A Novel Three Steps Method for Forest Parameters Extraction Using PolInSAR Images

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Abstract—**The accuracy of ground phase and volume only coherence estimation are decisive factors to the efficient of the estimated forest height using PolInSAR data. This article approaches a novel three steps method to enhance the ground phase as well as forest height estimation from PolInSAR data. The ground phase is extracted from two fist steps by using conditional optimization approach. In the last steps, the forest parameters are retrieved from the optimal loop by using two optimum coherence channel without any prior information. The accuracy of the suggested method was applied with PolInSAR simulated data, which is generated from PolSARprosim 5.2 software. Experimental results indicate that the proposed method has improved the accuracy of the estimated forest height compared to Tayebe method by more than 1.1m**

Keywords-PolInSAR, ground phase, forest parameter, conditional optimization, volume only coherence.

I. INTRODUCTION

Forest height is considered to be one of the main factors for assessing forest change as well as forest monitoring, modeling and management. Today, Polarimetric Synthetic Aperture Radar Interferometry (PolInSAR) technology [1, 2] has been performed outstanding features for assessing the impact of changes in forest ecosystems to climate change and global warming.

Along with the strong development of the PolInSAR system, a variety of methods have been suggested to improve the efficiency of estimating forest parameters using PolInSAR data [3-7]. The 3-stage inversion [6], which based on random volume over ground model (RVoG) [8], is one of pioneering methods for determination forest parameters under parameter inversion way. Although this manner has been popularly applied in extracting forest height but it still has some disadvantages. One of the disadvantages of this method is that the precision of the terrain phase is based greatly on the number of polarization channels used. The determination of this phase requires a large computation time and it does not provide high accuracy, especially in the dense forest areas. Another drawback of this algorithm is the assumption that $\tilde{\gamma}_{HV}$ is an ideal polarization channel for the scattering component from the canopy. Therefore, the accuracy of the forest's vertical structure and the extinction coefficient measured by this manner are not high. In 2018, Tayebe proposed an optimal method of volume coherence coefficients [9] to improve the efficient of the forest parameter evaluation for the 3-state inversion method. In this method, Tayebe still uses total line fit square method (TLS) to determine the terrain phase. The authors then searched optimum coherence coefficients that it lies in the ambiguity region of line coherence. Finally, the forest height was retrieved by comparing the optimum coherence coefficients with the prediction model as in the last stage of 3-stage method. The efficient of Tayebe method was remarkably improved for forest height retrieval. However, this method still assumes that the optimum coherence coefficients only have pure volume scattering components, that mean it does not have contribution from another scattering components ($\mu(\omega)=0$), and used TLS method to estimate the terrain phase. Because of these two shortcomings, the effectiveness of Tayebe's method of forest height estimation is not highly countable and does not accurately reflect the scattering process in the actual forest environment.

Based on the above analysis, this letter proposes a novel three steps manner to better the accuracy of estimating forest parameters. The proposed method is carried out in three steps. First, a conditional optimum algorithm is applied to identify two optimal polarization channels that represent for pure volume and surface scattering components. The surface phase is then determined based on the intersection point of the line through these two polarimetric channels with a complex unit circle. Finally, a 4-way lookup table is constructed to extract forest parameters based on the two optimum polarization channels. This method not only improves the quality of surface phase factors but also overcomes the inaccurate assumptions of the 3-state inversion algorithm as well as the Tayebe method [9].

II. METHODOLOGY

A. *Optimizing coherent set*

For the case of backscatter in reciprocal environment, each PolSAR system's Pauli backscatter vector is shown 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 which, $S_{p,q}\left(p,q=\{H,V\}\right)$ are complex scattering factors and $i=1,2$ represents two PolSAR systems. Data received from the PolInSAR system is usually represented by a (6×6) coherence matrix, and is represented in Eq. 2.

$$[T_6] = \left\langle \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} [k_1^{*T} \quad k_2^{*T}] \right\rangle = \begin{bmatrix} [T_{11}] & [\Omega_{12}] \\ [\Omega_{12}^*] & [T_{22}] \end{bmatrix} \tag{2}$$

