FOREST HEIGHT ESTIMATION FROM POLINSAR IMAGE USING COHERENCE SET AND CANCELLATION OF SCATTERING MECHANISMS

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***Abstract*: Forest height is one of the most important forest vertical structure parameter for many forest management and monitoring activities. Recently, great number of methods have been proposed for the forest height estimation using PolInSAR data, such as ESPRIT, three-stage inversion method but these methods tend to underestimate the forest height due to attenuation of the electromagnetic waves in the medium. This paper proposes a method to improve the accuracy of forest height estimation by combining the mean coherent set theory and cancellation of scattering mechanisms. The proposed method performance is evaluated with simulated data acquired by PolSARProSim software. Experimental results indicate that the accuracy of forestry parameter determination is improved.**

***Keywords: polarimetric SAR Interferometry, forest height, mean coherent set, cancellation of scattering mechanism*.**

1. Introduction

Forests are ecosystems in which trees plays a vital role in the relationship between organisms and environments. Their role is very important for the life of human being and the environment. Nowadays, to satisfy demands of estimating influences of forest ecosystem changes on climates changes and the warmth of earth, a variety of remote sensing technologies have been researched and developed. Among of them, Polarimetric Synthetic Aperture Radar Interferometry (PolInSAR) has received great interests because it combines the advantage of polarimetric SAR (PolSAR) and interferometry SAR (InSAR) for enhanced the accuracy of target parameter determination [1]. Estimation of forest height by means of polarimetric interferometry synthetic aperture radar (PolInSAR) observations is one of the most promising applications in the field of active microwave remote sensing. In two decades ago, many techniques have been proposed for forest height estimation such as ESPRIT [3], three-stage inversion [2], and forest parameters inversion methods [4], model-based decomposition techniques [5]. Among of them, three-stage inversion process proposed by Cloude and Papathanassiou is quite simple and most widely used. However, the estimation of volume decorrelation by using three-stage inversion process is not much inappropriate, and there is an ambiguity zone of volume decorrelation Therefore, accurate forest height estimation of three-stage inversion process is sometimes not reliable. Besides, the ESPRIT can detect local scattering centers corresponding to the canopy top and ground topographic in the forest area but the detection accuracy of these techniques become inappropriate for dense forest region due to strong volume scattering mechanism. The efficiency of the three-stage inversion method has also been tested with dual-polarization data [12]. Applying the model-based decomposition techniques to PolInSAR data is opened new way for forest height estimation. However, these methods still exist an underdetermined problem. One parameter in the single or double bounce scattering component is set to zero, thus leading to the instability of the decomposition techniques. The instability of these methods will cause false forest height estimation. For that reasons, this paper provides an approach for forest height estimation from PolInSAR images, which is avoid these limits.

The aim of this paper to present an accuracy improvement of forest height estimation by combining the mean coherent set and cancellation of scattering mechanisms. The proposed method is executed following three steps. Firstly, the ground topography phase is estimated by using mean coherent set theory. Secondly, the canopy phase is extracted by cancellation scattering mechanisms method. Finally, the forest height is estimated by phase differencing. The proposed method performance is evaluated with simulated data from PolSARProSim software [11]. Experimental results show that the accuracy of forest height estimation can be improved by proposed method.

2. Ground topography phase estimation using mean coherent set

2.1 Scattering model

The basic radar observably in fully polarimetric interferometric SAR system is a six-dimension complex matrix of a pixel in each resolution element in the scene, defined as shown in Eq. (1) [1]

$$[T] = \left\langle \vec{k}.\vec{k}^{*T} \right\rangle = \begin{bmatrix} T_1 & \Omega \\ \Omega^{*T} & T_2 \end{bmatrix} \text{with } \vec{k} = \begin{bmatrix} \vec{k}_1 \\ \vec{k}_2 \end{bmatrix} \quad (1)$$

where $\langle \bullet \rangle$ denotes the ensemble average in the data processing and $(\bullet)^*$ represents the complex conjugation. The matrices T_1 and T_2 are the conventional Hermitian polarimetric coherence matrices, which describe the polarimetric properties for each individual image separately, while Ω is a non-Hermitian complex matrix, which contains polarimetric and interferometric information.

