilde{\gamma}_i\right) \quad ; \overline{y} = \frac{1}{3}\sum_{i=1}^{3} \mathrm{Im}\left(\tilde{\gamma}_i\right) \\ &a_0 = \sum_{i=1}^{3}\left(\mathrm{Im}\left(\tilde{\gamma}_i\right) - \overline{y}\right)^2; \; a_2 = \sum_{i=1}^{3}\left(\mathrm{Re}\left(\tilde{\gamma}_i\right) - \overline{x}\right)^2 \\ &a_1 = -2\sum_{i=1}^{3}\left(\mathrm{Im}\left(\tilde{\gamma}_i\right) - \overline{y}\right)\left(\mathrm{Re}\left(\tilde{\gamma}_i\right) - \overline{x}\right) \end{aligned} \quad (12)$$

The surface phase is the intersection of the coherence straight line and the unit circle that is closest to $\tilde{\gamma}_{1\_opt}\left(\vec{\omega}_1\right)$, then the topographic phase values is determined as follows:

$$\phi_0 = \arg\left(x_0 + j\, y_0\right) \qquad (13)$$

In which

$$\begin{cases} x_0 = \dfrac{-\hat{M}\,\hat{C} - \sqrt{\hat{M}^2 - \hat{C}^2 + 1}}{1+\hat{M}^2} \\ y_0 = \hat{M}\,x_0 + \hat{C} \end{cases} \qquad (14)$$

It can be seen that the topographic phase estimated by the polarization state optimization method has overcome the disadvantages in determining the phase of the previous 3-state methods. The proposed method uses only 3 polar channels to draw a line through the unit circle at 2 points and determine the terrain phase while the TLS used at least 8 channels. Thus, the surface phase is estimated based on the optimal polarization state, which not only improved the accuracy and reduced the calculation time but also contributed to improving the efficiency of estimating the remaining forest parameters.

B. Estimating the forest parameters

The previous forest height inversion methods [7, 8], which often assumed that there is always a polarizing channel representing the tree canopy scattering component with little contribution of other scattering components. In fact, each polarizing channel is a combination of many different scattering components and this is one of the main causes of errors in the forest parameter extraction. In this paper, a solution for finding an interference coherence coefficient for the scattering component directly from the tree canopy is proposed to handle the disadvantages of the previous forest height inversion methods. The purpose of the proposed method is to find a polar channel $\tilde{\gamma}_{est}\left(\vec{\omega}\right)$ that has a higher phase than the HV polar channel and has the least contribution of surface scattering. To solve this problem, we assume that $\tilde{\gamma}_{2\_opt}\left(\vec{\omega}_2\right)$ defined in section 3.1, that is the optimal polarization channel for the scattering component directly from the canopy. Then the Eq.1 can be rewritten as follow:

$$\tilde{\gamma}_{est}\left(\vec{\omega}\right) = e^{j\phi_0}\left[\tilde{\gamma}_{2\_opt} + L\left(\vec{\omega}\right)\left(1-\tilde{\gamma}_{2\_opt}\right)\right] \qquad (15)$$

Where $L\left(\vec{\omega}\right)$ is a real coefficient, which ranges from 0 to 1. In order to determine the optimal interferential coherence coefficient $\tilde{\gamma}_{est}\left(\vec{\omega}\right)$, we change $L\left(\vec{\omega}\right)$ from 0 to 1. In order to determine the interference coherence coefficients for the scattering components from the canopy, we only select interference coherence coefficients that have their argument satisfying the conditions (16).

$$\arg\left(\tilde{\gamma}_{2\_opt}\right) > \arg\left(\tilde{\gamma}_{est}\right) > \arg\left(\tilde{\gamma}_{HV}\right) \qquad (16)$$

Based on a set of interference coherence coefficients found in the previous step, it is possible to determine the optimal interference coherence coefficients for the volume scattering component that lie on a straight line in the complex plane. The optimal interferential coherence coefficients are then determined under the following condition:

$$\min_{L\left(\vec{\omega}\right)} \left\| \mathrm{Im}\left(\tilde{\gamma}_{est}\right) - \hat{M}.\mathrm{Re}\left(\tilde{\gamma}_{est}\right) - \hat{C} \right\| \qquad (17)$$

In order to improve the accuracy for estimating forest height, we applied extinction coefficient range of Tayebe in developing a lookup table for the complex interference coherence coefficients of the direct scattering component from the canopy $\tilde{\gamma}_v\left(h_v,\sigma\right)$. The forest height and mean extinction coefficient are determined by comparing the values in the lookup table with $\tilde{\gamma}_{est}^{opt}\left(\vec{\omega}\right)$. The extracted values which are h_v and σ must meet the following condition:

$$\min_{h_v,\sigma_e} \left\| \tilde{\gamma}_{est}^{opt}\left(\vec{\omega}\right) - \tilde{\gamma}\left(h_v,\sigma\right) \right\| \qquad (18)$$

IV. SIMULATION RESULTS AND DISCUSSION

In this section, the proposed method is applied with simulated PolInSAR data [9] to evaluate the effectiveness, stability and reliability of the results of the estimated forest parameters. Based on the effectiveness that has been assessed with simulation data, it is completely reliable to apply the proposed method to the actual data. Simulation forest scenarios and system parameters are described in detail in TABLE II. Figure 2 shows a Pauli's color image of the forested area measuring 223 x 235 pixels.

