Forest height estimation algorithm using polarizatric interference UAV-SAR images

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ABSTRACT

This paper proposes a method to increase the accuracy in estimating forests height using polarimetric interferometry UAV-SAR images. The forest parameters extracted by the proposed method are implemented through three stages. The topographic phase and mean extinction coefficients can be determined in the first two steps through analyzing eigenvalues of the interferometry coherence matrix. The forest height is restored in the final stage based on the determination of a complex interferometry coherence factor for the canopy scattering component. The effectiveness of the proposed method are evaluated with UAV-SAR data from NASA/JPL's AfiSAR project.

Keywords: PolInSAR; UAV-SAR; Complex interferometry coherence; Mean extinction coefficients.

1. INTRODUCTION

Forest height is one of the essential parameters for forest managing, monitoring, and protecting activities. Along with the powerful development of science and technologies, many measures have been applied to improve the efficiency of forest managing, monitoring, and protecting. Nowadays, the PolInSAR system in general and the UAV-SAR system in particular still present outstanding advantages in extracting forest parameters [1-3].

In recent years, along with the robust development of the PolInSAR system, many models and algorithms have been introduced to improve the efficiency of estimating forest parameters using PolInSAR data [4-6]. In this field, Cloude was one of the pioneers in proposing a way to determine forest parameters by the inverse forest method. The three-state inversion algorithm [4] is based on a random volume scattering on the ground (RVoG) model [6]. One of the disadvantages of this approach is that the accuracy of the topographic phase depends predominantly on the number of polarization channels used. Determining ground phase requires a long calculating time, whereas the accuracy is low, especially in forest areas with high trees density. Another drawback of this algorithm is the assumption that is a polarization channel particularly dedicated to the scattering component from the canopy. Therefore, the forest height and mean extinction coefficient obtained by this way is not very accurate and is often considerably lower than the actual forest height.

In 2018, Tayebe posed a solution to optimize the complex polarimetric interferometry coherence coefficient [7] to improve the efficiency of forest parameter estimation of the three-state inversion method. In this technique, Tayebe still uses the method of finding the suitable line to determine the terrain phase. Then, the authors search for the conditional optimal coherence coefficient in the unambiguity region on complex unit circle. Finally, the forest height is extracted by comparing the optimization complex polarimetric interferometry coherence coefficient with the complex polarimetric interferometry coherence coefficient of HV channel. Tayebe approach has somewhat improved the efficiency of forest height estimation of the initial three-state inversion method mentioned [3]. However, this method still assumes that the optimal coherence coefficient only has the volume scattering component with no surface scattering component ($\mu(\omega)=0$) and it still uses the method of finding the line fit to estimate the ground phase. Because of these two disadvantages, the efficiency of Tayebe mode [7] in estimating forest height is not very high and does not accurately reflect the scattering process in the actual forest environment.

Based on the above analysis, this paper proposes a new process to improve the accuracy of forest height estimation. The proposed method is carried out through three steps. Firstly, an eigenvalue analysis algorithm combined with new constraint conditions to determine two optimal complex polarimetric interferometry coherence coefficient which is specific for the volume and surface scattering component. Then, the surface phase is determined based on the intersection point of the line through these two polarizatric channels with the complex unit circle. Finally, a three-dimensional lookup table is built to extract forest parameters based on two optimal polarizatric channels. This method not only improves the quality of the surface phase parameter but also overcomes the incorrect assumptions of the three-state inversion algorithm [3] and Tayebe proposal [7].

2. METHODOLOGY

2.1. Determine the optimal polarizatric channels based on eigenvalue analysis

For the case of backscatter in the reversible environment, the Pauli backscatter vector of each PolSAR system is described as follows:

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

In this equation, $S_{p,q}\left(p,q=\{h,v\}\right)$ are complex scattering coefficients and $i=1,2$ represents two PolSAR systems respectively. The data received from the PolInSAR systems is usually featured by a 6×6 complex coherence matrix, and is represented in (2).