In the general, the complex polarimetric interferometry coherence of PolInSAR system as a function of the polarization of the two images as [1]:

$$\tilde{\gamma}(\vec{\omega}_1, \vec{\omega}_2) = \frac{\vec{\omega}_1^{*T} \Omega \vec{\omega}_2}{\sqrt{\left(\vec{\omega}_1^{*T} T_{11} \vec{\omega}_1\right)\left(\vec{\omega}_2^{*T} T_{22} \vec{\omega}_2\right)}} \quad (2)$$

where $\vec{\omega}_1, \vec{\omega}_2$ is the unitary complex defining the selection of each polarization stage.

The Random Volume over Ground (RVoG) model [2] is an effective model for interpretation of electromagnetic wave interaction in the natural medium, by combining a volume with a ground scatter. According to the RVoG model, the coherent scattering model addresses the complex interferometry in the form [2]:

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

Where ϕ_0 is the ground topography phase, $\mu(\vec{\omega})$ is the effective ground-to-volume amplitude ratio and $\tilde{\gamma}_v$ denotes the complex coherence for the scattering from canopy layer, which depends on the mean wave extinction and forest height.

2.2 Ground topography phase estimation using mean coherent set

The three-stage inversion process [2] employs several typical polarization channels, such as HH, HV, VV… to do the least square line fit for the ground phase extraction. However, errors can be occurred in this ground phase estimation method since limited number of coherences is applied in line fit, while a large number of coherences will increase computation cost. Therefore, in this paper, the ground topography phase is estimated by using mean coherent set to overcome shortcomings in the three-stage inversion algorithm.

Tabb and Flynn first developed the numerical range of the contraction matrix for analyzing and processing PolInSAR [6]. It provides useful tool for coherence shape parameters extraction, which related to physical properties of scattering media. With assumption the projection vectors are forced to equal ($\vec{\omega}_1 = \vec{\omega}_2 = \vec{\omega}$), to obtain a single scattering mechanism coherence set. In the general case, using equal projection vectors, the single scattering mechanism coherence set is given:

$$\Gamma_{SSM} = \left\{\vec{\upsilon}^{*T}\Pi\vec{\upsilon} : \vec{\upsilon} \in \mathbb{C}^3, \vec{\upsilon}^{*T}\vec{\upsilon} = 1\right\} \tag{4}$$

Where $\Pi = T^{-1/2}\Omega T^{1/2}$ is the coherency contraction matrix, since by definition the largest singular value of Π less than one, and $\vec{\upsilon} = \frac{\sqrt{T}\vec{\omega}}{\vec{\omega}^{*T}\sqrt{T}\vec{\omega}}$.

Then, an equivalent formula to handle representation of the PolInSAR coherence coefficient can be rewritten with the use of the coherency contraction matrix:

$$\tilde{\gamma}(\vec{\omega}) = \left|\tilde{\gamma}(\vec{\omega})\right| e^{j\phi_0} = \vec{\upsilon}^{*T}\Pi\vec{\upsilon};\ \vec{\upsilon}^{*T}\vec{\upsilon} = 1 \tag{5}$$

In the numerical range theory, the single scattering mechanism coherence set Γ_{SSM} can be represented by the generalized inner product numerical range of a square matrix $A \in \mathbb{C}^{3\times 3}$:

$$W(A) = \left\{x^{*T}Ax : x \in \mathbb{C}^3, x^{*T}x = 1\right\} \tag{6}$$

Hence, the numerical range of Π can be considered as coherence set region.

Under the common assumption of reciprocity and reflection symmetry in the natural medium, the coherency contraction Π can be rewritten as [7]:

$$\Pi = \begin{bmatrix} \gamma_{11} & \rho_{12} & 0 \\ \rho_{12}^* & \gamma_{22} & 0 \\ 0 & 0 & \gamma_{33} \end{bmatrix};\ \gamma_{ii}\{i = 1,2,3\}, \rho_{12} \in \mathbb{C} \tag{7}$$

