An Improved Forest Height Inversion Method Using Dual-Polarization PolInSAR Data

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Abstract. The Extended 3-stage method has somewhat improved the precision of estimating forest parameters of the traditional 3-stage inversion method. However, the topography phase and optimal volume coherence coefficient determined by this method are not really optimal, that lead to the forest parameters estimation of this method is unstable and inaccuracy. Therefore, this paper proposes an improved forest height inversion method by dual-polarization channel PolInSAR data to enhance the precision of forest parameters extraction. In the suggested approach, the surface phase is calculated based on the mean coherence set theory. A comprehensive search method is then proposed to determine the polarization channels corresponding to the optimal polarization channel coherence coefficients for the volume scattering component. The effectiveness of the suggested approach was assessed with simulation data from PolSARprosim 5.2 software. The empirical results show that the suggested approach not only improves the effectiveness of the forest parameters estimation of the extended 3-stage method but also reduces the complexity in the calculation.

Keywords: Dual-polarization PolInSAR · Extended 3-stage inversion method · Forest height · Mean coherence set · Ground phase estimation

1 Introduction

Forest height is one vital parameters to serve forest management, monitoring and protection activities. Along with the strong development of science-technique and technology, many methods have been applied to improve the effectiveness of the mentioned activities related to forest. Currently, the polarimetric interferometry synthetic aperture radar (PolInSAR) system still shows superior advantages in extracting forest parameters [1–3]. The fully polarimetric PolInSAR system provides full information and a more complete description of the vertical structure of the forest. However, it does not have high resolution and its viewing area is not large compared to the dual-polarization PolInSAR system. Hence, the dual-polarization PolInSAR system can meet the requirements of large-scale surveys and global survey. In recent years, there has been a great deal of researches on estimating forest height using dual-polarization PolInSAR images [4–6], which shows a great potential of this technique. Nonetheless, the previously introduced

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method mainly performed calibration based on the combination of HH and HV polarization channels without any process of optimal region coherence. Therefore, the region coherence with few polarization channels can results in instability and inaccuracy for the extraction of forest parameters. In 2016, Fu Wenxue suggested the extended 3-stage inversion manner [5] by dual-polarization PolInSAR data. This method somewhat improved on two disadvantages of the previously suggested approaches: (1) an optimization coherence process with the line fit method to estimate the surface phase; (2) optimal search technique is introduced to estimate polarimetric coherence coefficient for the volume scattering component. The extended 3-stage inversion method has significantly improved the effectiveness of estimating forest parameters compared to the 3-stage inversion approach. However, this method still has some drawbacks. Firstly, this method used four polarization channels $\tilde{\gamma}_{opt1},\ \tilde{\gamma}_{opt2},\ \tilde{\gamma}_{HH}$ and $\tilde{\gamma}_{HV}$ for ground phase estimation but the accuracy was not high. In addition, the process of determining this parameter is time-consuming and increases the complexity of the algorithm. Secondly, one of the two optimum polarization channels $\left(\tilde{\gamma}_{opt1},\ \tilde{\gamma}_{opt2}\right)$ will be selected as the polarization channel for the volume alone scattering component, which causes large errors when calculating forest height.

From the mentioned reasons, this article suggests an advanced forest height conversion method using dual-polarization channels PolInSAR data for accuracy improvement in extracting forest parameters. In the suggested approach, the topography phase is estimated based on the mean coherence set theory. This method not only improves the accuracy of the topography phase estimation, but also minimizes the computation complexity of the suggested approach. After that, a comprehensive search method to identify the polarimetric channels corresponds to the volume scattering component. Finally, the forest height is extracted by comparing the forecast model with the optimal volume coherence factors for the scattering component directly from the canopy. Thus, the suggested approach not only improves the efficiency of the extended 3-stage inversion method, but also lessens the complexity in the calculation.