$$[\mathrm{T}_6]=\left\langle \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} [k_1^{*\mathrm{T}} \quad k_2^{*T}] \right\rangle = \begin{bmatrix} [\mathrm{T}_{11}] & [\Omega_{12}] \\ [\Omega^*_{12}] & [\mathrm{T}_{22}] \end{bmatrix} \tag{2}$$

In this equation, $[\mathrm{T}_{11}]$ and $[\mathrm{T}_{22}]$ are Hermitian polarimetric coherence matrices describing the polarizatric properties of the target obtained from each individual PolSAR system, $[\Omega_{12}]$ is a complex matrix containing the information on interference and polarization of the target. The $\langle \bullet \rangle$ operator represents the overall average in data processing and the $(\bullet)^*$ operator represents the conjugation. To determine the complex interferometry coherence coefficients that characterize the direct scattering components from the tree canopy and the ground, a Γ matrix is defined as follows [7].

$$\Gamma = [T]^{-1}[\Omega_H] \quad \begin{cases} \Omega_H = \dfrac{\Omega_{12}.\mathrm{e}^{j\psi}+\Omega^*_{12}.\mathrm{e}^{-j\psi}}{2} \\ T = \dfrac{T_{11}+T_{22}}{2} \end{cases} \tag{3}$$

In which, ψ $\left(\psi \in (0,\pi)\right)$ is a free phase parameter added to the matrix Ω_{12}. This addition does not change the intensity of the scattering components, but shows its effect in determining the interference phase of the scattering components. Next, we take N values of the free phase in the range $(0 \div \pi)$, and get a set of N corresponding Γ matrices. After analyzing eigenvalue and eigenvector for these N Γ matrices, we will get two sets of eigenvectors corresponding to the maximum and minimum eigenvalues. These two sets of eigenvectors are defined as follows:

$$\begin{aligned} W_{\max} &= \{\omega_{1\max} \quad \omega_{2\max} \quad \dots \quad \omega_{N\max}\} \\ W_{\min} &= \{\omega_{1\min} \quad \omega_{2\min} \quad \dots \quad \omega_{N\min}\} \end{aligned} \tag{4}$$

It is obvious that these two sets of eigenvectors correspond to two sets of polarizatric vectors which are respective to the direct scattering component from the tree canopy and the ground. Equation (4) determines the complex interferometry coherence coefficients for these scattering components as follows:

$$\begin{cases} \tilde{\gamma}_{i\max} = \dfrac{\omega_{i\max}^H \Omega_{12} \omega_{i\max}}{\omega_{i\max}^H T \omega_{i\max}} \\ \tilde{\gamma}_{i\min} = \dfrac{\omega_{i\min}^H \Omega_{12} \omega_{i\min}}{\omega_{i\min}^H T \omega_{i\min}} \end{cases} \text{với } i = 1, 2, \dots, N \tag{5}$$

Corresponding to the complex polarimetric interferometry coherence coefficients $(\tilde{\gamma}_{\max}, \tilde{\gamma}_{\min})$, we choose a set of complex polarizatric interferometry coherence coefficients that satisfies the condition (6).

$$\begin{cases} \arg(\tilde{\gamma}_{i\max}) \geq \arg(\tilde{\gamma}_{HV}) \\ \arg(\tilde{\gamma}_{i\min}) \leq \arg(\tilde{\gamma}_{HH-VV}) \end{cases} \tag{6}$$

In which arg(.) is the argument function of the complex number. Then the optimal complex polarizatric interferometry coherence coefficient pair representing the direct scattering component from the tree canopy and the ground is determined based on condition (7).

$$\underset{i=1,\dots L,\, j=1,\dots M}{D} = \left\| \tilde{\gamma}_{i\max} - \tilde{\gamma}_{j\min} \right\| \tag{7}$$

In this equation $\tilde{\gamma}_{vol}$ is the complex polarizatric interferometry coherence coefficient that characterizes the direct scattering component from the tree canopy and $\tilde{\gamma}_{ground}$ is the complex polarizatric interferometry coherence coefficient that characterizes the direct scattering component from the ground.

2.2. Estimate the ground phase

Accuracy and stability in estimating the ground phase play a decisive role in the effectiveness of forest parameter recovery algorithms using remote sensing radar images. In order to improve the accuracy of evaluating terrain phase estimation and reduce the calculating time, we propose to use the method of optimizing the interferometry coherence region.