TABLE II. FOREST PARAMETERS OF THE SIMULATION SCENARIO

Altitude	**Vertical baseline**	**Central frequency**	**Horizontal baseline**
3000m	1.5 m	1.3 GHz	15m
Incidence angle	**Density**	**Tree species**	**Tree height**
40^0	800 Trees/Ha	Deciduous	18 m

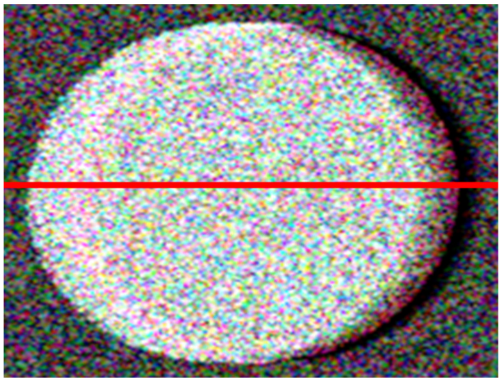
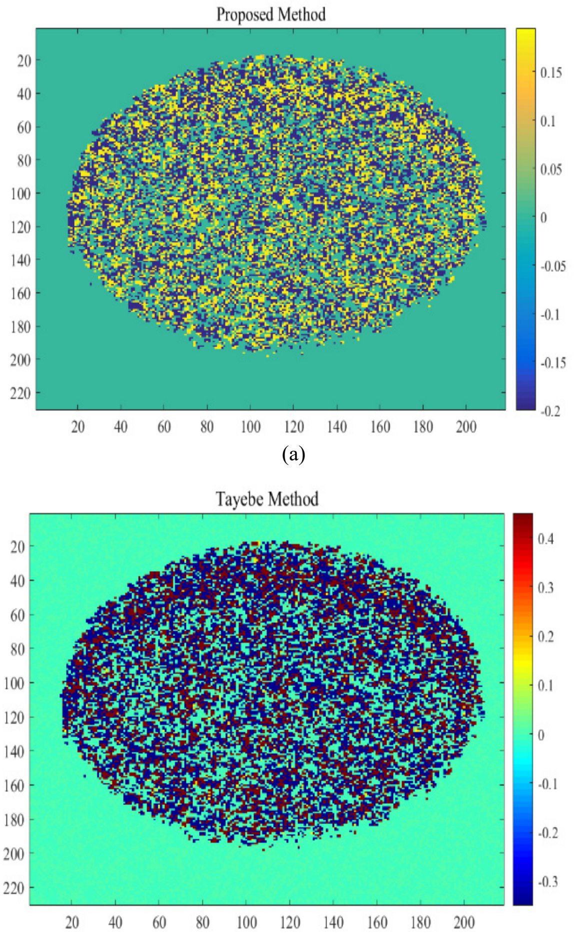


Fig 2. RGB Pauli image of simulated forest scene

Figure 3 (a) describes the topographic phase of the observed forest area estimated by the proposed method as the values of change in the range [-0.2-0.18] rad and the average value of the topographic phase is 0.0936 rad. Whereas the topographic phase of the observed forest area estimated by Tayebe's method is shown in Figure 3 (b), they often fluctuate dramatically in the range of [-0.35 - 0.45] rad and its average value is about 0.1612 rad. Noticeably, the topographic phase estimated by the Tayebe's method has a larger error compared to the standard ground phase of 0.0875 rad. The reason for these errors is that Tayebe still uses the least square line fit method to determine the terrain phase. From the results presented in Figure 3 and TABLE III, it can be seen that the topographic phase determined by the proposed method is more precise than the Tayebe's method.



(a)

(b)

Fig 3. 2D diagram comparing the topographic phase of two methods

Figure 4 describes the forest height estimated by the proposed and the Tayebe's method. In this figure, the average value of the forest height estimated by the proposed method is approximately 17.6m and usually slight fluctuation ranges between (16.5m – 18m), (except for some pixels 68, 127 and 213 are over 20m).