In which, matrices $[T_{11}]$ and $[T_{22}]$ are Hermitian matrices that illustrate the polarimetric properties of the target obtained from each distinct PolSAR system, matrix $[\Omega_{12}]$ is the complex matrix containing information about the interference and polarization of the target. With the operator $\langle \bullet \rangle$ expressing the average entire process of data processing and the $(\bullet)^*$ expresses the complex conjugation. Under whitening process of PolInSAR data, the contraction coherency matrix can be obtained as follow:

$$\bar{\Omega}_{12} = T^{-\frac{1}{2}}.\Omega_{12}.T^{-\frac{1}{2}} \quad \text{with} \quad T = \left(T_1 + T_2\right)/2 \tag{3}$$

In order to find the true global optimal values, we suggest a matrix Γ by adding a free phase parameter to contraction coherency matrix:

$$\Gamma(\psi) = \frac{\bar{\Omega}_{12}.e^{j\psi} + \bar{\Omega}_{12}^*.e^{-j\psi}}{2} \tag{4}$$

With each value of free phase in range $(0 \div \pi)$ we can achieve a pair eigenvector $\left(\vec{\omega}_1^k, \vec{\omega}_3^k\right)$ that corresponds to two eigenvalue λ_1^k and λ_3^k of matrix $\Gamma\left(\psi^k\right)$. In this paper, we assumption that $\left(\arg\left(\lambda_1^k\right) \le \arg\left(\lambda_2^k\right) \le \arg\left(\lambda_3^k\right)\right)$. Under the interferometry principle of the radar wave in the natural medium, we can see that the argument of the third eigenvalue $\arg\left(\lambda_3^k\right)$ approximately with the central phase of the direct scattering component from tree crown. In contrast, argument of the first eigenvalue $\arg\left(\lambda_1^k\right)$ is approximate to the central phase of the scattering comonent from the ground. Then, the pair of complex interferometry coherence factors for volume scattering and ground scattering mechanism can be extracted as follows:

$$\tilde{\gamma}_i\left(\psi_k\right) = \frac{\vec{\upsilon}_i^H\, \Omega\, \vec{\upsilon}_i}{\vec{\upsilon}_i^H\, T\, \vec{\upsilon}_i} \quad \text{with} \quad \vec{\upsilon}_i = \vec{\omega}_i^k.T^{\frac{1}{2}}; i = 1,3 \tag{5}$$

Based on two set $\tilde{\gamma}_1\left(\psi_k\right)$ and $\tilde{\gamma}_3\left(\psi_k\right)$ that are acquired from fomula 5, the complex coherence factors can be selected for volume and ground scattering component that meet the conditions as:

$$\begin{cases} \arg\left(\tilde{\gamma}_3\right) \ge \arg\left(\tilde{\gamma}_{HV}\right) \\ \arg\left(\tilde{\gamma}_1\right) \le \arg\left(\tilde{\gamma}_{HH-VV}\right) \end{cases} \tag{6}$$

After selecting the pairs of complex interferometry coherence coefficients $\tilde{\gamma}_1, \tilde{\gamma}_3$ satisfying the condition (6), the pair of optimal interferometry coefficients $\left(\tilde{\gamma}_{1opt}, \tilde{\gamma}_{3opt}\right)$ was determined based on the standard in Eq. 7.

$$d = \left\|\tilde{\gamma}_3 - \tilde{\gamma}_1\right\|_{\max} \tag{7}$$

B. Estimate Ground Phase

The accuracy and stability in topographic phase estimation play a decisive role to the effectiveness of forest parameter retrieval algorithms using remote sensing radar images. In order to better the precision for the determination of the terrain phase, we propose to use the coherence set optimization method.