According to the theory of backscattering of radar waves in the natural environment [8], it can be seen that $\tilde{\gamma}_{vol}$ corresponds to the scattering component from the tree canopy and $\tilde{\gamma}_{ground}$ corresponds to the direct scattering component from the ground. We draw a line passing through two points $(\tilde{\gamma}_{vol}, \tilde{\gamma}_{ground})$ on the complex plane and this line intersects the complex unit circle at two points A and B (figure 1).

Then the ground phase ϕ_0 will be determined according to formula (8).

$$\phi_0 = \arg\{\tilde{\gamma}_{ground} - (1-K)\tilde{\gamma}_{vol}\} \tag{8}$$

In which K is the solution of the quadratic equation:

$$A_0K^2 + A_1K + A_2 = 0$$
$$\Rightarrow K = \frac{-A_1 - \sqrt{A_1^2 - 4A_0A_2}}{2A_0} \tag{9}$$

With $A_0 = |\tilde{\gamma}_{vol}|^2 - 1$, $A_1 = 2\,\mathrm{Re}\{(\tilde{\gamma}_{ground} - \tilde{\gamma}_{vol})\tilde{\gamma}_{vol}\}$, $A_2 = |\tilde{\gamma}_{ground} - \tilde{\gamma}_{vol}|^2$

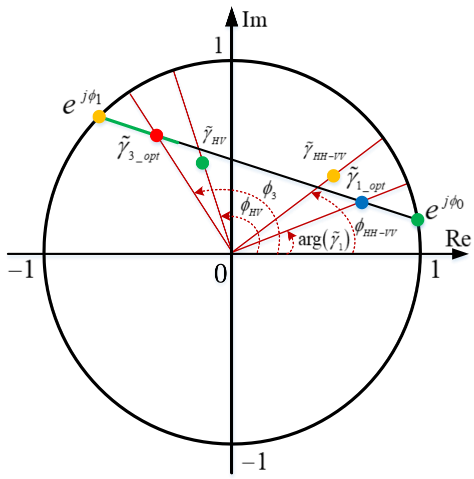

Figure 1. *Present the complex polarizatric interferometry coherence coefficients in the unit circle.*

2.3. Estimate forest height based on the optimal loop

Previous forest height conversion methods [3-7] often assumed that there was always a polarization channel representing the canopy scattering component with the least contribution of the dihedral and ground scattering component. In fact, each polarization channel is a combination of many different scattering constituents [9] and this is one of the main causes of errors in extracting forest parameters in previous methods.

In this paper, a solution to find a complex polarimetric interferometry coherence factor for the direct scattering component from the canopy is proposed to overcome the disadvantages of previous forest height conversion methods. We know that, if we know the complex polarimetric interferometry coherence parameter for the tree canopy scattering component in advance, we can totally estimate an interferometry coherence coefficient for any polarizatric channel as follows [10]:

$$\tilde{\gamma}_{est}(\omega) = e^{j\phi_0}\frac{\tilde{\gamma}_v + m(\omega)}{1+m(\omega)} = e^{j\phi_0}\left[\tilde{\gamma}_v + L(\omega)(1-\tilde{\gamma}_v)\right] \tag{10}$$

In which $m(\omega)$ is the scattering power ratio between the ground scattering and the tree canopy scattering component, and $L(\omega) = m(\omega)/(1+m(\omega))$ is a real factor in the range from 0 to 1. $\tilde{\gamma}_v$ is the complex polarizatric interferometry coherence coefficient for the direct scattering component from tree canopy, and this coefficient is defined as follows [2].

$$\tilde{\gamma}_v(h_v,\sigma) = \frac{2\sigma}{2\sigma + jk_z'\cos(\theta-\alpha)} * \frac{\exp\left(\frac{2\sigma h_v}{\cos(\theta-\alpha)}\cos\alpha + jk_z'h_v\cos\alpha\right) - 1}{\exp\left(\frac{2\sigma h_v\cos\alpha}{\cos(\theta-\alpha)}\right) - 1} \tag{11}$$