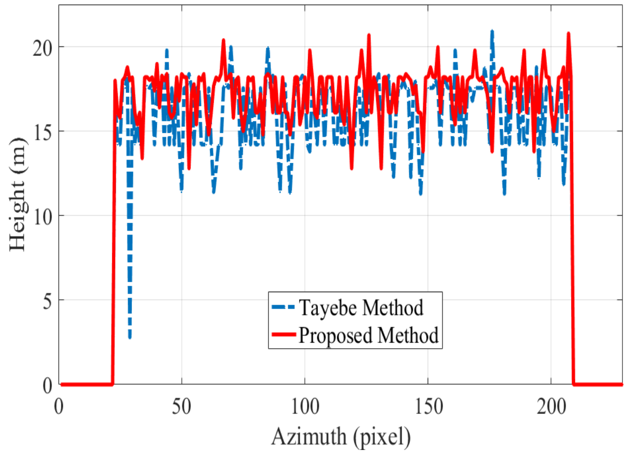


Fig 4. A graph comparing the estimated forest heights of the two methods.

Meanwhile, the average forest height estimated by Tayebe's method is approximately 16.4m and it varies widely between 14m and 17.5m (especially with a pixel lower than 12m). From the results in Figure 4, it can be seen that the forest height determined by the proposed method is more accurate and reliable.

TABLE III. FOREST PARAMETERS ESTIMATED BY TWO METHODS

Parameters	**System's real values**	**Tayebe's method**	**Proposed method**
$h_v\left[m\right]$	18	16.3564	17.5885
$\phi_0\left[rad\right]$	0.0875	0.1612	0.0936
$\sigma\left[dB/m\right]$	0.1729	0.2738	0.2156
RMSE (m)	0	3.1258	1.3662
Accuracy (%)	100	90.868	97.715

TABLE III presents the forest parameters estimated by the proposed method and the Tayebe's method. In particular, the forest height determined by the proposed method has a higher accuracy than the Tayebe's method of 6.85%. At the same time, the root mean square error (RMSE) value of the proposed method is smaller, meaning that the efficiency of the forest height estimated from the proposed method is higher than the Tayebe's method. Besides, the extinction coefficient and ground phase of the proposed method all showed high accuracy and close to the value of the system.

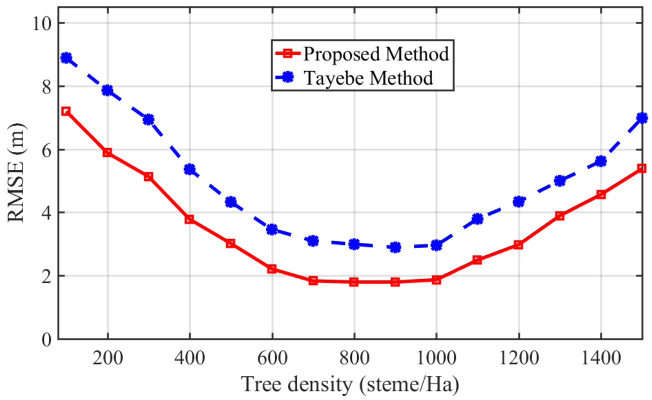


Fig 5. A graph comparing RMSE values of the two methods.

Next, we use PolSARprosim 5.2 software to create simulated forest data with tree densities ranging from 100 (trees/ha) to 1500 (trees/ha). The other parameters of the data are kept as shown in TABLE II. Figure 5 describes RMSE of the forest height estimated by the proposed and the Tayebe's method with different tree densities. It can be seen that the sparse tree density (100-500 trees/ha) or dense tree density (1100-1500 trees/ha) often cause large errors. In contrast, RMSE values reduce and stable within a tree density range from 600 trees/ha to 1000 trees/ha. The smaller the RMSE value, the better the accuracy of the forest height. The results in Figure 5 show that when the tree density of the forest is suitable, the radar waves will both be able to penetrate to the surface and scatter on the canopy. Therefore, the backscattering signals will be ensured and the center phase deviation of the volume scattering and surface scattering components ensure the calculation of forest parameters. From the above analysis, it can be concluded that tree density is a very important parameter and has a direct impact on the efficiency of estimating forest parameters of the methods.

V. CONCLUSSION

The Tayebe's method has somewhat improved the efficiency of estimating forest parameters of the former one. However, the accuracy of the Tayebe's method is not yet truly reliable. In the proposed algorithm, a specific geometric method is applied to determine the wave extinction factor more accurately and reduce calculation time. Moreover, the optimal interference coherence factor with at least the effect of surface scattering components was sought to improve the forest height estimation results of the proposed method. Experimental results show that the forest height estimated by the proposed method has improved by approximately 1.23m compared to the Tayebe's method. At the same time, other estimated parameters of the proposed method also show greater accuracy. In the future, the proposed method will be applied to different types of data and in different actual forest topography to further improve efficiency.

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