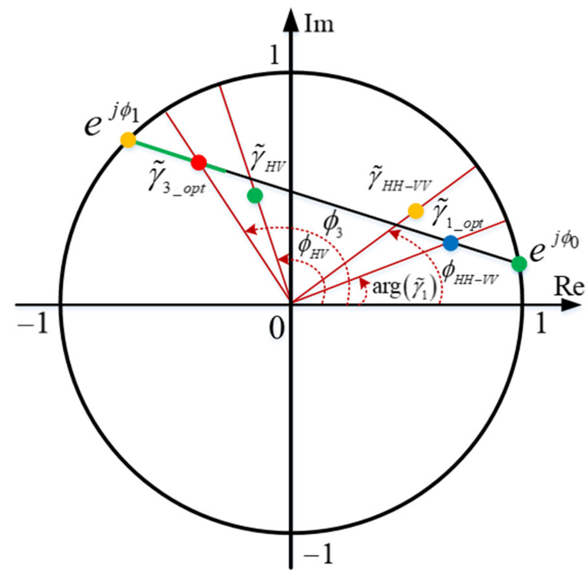

Fig 1. Schematic representation of the optimization procedure of the mentioned method.

According to the backscatter theory of radar waves in the natural environment, we can see that $\tilde{\gamma}_{3opt}$ corresponds to the scattering component from the canopy and $\tilde{\gamma}_{1opt}$ corresponding to the direct scattering component from the surface. Draw a line through these two points on a complex plane. This line will intersect the unit circle at 2 points and 1 of these 2 points will be the phase of the ground.

Then the surface phase ϕ_0 will be determined by the formula

$$\phi_0 = \arg\left\{\tilde{\gamma}_{1opt} - (1-K)\tilde{\gamma}_{3opt}\right\} \tag{8}$$

Where K is the solution of the quadratic equation.

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

With

$$A_0 = \left|\tilde{\gamma}_{3opt}\right|^2 - 1;\; A_1 = 2\,\mathrm{Re}\left\{\left(\tilde{\gamma}_{1opt} - \tilde{\gamma}_{3opt}\right)\tilde{\gamma}_{3opt}^*\right\}; \quad A_2 = \left|\tilde{\gamma}_{1opt} - \tilde{\gamma}_{3opt}\right|^2 \quad (10)$$

It is obvious that the topographic phase detected by the polarization state optimization method has overcome the disadvantages in determining the phase of the previous 3-stage inversion algorithm. In [9] 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 8 to 12 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 unit circle at two points and determine the terrain phase according to conditions (8). Thus, the surface phase estimated by the proposed method has not only improved the accuracy but also reduced the calculation time.

C. *Estimate the forest parameters using optimal loop*

We know that any polarizing channel always has the contribution of surface scattering. 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 of the previous methods. In this paper, the coefficients of interference for the scattering components directly from the canopy were determined based on an optimal loop to overcome the disadvantages of the previous forest height retrieval methods. Therefore, for each given value h_v, σ , and $L_1(\vec{\omega}), L_3(\vec{\omega})$ change in the range (0 ÷1), then two optimal polarization channels can be estimated as follow:

$$\tilde{\gamma}_{1est} = e^{j\phi_0}\left[\tilde{\gamma}_v(h_v,\sigma) - L_1(\vec{\omega})\left(1-\tilde{\gamma}_v(h_v,\sigma)\right)\right]$$
$$\tilde{\gamma}_{3est} = e^{j\phi_0}\left[\tilde{\gamma}_v(h_v,\sigma) - L_3(\vec{\omega})\left(1-\tilde{\gamma}_v(h_v,\sigma)\right)\right] \quad (11)$$

Where $\tilde{\gamma}_v(h_v,\sigma)$ is the volume only coherence, which is a function of tree height and mean extinction factor:

$$\tilde{\gamma}_v(h_v,\sigma) = \frac{2\sigma}{cos\theta_0\left(e^{\frac{2\sigma h_v}{cos\theta_0 - 1}}\right)}\int_0^{h_v} e^{jk_z z}.e^{\frac{2\sigma z}{cos\theta_0}}\,dz \quad (12)$$

Where θ_0 denotes the incidence angle of PolInSAR system and k_z represents the vertical wavenumber.