In which h_v is the height of the forest, $k'_z = k_z \sin\theta / \sin(\theta - \alpha)$ is the standing wave coefficient on sloping terrain. α and θ are the slope of the terrain and the incident angle of the SAR system, respectively. The purpose of the proposed method is to find a polarizatric channel that most closely reflects the complex polarizatric interferometry coherence coefficient for the scattering element from the canopy, that is, it has the least contribution of the remain scattering component. Next, we construct a three-dimensional lookup table according to the parameters $h_v \in (0, 2\pi / k_z)$, $\sigma \in (0,1)\ dB/m$ and $L(\omega) \in (0,1)$ to achieve the complex polarizatric interferometry coherence factor based on expression (10). Finally, the forest parameters are extracted based on the following condition:

$$\min_{h_v, \sigma, L(\omega)} \left\| \tilde{\gamma}_{vol} - \tilde{\gamma}_{est} \right\| \tag{12}$$

It is clear that the optimal coherence coefficient determined based on the proposed method has improved the efficiency of estimating forest height of the proposed method. The way to find the ideal complex polarimetric interferometry coherence coefficient of the proposed method has overcome the assumption $m(\omega) = 0$ of the previous method and has simultaneously improved the efficiency of the estimated forest parameters. The effectiveness of the proposed method will be verified with UAV-SAR data in the next section.

3. EXPERIMENTAL RESULT

To evaluate the effectiveness of the suggested method, we apply it and the Tayebe one to the data set collected by the open-surface synthetic radar mounted on unmanned aerial vehicles (UAV- SAR) of NASA/JPL under the AfriSAR project. The radar operates in L-band, with the incident angle from 21^o to 65° and baseline from 0 m to 160 m. Accordingly, this dataset provides PolInSAR images to calculate the height of tree canopy in Lope National Park in Gabon. Both datasets were measured on February 25, 2016 by NASA's association with ESA and the Babon Space Agency.

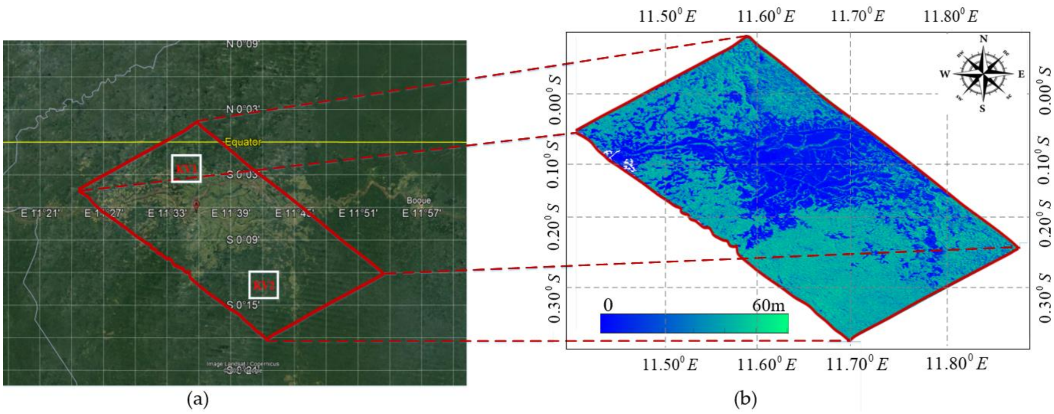

Figure 2. *Image of the researched forest area: (a) Optical image from Google Earth; (b) LiDAR image.*

The researched area is mountainous terrain with different slopes, rich and different types of forest resources and different trees heights. In order to accurately assess the forest height of the study area, the project has published the LiDAR measurement data corresponding to each stand. LiDAR measurement data will be used as a reference to evaluate the accuracy of the proposed method. LiDAR data downloaded from the Distributed Active Archive Center for Biogeochemical Dynamics (ORNL DACC) are respectively shown in figure 2(b).