We show that coherency contraction Π has three eigenvalues λ_1, λ_2 and γ_{33} ($\arg(\lambda_2) < \arg(\lambda_1) < \arg(\gamma_{33})$). Under the theory of radiative transfer in natural media, we usually assume that there is not any ground scattering component in the HV channel, therefore, the third eigenvalue γ_{33} is an approximation of $\tilde{\gamma}_{HV}$. Whereas, the both eigenvalue λ_1 and λ_2 are related to $\tilde{\gamma}_{HH}$ and $\tilde{\gamma}_{VV}$, respectively. Hence, there are two line structures ($\lambda_1\lambda_2$ and $\lambda_2\gamma_{33}$) in the coherence shape. Usually, HV channel is taken to be complex volume coherence, as this channel is dominated by volume scattering component. Using these properties, linear structure of the polarimetric variation of interferometric coherence can be estimated by linking point γ_{33} and eigenvalue λ_2 in the complex plane, and then the ground topography phase can be extracted as following [7]:

$$\phi_0 = \arg\left\{\lambda_2 - \gamma_{33}(1-L)\right\} \tag{8}$$

L can be determined by solution of a quadratic equation:

$$AL^2 + BL + C = 0 \rightarrow L = \frac{-B - \sqrt{B^2 - 4AC}}{2A} \tag{9}$$

where $A = |\gamma_{33}|^2 - 1; B = 2\,\mathrm{Re}\left\{(\lambda_2 - \gamma_{33})\gamma_{33}^*\right\}; C = |\lambda_2 - \gamma_{33}|^2$

3. Forest height estimation

3.1 Canopy phase estimation using cancellation of scattering mechanisms.

In order to estimate the canopy phase by using cancellation of scattering mechanism method, we first extract canopy and ground parameters using decomposition techniques. Under the hypothesis of reflection, the volume scattering and ground scattering contribution are represented through the following coherency matrices.

$$T_v = \begin{bmatrix} a & b & 0 \\ b^* & c & 0 \\ 0 & 0 & d \end{bmatrix}; \quad T_g = \begin{bmatrix} m_{11} & m_{12} & 0 \\ m_{12}^* & m_{22} & 0 \\ 0 & 0 & m_{33} \end{bmatrix} \tag{10}$$

where a, b, c, and d are the coefficient of volume scattering matrix, as presented in [8].

For PolInSAR data, the polarimetric coherence and polarimetric interferometry coherence matrix are decomposed into two scattering mechanism corresponding to ground scattering and volume scattering [9].

$$T = f_v T_v + f_g T_g \\ \Omega = e^{j\phi_v} f_v T_v + e^{j\phi_g} f_g T_g \tag{11}$$

where $f_i, \phi_i, \{i = v, g\}$ denote the amplitude and phase center for volume and ground scattering, respectively. In Eq. (11), the first equation is used to calculate the volume scattering amplitude. The eigenvalues of matrix $\left[T - f_v T_v\right]$ are determined by eigen-decomposition technique, confined to zero, and then we can obtain three volume scattering amplitude coefficients f_v. We show that the optimum coefficient f_v corresponds to the maximum volume scattering amplitude coefficient. Hence, we are easy to derive an approximated expression for T_g.

$$\hat{T}_g = \begin{bmatrix} T_{11}(1,1) - f_v a & T_{11}(1,2) - f_v b & 0 \\ T_{11}^*(1,2) - f_v b^* & T_{11}(2,2) - f_v c & 0 \\ 0 & 0 & T_{11}(3,3) - f_v d \end{bmatrix} \tag{12}$$

Where $T_{11}(i,j)$ represent the element of the column i and the row j of the matrix T_{11}.

By combining Eq. (2) and (11), the complex interferometric coherence can be derived as:

$$\tilde{\gamma}(\vec{\omega}_1,\vec{\omega}_2) = \tilde{\gamma}_v(\vec{\omega}_1,\vec{\omega}_2) + \tilde{\gamma}_g(\vec{\omega}_1,\vec{\omega}_2) = \frac{\vec{\omega}_1^{*T}\Omega\vec{\omega}_2}{\sqrt{\left(\vec{\omega}_1^{*T}T_{11}\vec{\omega}_1\right)\left(\vec{\omega}_2^{*T}T_{22}\vec{\omega}_2\right)}}$$

$$= \frac{e^{j\phi_v} f_v \vec{\omega}_1^{*T} T_v \vec{\omega}_2 +}{\sqrt{\left(f_v\vec{\omega}_1^{*T}T_v\vec{\omega}_1 + f_g\vec{\omega}_1^{*T}T_g\vec{\omega}_1\right)\left(f_v\vec{\omega}_2^{*T}T_v\vec{\omega}_2 + f_g\vec{\omega}_2^{*T}T_g\vec{\omega}_2\right)}}$$

$$+ \frac{e^{j\phi_g} f_g \vec{\omega}_1^{*T} T_g \vec{\omega}_2}{\sqrt{\left(f_v\vec{\omega}_1^{*T}T_v\vec{\omega}_1 + f_g\vec{\omega}_1^{*T}T_g\vec{\omega}_1\right)\left(f_v\vec{\omega}_2^{*T}T_v\vec{\omega}_2 + f_g\vec{\omega}_2^{*T}T_g\vec{\omega}_2\right)}} \tag{13}$$