With each given (h_v,σ) we can achieve distance between estimated complex coherence and two optimal complex coherence $(\tilde{\gamma}_{1opt}, \tilde{\gamma}_{3opt})$ as:

$$\begin{cases} d_1 = \left\|\tilde{\gamma}_{1opt} - \tilde{\gamma}_{1est}\right\| \\ d_2 = \left\|\tilde{\gamma}_{3opt} - \tilde{\gamma}_{3est}\right\| \end{cases} \quad (13)$$

The optimal complex coherence for each given (h_v,σ) are then obtained under constrain as follow:

$$D\left(h_v^m, \sigma^n\right) = \min\left\{\sum_{i=1}^{2} d_i\right\} \quad (14)$$

Finally, we change the tree height $h_v\left(0 \le h_v \le 2\pi / k_z\right)$ and mean extinction factor $\sigma\left(0 \le \sigma \le 2dB/m\right)$ and repeat above optimal loop. Then we can achieve a set of $D\left(h_v^m,\sigma^n\right)$ and the best forest parameters can be retrieved under condition (15)

$$\min_{\substack{m=1\ldots M \\ n=1\ldots N}}\left\{D\left(h_v^m,\sigma^n\right)\right\} \quad (15)$$

It is obvious that the optimal volume coherence factor is determined based on the optimal loop method to improve the forest height estimation efficiency of the proposed method. The way to find the optimal block coefficients of the proposed method has been assumed ($\mu(\omega) = 0$) 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.

III. RESULTS

The effectiveness of the proposed method was assessed with simulation data created by PolSARProSim 5.2 software [10]. Simulation data was received from PolInSAR system at 1.3 GHz with a vertical baseline of 1.5 m and a horizontal one of 20 m. The surveyed forest area has an average vegetation height of 20m. The surveyed forest covers an area of 2.8274 Ha with a density of 900 trees/ha and type of Hedge tree. Figure 2 shows a Pauli color image of the observed forest area with 225x217 pixels in size. The effectiveness of the proposed method is assessed by comparing the outcomes of the proposed method with the Tayebe method.

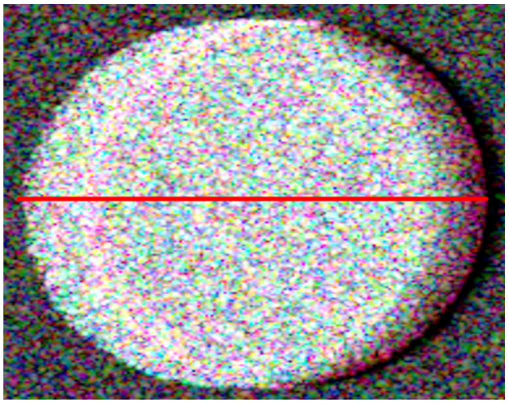

Fig 2. RGB Pauli image of simulated forest scene.

Figure 3 is a chart evaluating the estimated forest elevation from the proposed method (red line) with the Tayebe (blue line) method. It can be seen that the estimated average forest height of the proposed method fluctuates steadily around the height of 20m (except for pixels 42, 69 and 146 being 22m high). Meanwhile, the forest height estimated by Tayebe method often fluctuates widely in the range from 16m to 19.6m (especially, there are many pixels lower than 15m). Although the Tayebe method has significantly improved the accuracy better than the traditional 3-stage method. However, the results of forest height determined by this algorithm have not yet been highly effective and unstable. In addition, TABLE I also shows that the average forest height determined by the proposed method and the Tayebe method is 19.5864m and 18.4821m, while the actual forest height is 20m. From the forest height estimation results in Figure 3 and TABLE I, it can be seen that the forest height estimated by the proposed method is about 1.1 m more accurate than the Tayebe method.

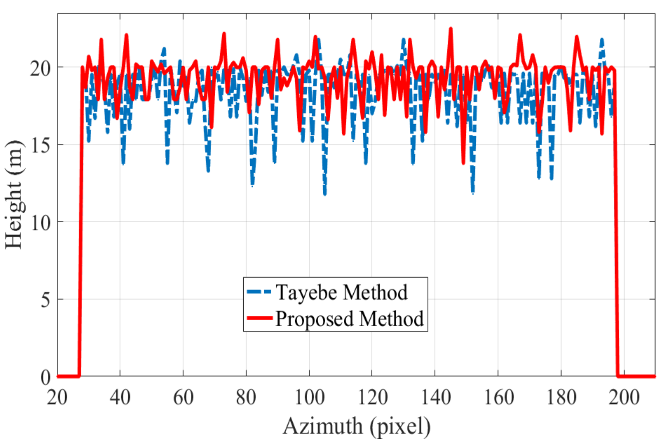

Fig 3. Height result comparison of two methods.