Figure 2(a) shows an optical image of Lope Park, Gabon from Google Earth. Since the data of the forest area provided by the UAV-SAR system is large (with (8618 x 4922) pixels). Therefore, a small area has been separated for analysing and valuating forest parameters. The survey areas have been placed into optical images from Google earth and signed as KV1 and KV2, each of which is (500 x 500) pixels in size.

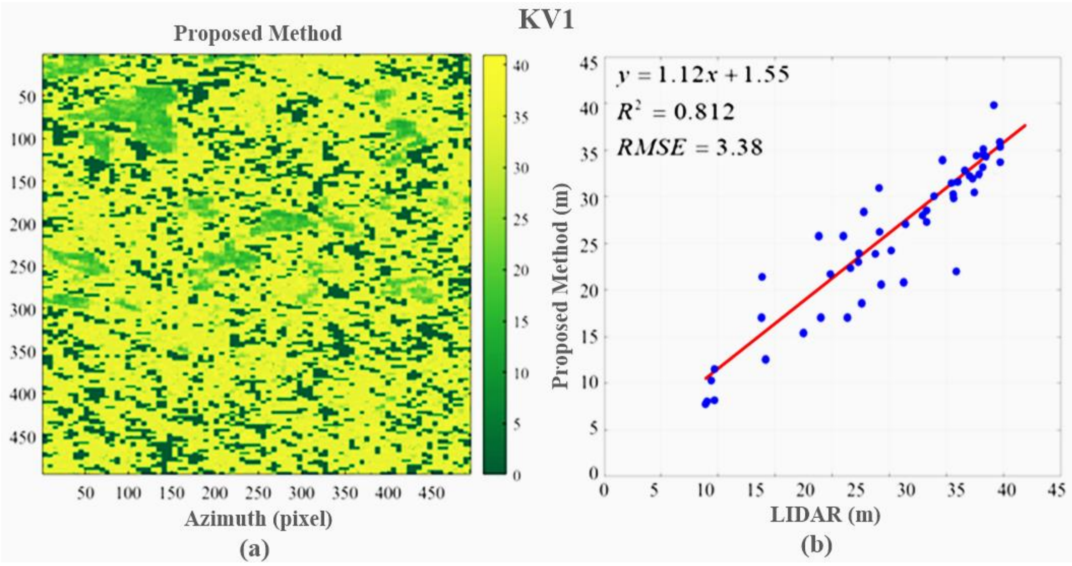

Figure 3. *Area 1: (a) Forest height results estimated by the proposed method, (b) Effectiveness of the proposed method and LiDAR data.*

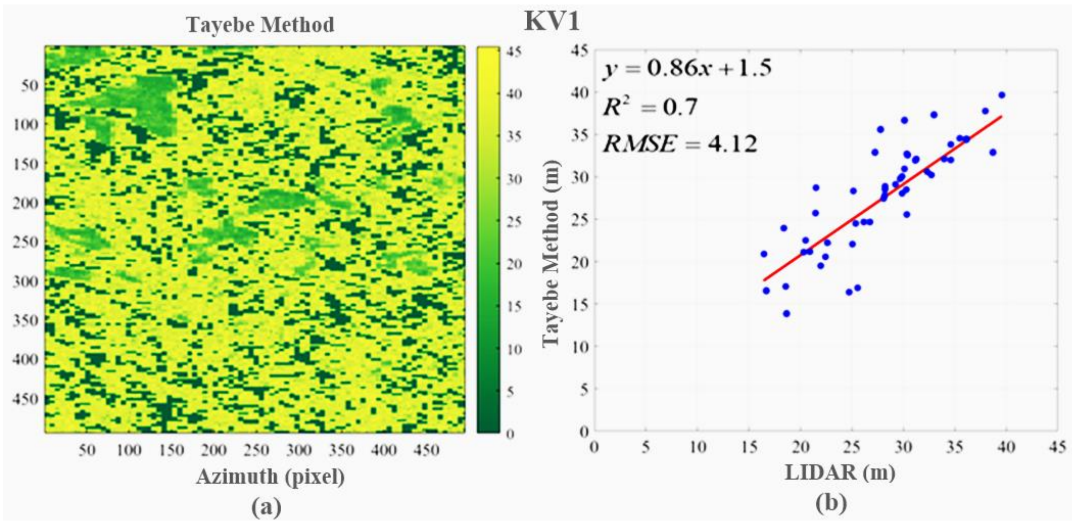

Figure 4. *Area 1: (a) Forest height results estimated by Tayebe method, (b) Efficiency of Tayebe method and LiDAR data.*