2 Methodology

2.1 The Complex Interferometry Coherence Coefficient of the Dual-Polarization PolInSAR System

In comparison with the full polarization PolInSAR system, scattering vector of the 2-polarization channels PolInSAR system will not have the VH and VV polarization components. So, its scattering vector is expressed as follow:

$$\begin{aligned} \vec{k}_1 &= \sqrt{2}\left[S_{HH}^{1}\ S_{HV}^{1}\right]^T \\ \vec{k}_2 &= \sqrt{2}\left[S_{HH}^{2}\ S_{HV}^{2}\right]^T \end{aligned} \tag{1}$$

Then, the coherence matrix and cross decorrelation matrix of dual Pol - PolInSAR system become level 2 square matrices as follows:

$$[T_4] = \left\langle \vec{k}.\vec{k}^H \right\rangle = \begin{bmatrix} T_{11} & \Omega \\ \Omega^H & T_{22} \end{bmatrix} \text{ with } \vec{k} = \begin{bmatrix} \vec{k}_1 \\ \vec{k}_2 \end{bmatrix} \tag{2}$$

The complex interferometry coherence coefficient of the dual-polarization PolInSAR system is presented as Eq. 3.

$$\tilde{\gamma}(\vec{\omega}) = \frac{\vec{\omega}_1^H \, \Omega \, \vec{\omega}_2}{\sqrt{\langle \vec{\omega}_1^H \, T_{11} \, \vec{\omega}_1 \rangle \langle \vec{\omega}_2^H \, T_{22} \, \vec{\omega}_2 \rangle}} = \frac{\vec{\omega}^H \, \Omega \, \vec{\omega}}{\vec{\omega}^H \, T \, \vec{\omega}} \tag{3}$$

Where $\vec{\omega}_1 = \vec{\omega}_2 = \vec{\omega}$ are 2-dimension complex unitary vectors, the superscript "H" denotes complex conjugation and transposition and $T = (T_{11} + T_{22})/2$.

2.2 Estimating Ground Phase Based on the Mean Coherence Set Theory

Tabb and Flynn are pioneers in applying the numerical range theory of square matrix in analyzing and processing PolInSAR data [8, 9]. The shape of coherence region in the complex plane will then be extracted by using phase density function of the complex interferometry coherence coefficients. Thus, the complex coherence coefficient of dual-polarization PolInSAR data was defined as Eq. 4.

$$\tilde{\gamma}(\vec{\omega}) = \frac{\vec{\omega}^H \, \Omega \, \vec{\omega}}{\vec{\omega}^H \, T \, \vec{\omega}} = \vec{\nu}_i^H . H . \vec{\nu} \tag{4}$$

In which $H = T^{\frac{1}{2}} \, \Omega \, T^{\frac{1}{2}}$, $\vec{\nu} = \frac{\sqrt{T}.\vec{\omega}}{\vec{\omega}^H T^{\frac{1}{2}} \, \vec{\omega}}$ and $\vec{\nu}_i^H . \vec{\nu} = 1$.

According to the numerical range theory of square matrix, coherence set of all complex interferometry coherence coefficients is defined as below:

$$\Gamma = \left\{ \vec{\nu}^H . H . \nu : \ \vec{\nu}^H . \vec{\nu} = 1, \ \vec{\nu} \in \mathbb{C}^2 \right\} \tag{5}$$

The Eq. (5) has the similar form with the numerical range theory of a square matrix $[A]$ $\left(A \in \mathbb{C}^{2\times 2}\right)$. Then, we have the numerical range of A matrix as follow:

$$[A] = \left\{ x^n A . x : \ x^H . x = 1, \ x \in \mathbb{C}^2 \right\} \tag{6}$$

Therefore, according to the theorem of numerical range of the matrix, the theorem of numerical distance of matrix H is a convex contour of its eigenvalues. Without the loss of generality, we assume that matrix H have two eigenvalues $\lambda_1, \ \lambda_2$ with $(\arg(\lambda_1) < \arg(\lambda_2))$. In fact, λ_2 is very close to the value of $\tilde{\gamma}_{HV}$ [7]. Therefore, when connecting two points $\lambda_1, \ \lambda_2$ we get a straightforward line intersecting the complex unit circle (CuC) at two positions and one of these two positions will be the topography phase. Then the terrain phase will be determined as formula (7).

$$\phi_0 = \arg\{\lambda_1 - \lambda_2(1 - B)\} \tag{7}$$

Wherein, B is defined as follow:

$$a_0 B^2 + a_1 B + a_2 = 0 \Rightarrow B = \frac{-a_1 - \sqrt{a_1^2 - 4 a_0 a_2}}{2 a_0} \tag{8}$$

$$\text{With } \mathrm{a}_0 = |\lambda_2|^2 - 1, \ \ \mathrm{a}_1 = 2\mathrm{Re}\{(\lambda_1 - \lambda_2)\lambda_2\} \ \text{ and } \ a_2 = |\lambda_1 - \lambda_2|^2 \tag{9}$$

2.3 Estimating Forest Parameters by the Polarimetric Channel Comprehensive Search Method

To overcome the drawbacks of the extended 3-stage inversion method, we propose a comprehensive search method to find an optimum polarimetric channel of which there is at least the contribution of surface scattering component.