It is important note that $\tilde{\gamma}_v(\vec{\omega}_1,\vec{\omega}_2)$ and $\tilde{\gamma}_g(\vec{\omega}_1,\vec{\omega}_2)$ may be considered as coherence only when one of them is zero. In Eq. (13), if a pair of projection vectors $(\vec{\omega}_1,\vec{\omega}_2)$ is properly selected, it may be possible to cancel the ground contribution, in term of the numerator, in the complex correlation coefficient [9]:

$$\left(\vec{\omega}_1^g\right)^{*T} T_g \vec{\omega}_2^g = 0 \tag{14}$$

The proper selection of the projection vector $\vec{\omega}_i^g\ (i=1,2)$ may cancel the ground scattering contribution such that the interferometric phase will correspond to volume scattering contribution. The way to solve this problem is to find the condition under which $\vec{\omega}_i^g$ cancel the ground scattering contribution. The cancellation of ground contribution may be get by choosing $\vec{\omega}_i^g$ corresponding to an eigenvector of the matrix T_g. Based on the eigen-decomposition of the matrix T_g, we can choose a pair of projection vector for $\left(\vec{\omega}_1^d,\vec{\omega}_2^d\right)$ cancellation of the ground scattering contribution.

$$\vec{\omega}_1^g = \begin{bmatrix} \dfrac{m_{g22} - m_{g11} + \sqrt{\left(m_{g11} - m_{g22}\right)^2 + 4\left|m_{g12}\right|^2}}{2m_{g12}} & 1 & 0 \end{bmatrix}^T$$

$$\vec{\omega}_2^g = \begin{bmatrix} \dfrac{m_{g22} - m_{g11} - \sqrt{\left(m_{g11} - m_{g22}\right)^2 + 4\left|m_{g12}\right|^2}}{2m_{g12}} & 1 & 0 \end{bmatrix}^T \tag{15}$$

where $m_{gij}\ \{i,j=1,2\}$ represent the element of column i and the row j of the matrix $\hat{T}_g$. We note that the ground contribution can be cancelled but the phase term of the complex coherence will still contain polarimetric as well as interferometric contribution. After cancellation of the ground scattering component from the complex coherence coefficient, we can obtain two expression related to the canopy phase.

$$\left(\vec{\omega}_1^g\right)^{*T}\Omega\vec{\omega}_2^g = e^{j\phi_v} f_v \left(\vec{\omega}_1^g\right)^{*T} T_v \vec{\omega}_2^g \tag{16}$$

If the projection vectors are inverted, then

$$\left(\vec{\omega}_2^g\right)^{*T}\Omega\vec{\omega}_1^g = e^{j\phi_v} f_v \left(\vec{\omega}_2^g\right)^{*T} T_v \vec{\omega}_1^g \tag{17}$$

Since, we can estimate the canopy phase as follows:

$$\begin{aligned} &\arg\left\{\left(\vec{\omega}_1^g\right)^{*T}\Omega\vec{\omega}_2^g\right\} = \phi_v + \arg\left\{f_v\left(\vec{\omega}_1^g\right)^{*T}T_v\vec{\omega}_2^g\right\} \\ &\arg\left\{\left(\vec{\omega}_2^g\right)^{*T}\Omega\vec{\omega}_1^g\right\} = \phi_v - \arg\left\{f_v\left(\vec{\omega}_1^g\right)^{*T}T_v\vec{\omega}_2^g\right\} \\ &\Rightarrow \phi_v = \frac{1}{2}\left\{\arg\left\{\left(\vec{\omega}_1^g\right)^{*T}\Omega\vec{\omega}_2^g\right\} + \arg\left\{\left(\vec{\omega}_2^g\right)^{*T}\Omega\vec{\omega}_1^g\right\}\right\} \end{aligned} \tag{18}$$

3.2 Forest height estimation.

One of simplest approaches to forest height estimation is to use the phase difference between interferogram. Therefore, the forest height first can be extracted by using the phase differencing between the canopy phase and ground phase.

$$h_v = \frac{\phi_v - \phi_0}{k_z} = \left(\phi_v - \phi_0\right)\frac{\lambda}{4\pi}\frac{R\sin\theta}{B\cos(\theta-\delta)} \tag{19}$$

Where θ is the mean incident angle, R is the distance between radar and an observed point, δ is the baseline tilt angle, B is the baseline, and λ is the wavelength.