The results of forest parameters in the KV1 survey forest area estimated by the proposed method and the Tayebe's (figures 3 (a), 4 (a)) show the similarity between the forest terrain and the actual terrain. However, the forest height estimated by Tayebe method [7] often tends to be higher than the forest height obtained by the intended method. In addition, the results in figure 3(b) and figure 4(b) show a comparison between forest heights extracted from LiDAR data and methods at KV1. In which, the parameter R^2 depicts that the correlation between the forest height extracted from LiDAR data with the recommended method is 0.862 while the Tayebe manner has a lower value ($R^2 = 0,746$). Additionally, the root mean square error of the proposed method is 3.38 (m), which is smaller than 4.12 (m) of Tayebe approach.

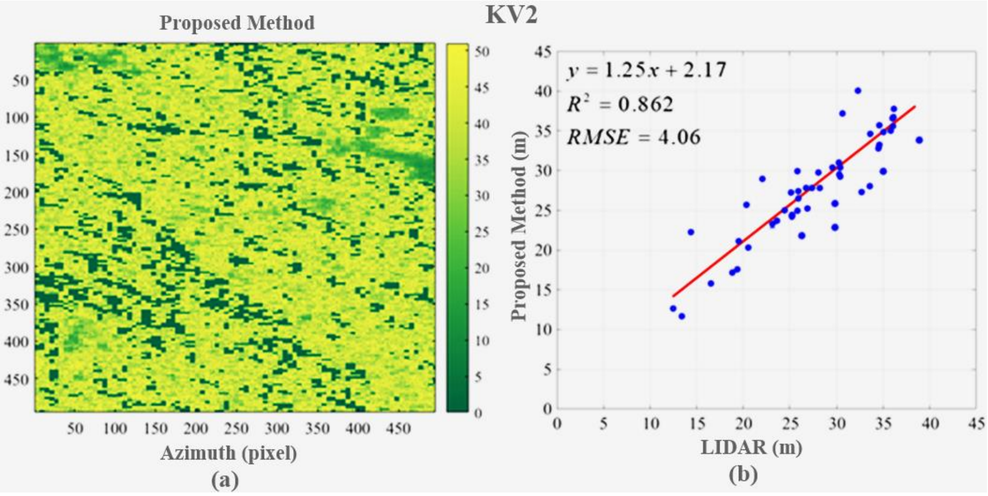

Figure 5. *Area 2: (a) Forest height results estimated by the proposed method; (b) Effectiveness of the proposed method and LiDAR data.*

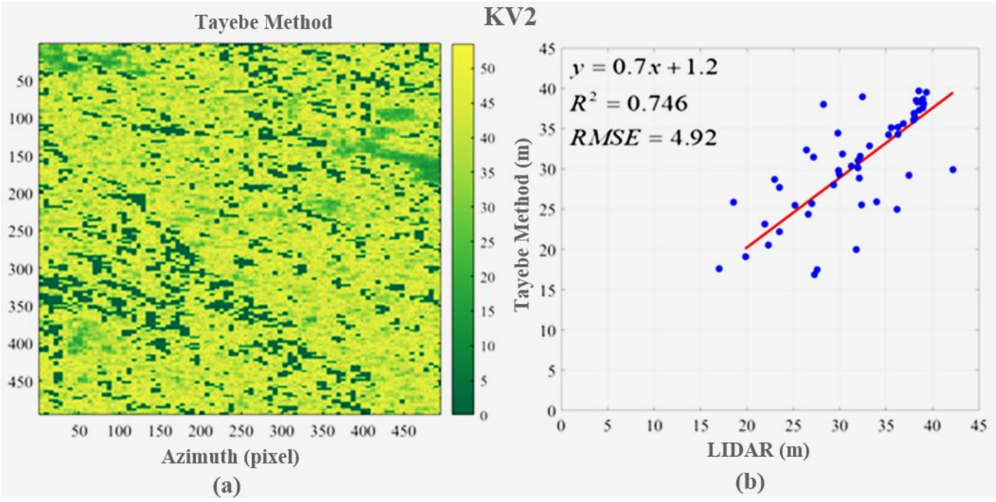

Figure 6. *Area 2: (a) Forest height results estimated by Tayebe method; (b) Efficiency of Tayebe method and LiDAR data.*