Figure 4 is 2D chart depicting forest height estimated by the proposed method over the entire observed forest pole. These figures provide an overview of the accuracy of the forest height determined by the proposed method.

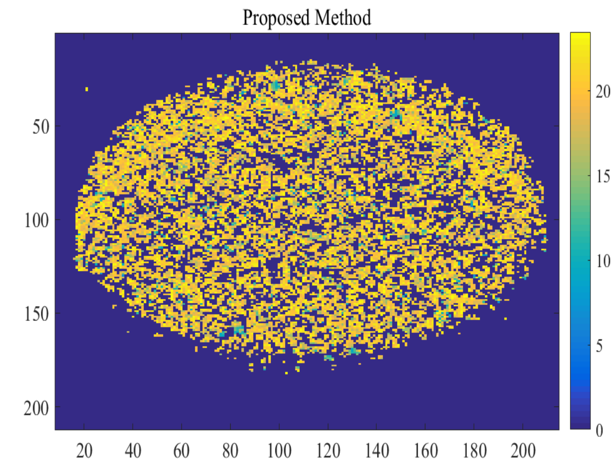

Fig 4. The 2D chart describers forest height is estimated by the proposed method.

Specifically, the results in Figures 4 show that the height of the forest is estimated to be concentrated at a tree height of 20m. Although, there are some pixels lower than 16m and higher than 22m but not significant. Thus, it can be concluded that the forest height determined by the proposed method is more reliable and precise than the previous 3-stage method.

TABLE I. FOREST PARAMETERS ESTIMATED BY TWO METHODS

Parameter	**The real value of the scene**	**Tayebe's Method**	**Proposed method**
$h_v[m]$	20	18.4821	19.5864
$\phi_0[rad]$	0.0615	0.1989	0.0971
$\sigma[dB/m]$	0.1926	0.2439	0.2155
RMSE (m)	0	2.3891	1.5985
Accuracy (%)	100	92.411	97.932

TABLE I shows the forest parameters estimated by the proposed method and the Tayebe method. In particular, the average square error value (RMSE) of the proposed method and Tayebe method are 1.5985 and 2.3891, respectively. It can be seen that the RMSE value of the Tayebe method is nearly 2 times higher than the RMSE of the proposed method, meaning that the efficiency of the forest height estimated from the Tayebe method is lower than the proposed method. TABLE I shows the accuracy of the estimated forest height of two methods, 97.932% and 92.411%, respectively. Thus, the accuracy of the average forest height estimated by the proposed method is approximately 5.5% higher than the Tayebe method. Furthermore, the soil phase is determined by the method of 0.0971, which is close to the system's ground phase value

(0.0615). In contrast, the terrain phase estimated by Tayebe method is 0.1989, a large deviation from the value of the soil phase of the system. The cause of this error is as analyzed in section 2. In addition, the wave absorption coefficient extracted by the proposed method also gives more accurate results and is closer to the system value than the Tayebe method. From these analyses, it can be concluded that the estimated forest parameters of the proposed method are more reliable than the Tayebe method.