The phase difference method is the simple to apply in the practice but its accuracy is not relative high. A possible reason is that the interferometry phase corresponding to canopy layer increases with real forest height. The difference between the actual forest and canopy height depends on the incident angle, forest species, and forest shape and it not change with real forest height. Hence, the scattering center of canopy is always lower than the real forest height. To overcome these shortcomings, one key idea is that this error can be at least partly compensated by using a coherence amplitude correction term, as introduced by Cloude [10]. Finally, by combining these two terms with a scaling parameter η, we then obtain an approximate method that can compensate for the variation in vertical structure, as shown in Eq. (20) [10]:

$$h_v = (\phi_v - \phi_0)\frac{\lambda}{4\pi}\frac{R\sin\theta}{B\cos(\theta-\delta)} + \eta\frac{\pi - 2\arcsin\left(|\tilde{\gamma}_v|^{0.8}\right)}{k_z} \quad (20)$$

Where $\tilde{\gamma}_v$ is the complex coherence for the volume scattering alone. This expression has the right kind of behavior in two special case. If the medium has a uniform structure function, then the first term give half the height and the second will then also obtain half the true height (if we set η=0.5). Whereas, if the vertical structure function in the volume channel is localized near top of the layer, then the phase height will give the true height, and second term will approach zero (if we set η=0). To reduce the error from change of extinction coefficient and the vertical structure, we select η=0.4, as reported in [10].

4. Experimental Result and discussion

In this section, the proposed approach has been evaluated with simulated forest scenario, which is generated with PolSARProSim software [11]. Fig. 1shows a red, green, and blue (RGB) coding Pauli image of forest scenario under the system parameters shown in Table 1. The top of image correspond to far range, which can be identified due to the shadowing effect at the borders of forest. Fig.2 is a plot of the forest height estimation of the proposed approach compared with the three-stage inversion process and the extended three-stage in the 138th row of the azimuth transect line (the red line in figure 1).

Table 1. Value of simulation parameters

Altitude	Look angle	Horizontal baseline	Vertical baseline
3000m	30^0	16m	2 m
Central frequency	Tree species	Tree height	Density
1.3 GHz	Pines	18 m	800 stem/Ha

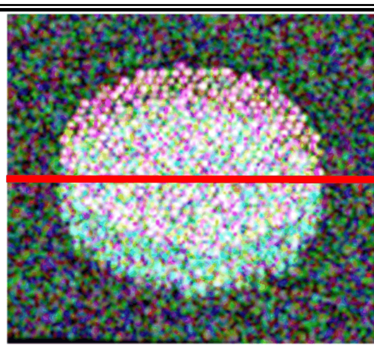

Fig 1. Pauli image on RGB coding of simulated data

Compare with the actual 18 m tree height and three-stage inversion process, the proposed method provides more accuracy results. Three-stage inversion process uses RVoG model to retrieve forest height [2]. This algorithm divides the inversion process into three stages, which involves talking observation of the complex coherence values at number different polarization channels and then minimizing the different between the models prediction and observation in a least squares sense. In this method, the ground topographic phase is extracted in the first two stages by using the total line fit method and the forest height is estimated in the last stage. In these stages, Cloude and Papathanassiou assumed that there is not any ground scattering contribution in the HV channel, and then they construct a look-up table (LUT) of the volume coherence only $\tilde{\gamma}_v$ as a function of forest height h_v and the extinction coefficient σ. By comparing $\tilde{\gamma}_{HV}$ with the LUT, they can obtained the forest height. Therefore, the accurate forest height estimation of three-stage inversion process depends significantly on the accurate estimation of prediction model. Besides, in the three-stage inversion process, the estimation of forest height and extinction coefficient are not reliable, while the ground phase estimation is time consuming and reliable. To improve the accuracy in the forest height estimation, Fu Wenxue proposed the extended three-stage. This method used the HH and HV polarization channels to find the volume-only coherence on the ambiguous line segment. Finally, estimate the forest height and extinction coefficient by comparing the volume-only coherence with the LUT. As results, the forest height estimation is more accurate than original method. Based on Fig. 2 and Tab.2, we can say that the forest height and ground phase estimation by using proposed method are more accurate and reliable than its by using three-stage inversion process.