Figures 5(a) and 6(a) show the results of forest height estimation in KV2 by the methods. This result points out that KV2 has a denser tree density and higher average height than KV1. The results in figures 5 (b) and 6 (b) show that the offered method (with $R^2 = 0,862$; $RMSE = 4,06$) has a higher accuracy than the Tayebe's (with $R^2 = 0,746$; $RMSE = 4,92$).

Table 1 shows the effectiveness of the methods compared with LiDAR data on the two surveyed forest areas. In which, the average tree height estimated by the proposed solution is 26.2 (m), which is 1.4 (m) lower than value from LiDAR data. The Tayebe method has an estimated height of 29.3 (m) which is 1.7 (m) higher than the value from LiDAR data and this result shows a threshold error. There is threshold error because the Tayebe approach assumes that the studied forest area is a relatively flat terrain $\mu(\vec{\omega}) = 0$, so the estimated forest height results of this method often trigger large errors on steep terrain.

Table 1. *Effectiveness of methods compared with LiDAR data.*

The surveyed forest area	Forest parameters	LiDAR data (m)	Tayebe method	Proposed method
KV1	$\bar{h}_v(m)$	27.6	29.3	26.2
	α	-	-	10.6^o
	$\sigma(dB/m)$	-	0.17	0.15
KV2	$\bar{h}_v(m)$	31.2	33.8	29.1
	α	-	-	16.2^o
	$\sigma(dB/m)$	-	0.26	0.21

In the KV2 study area, the average forest height from LiDAR data is 31.2 (m), the introduced method is 29.1 (m) and the Tayebe method is 33.8 (m). Moreover, the average terrain slopes of KV1 and KV2 extracted by the proposed method are 10.6^0 and 16.2^0. From the above results, it is shown that this technique is able to calculate diversely on different terrains with high efficiency and reliability than Tayebe method [7].

4. CONCLUSION

This paper suggests a new method to estimate forest parameters using L-band polarizatric interference UAV-SAR images. The proposed approach not only overcomes the limitations of the former, but also considerably improves the accuracy of forest height. Through the evaluation with UAV-SAR and LiDAR data, the suggested method has significantly improved the precision compared to Tayebe one [7]. Contemporaneously, when analyzing and evaluating UAV-SAR data that are forest areas with different slopes, it also shows high efficiency and reliability.

Although these proposals have achieved high performance and substantially improved the accuracy for estimated forest parameters in comparison with Tayebe solution [7]. However, the construction and addition of many constraints for the optimal problem have increased these proposals' computational complexity. This also means that the processing time will greatly extend compared to the three-state inversion methods.

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TÓM TẮT

Phương pháp ước lượng độ cao rừng sử dụng ảnh UAV-SAR giao thoa phân cực

Bài báo này đề xuất một phương pháp nhằm nâng cao độ chính xác trong ước lượng độ cao rừng sử dụng ảnh UAV-SAR giao thoa phân cực. Các tham số rừng được trích xuất bởi phương pháp đề xuất được thực hiện thông qua ba bước. Pha địa hình và dải hệ số hấp thụ sóng có thể được xác định trong hai giai đoạn đầu tiên thông qua phân tích trị riêng ma trận tương can giao thoa. Độ cao rừng được khôi phục trong giai đoạn cuối dựa trên quá trình xác định một hệ số kết hợp giao thoa phức cho thành phần tán xạ tán cây. Hiệu quả của phương pháp đề xuất được đánh giá với dữ liệu UAV-SAR nhận được từ dự án AfiSAR của NASA/JPL.

Từ khóa: PolInSAR; UAV-SAR; Hệ số tương can giao thoa phân cực phức.