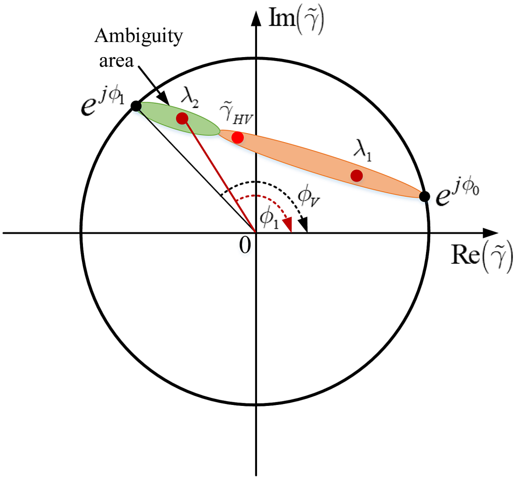

Fig. 1. Schematic representation of the optimization procedure of the mentioned method.

Equation (6) shows that the complex volume coherence factor of the dual-polarization PolInSAR system is a factor, which depends on polarization vectors. In this case, the polarization vector is a 2-dimension complex unitary vector and is represented as follow:

$$\vec{\omega} = \left[\cos\alpha \ \sin\alpha \, e^{j\psi}\right]^T \tag{10}$$

Where α and ψ are real coefficients that satisfy the conditions in Eq. (11).

$$\begin{cases} 0 \leq \alpha \leq \pi/2 \\ 0 \leq \psi \leq 2\pi \end{cases} \tag{11}$$

In this paper, we suggest a comprehensive search method to find a complex interferometry coherence coefficient representing for volume alone scattering component. This mean that, we search for the complex unitary vectors $\vec{\omega}$ to determine all phases of the coherence coefficient on the ambiguity area (the green domain in Fig. 2). For this purpose, we allow values $(\alpha, \ \psi)$ to vary within their value range. After that, a set of complex interferometry coherence coefficients $\tilde{\gamma}_c(\vec{\omega})$ will be determined according to the following condition.

$$\phi_1 > \arg(\tilde{\gamma}_c(\vec{\omega})) > \phi_{HV} \tag{12}$$

In which ϕ_1 is the phase respective to the second position between the coherency straight line and CuC, as is depicted in Fig. 1.

With the set of complex coherence coefficients $\tilde{\gamma}_c(\vec{\omega})$ satisfying the condition (12), we can completely estimate the HV and HH polarization channels from the Eq. 13.

$$\begin{cases} \tilde{\gamma}_{HH\_est} = e^{j\phi_0}\left[\tilde{\gamma}_c(\vec{\omega}) + L_{HH}(\vec{\omega})(1 - \tilde{\gamma}_c(\vec{\omega}))\right] \\ \tilde{\gamma}_{HV\_est} = e^{j\phi_0}\left[\tilde{\gamma}_c(\vec{\omega}) + L_{HV}(\vec{\omega})(1 - \tilde{\gamma}_c(\vec{\omega}))\right] \end{cases} \tag{13}$$

In which, the distance between the estimated channels and the two polarization interferometry channels is as follow:

$$\begin{cases} d_1 = \left|\tilde{\gamma}_{HH} - \tilde{\gamma}_{HH\_est}\right| \\ d_2 = \left|\tilde{\gamma}_{HV} - \tilde{\gamma}_{HV\_est}\right| \end{cases} \tag{14}$$

The coherence coefficient of the optimum polarization channel $\tilde{\gamma}_{c\_opt}\left(\vec{\omega}_{opt}\right)$ will then be determined according to condition (15).

$$\min_{\alpha,\psi} \left\| \sum_{i=1}^{2} d_i \right\| \tag{15}$$

After that, a look-up table (LUT) for volume only coherence is developed based on formula (3). Finally, forest height and the mean extinction coefficient will be extracted by comparing the coherence coefficient of the optimal polarization channel $\tilde{\gamma}_{c\_opt}\left(\vec{\omega}_{opt}\right)$ with values in LUT.