Table 2. Forest parameters estimation from two method

Parameters	True	Three-stage inversion	Extended three-stage	Proposed method
$h_v\,[m]$	18	15.4865	17.6284	18.0142
$\phi_0\,[rad]$	0	-0.0921	-0.0921	-0.0109
Extinction [dB/m]	0.2	0.2607	0.0157	0.1746
Average error [m]	0	3.3135	0.3716	0.0142
RMSE [m]	0	1.8724	4.3367	1.4515

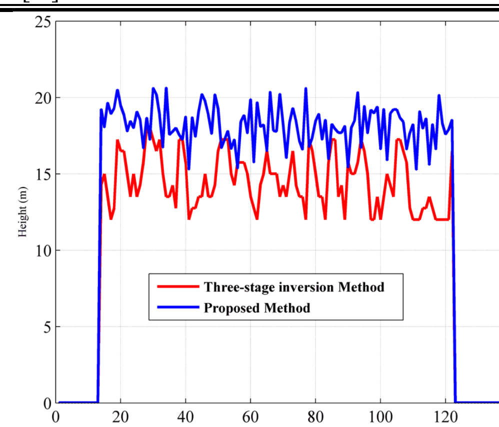

Fig 2. Plot of the forest height results comparison

The forest height estimation by using three-stage inversion process and proposed method for whole scene are represented in Fig. 3 and Fig. 4, respectively. From Fig. 3 it is shown that the peak differential of the forest height by using three-stage inversion process is located approximately at 15.5m and the forest height estimation ranges from 10m to 19m. On other hand, Fig. 4 shows that the forest height estimation by proposed method located in a range from 16m to 22m and the mean of forest height estimation is 18.0142m. In this figure, we show that the forest height estimation at some pixels is overestimated but it is mostly less than 23m. However, these values are almost lower than the 2π height ambiguities, which about 25m. Besides, the real effective tree height will be higher than these values so we can say that the results are acceptable. As can be seen in this figure, the tree height was recovered by the proposed method. Likewise, the proposed method provides relative accuracy with small error, and is more accurate for vertical structural variations.

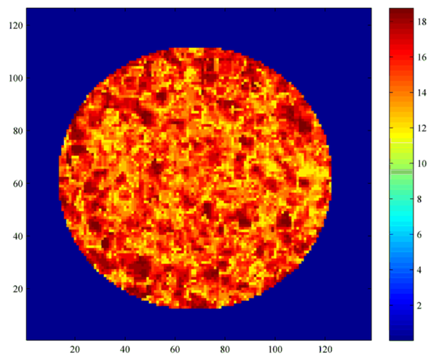

Fig.3 Forest height estimation by three-stage inversion process

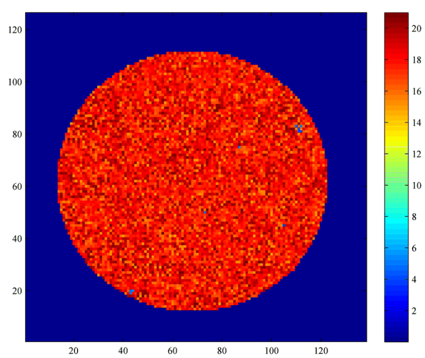

Fig. 4 Forest height estimation by using proposed method

5. Conclusion

An accuracy improvement method of forest height estimation by combining the mean coherent set and cancellation of scattering mechanisms for PolInSAR image is proposed in this paper. In the proposed method, the canopy phase is estimated by using the cancellation of scattering mechanism, while the ground topographical phase is extracted by using the mean coherence set theory. In comparison to three-stage inversion method, the proposed approach enables us to improve the accuracy of forest height and ground topography estimations. Experimental results indicate that the forest parameters can be retrieved directly and more accurately by the proposed approach. In the future, further theoretical and experimental investigations will be done to improve the performance of the proposed approach.

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