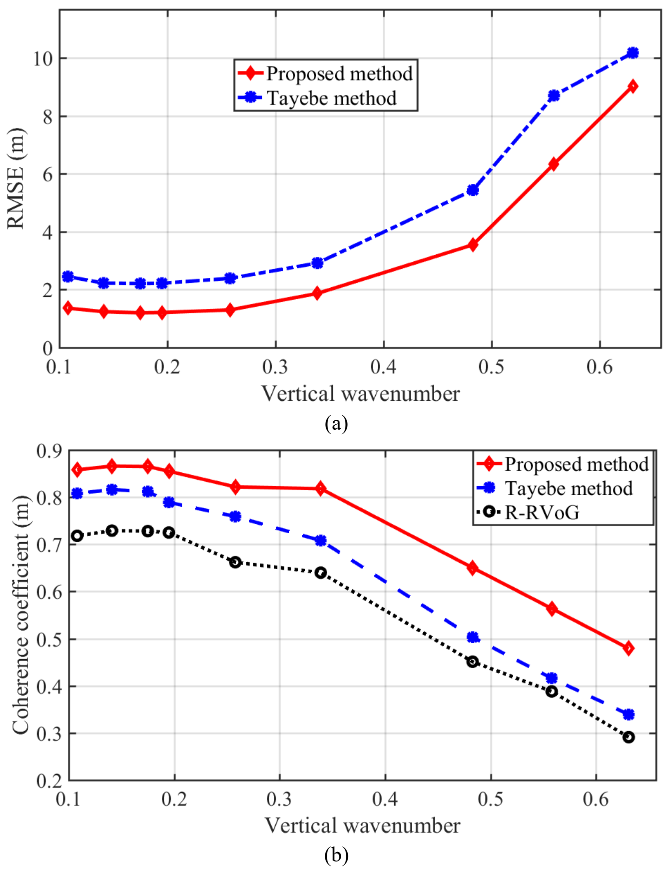

Fig 5. (a) The RMSE values, (b) The coherence coefficients of methods.

Next, we applied both methods on the simulated forest data with different standing wave ratios. Simulation forest data is created by changing the satellite's incident angle; the other parameters remain the same. The experiments were conducted with 9 different data, the incident angle varied from 20 degrees to 60 degrees (The angle of incidence of each simulation data was 5 degrees), corresponding to the values of the wave ratio stand from 0.108 rad to 0.631 rad. As is well known, most polarization channels (HH, HV and VV) are related to the polarization interference coefficients and they are all influenced by the standing wave ratio. Therefore, changes in vertical wave ratio values will directly cause changes in the estimated forest elevation.

Figure 5(a) describes the root mean square error of the proposed method (red line) and the Tayebe method (blue line). The results of Figure 5(a) show that the RMSE value of the two methods is very large when the ratio of standing waves is from 0.339 rad to 0.631 rad. Conversely, when the ratio of standing waves decreases from 0.258 rad to 0.108 rad, the RMSE values of both methods are also more stable and reliable. The result in Figure 5(a) tells the teacher that the average square error of the proposed method is always smaller than this parameter of the Tayebe method on all 9 calculated data. It means that the extracted forest height of the Tayebe method is not as accurate as the suggested method.

Figure 5(b) shows the interference coherence factor of HV channel $\tilde{\gamma}_{HV}$, the volume coherence coefficient of Tayebe method and the optimal volume coherence interference factor $\tilde{\gamma}_{opt}$ of the proposed method. As with the RMSE value when the standing wave ratio decreases from 0.258 rad to 0.108 rad, the volume coherence coefficient of the methods also gives more accurate and stable values. Figure 5(b) shows that the optimal optimal volume coherence factor of the proposed method always achieves higher values than the coefficients of HV channel coefficients and the coherent coefficients of the Tayebe method over 9 different standing wave ratios. This is completely true with the results of estimating the forest height of the methods shown in Figure 3. From the results in Figure 5, we can make the assumption that the price of the standing wave ratio is appropriate (suitable angle) from 0.108 rad to 0.258 rad gives the result of the RMSE and coefficient of channel combination of stable and accurate methods. In addition, the values of large standing wave ratios often result in estimating forest parameters due to inaccurate methods and causing large errors.

IV. CONCLUSION

The letter proposes a novel three steps algorithm for estimating forest parameters using L band PolInSAR data. The proposed method can both overcome the limitations of the Tayebe method and greatly improve the accuracy of the estimated forest height is estimated. Experimental results point out that forest parameters can be extracted directly and more accurately by the proposed method. In particular, the accuracy of the forest height calculated by the proposed method has improved by roughly 5.5% compared to the Tayebe 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 various types of data and in actual forest terrain to further improve efficiency.

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