3 Experimental Result

The effectiveness of the suggested approach was assessed with simulation data generated from PolSARProSim 5.2 software [10]. Simulation data is received from the PolInSAR

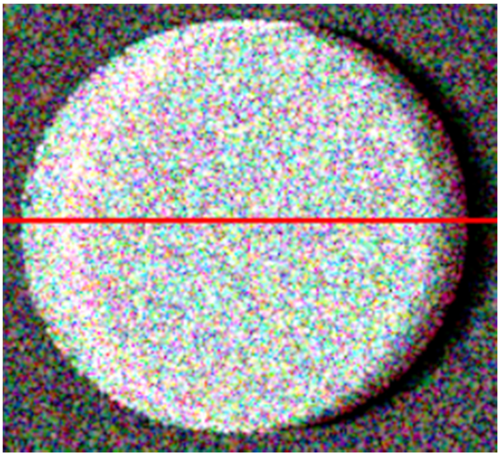

Fig. 2. Pauli image of the surveyed forest area (Color figure online)

band L system at the central frequency of 1.3 GHz with baseline of the 20 m horizontally and the 1.5 m vertically. The surveyed forest area has an average wood height of 20 m over place on a relatively flat terrain. The surveyed forest covers an area of 2,8274 Ha with a distribution of 900 trees per hectare. Figure 2 illustrates a Pauli color image of the observed forest area of 221 × 259 pixels. The effectiveness of the proposed model is assessed by comparing the results of the suggested approach with the extended 3-stage inversion manner [5].

Figure 3 is a chart comparing the topology phase that is detected by the proposed manner (the black line) and the extended 3-stage inversion algorithm. It can be seen that the estimated ground phase of the mean coherence set method has an average of 0.0982 rad and fluctuates quite close to the true topology phase. Meanwhile, what is estimated by the line fit method has an average of 0.1585 rad and usually oscillates over a relatively wide range and it has a large error compared to the true topology phase. Thus, the ground phase estimated by the suggested approach gives higher precision and reduces the computation time compared to the extended 3-stage inversion method.

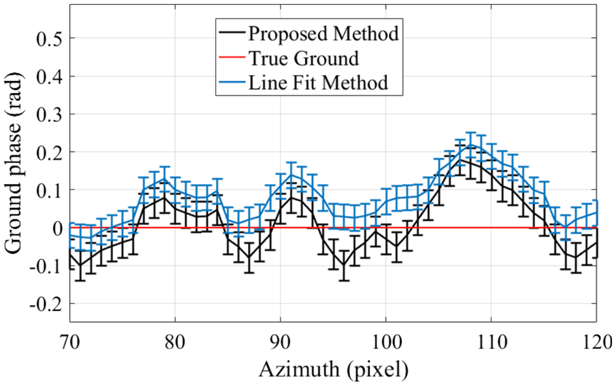

Fig. 3. The chart of estimated ground phases of the two methods.

Figure 4 is a line chart comparing the detected forest heights from the suggested approach (red line) with the extended three-stage inversion procedure (blue line). Figure 4 indicates that the average estimated forest height of the suggested approach fluctuates steadily around the height of 20 m (except for some pixels that exceed 21 m). Meanwhile, the volume height estimated by the extended 3-stage inversion procedure often oscillates strongly in the range of 16 m to 19.5 m (Especially, there are some pixels lower than 12 m). Although this method has significantly improved the accuracy better than the traditional 3-stage method. However, the estimated forest height has not yet been highly effective and stable.

Table 1 shows the forest height estimated by the extended 3-stage inversion manner and suggested approach with average values of 18,696 and 19,629 m, respectively. With the actual forest height in the simulation data of 20 m, we can see that the accuracy of the tree height estimated by the suggested approach is higher than that in the extended 3-stage inversion method of 4.67%. In addition, an important parameter representing the

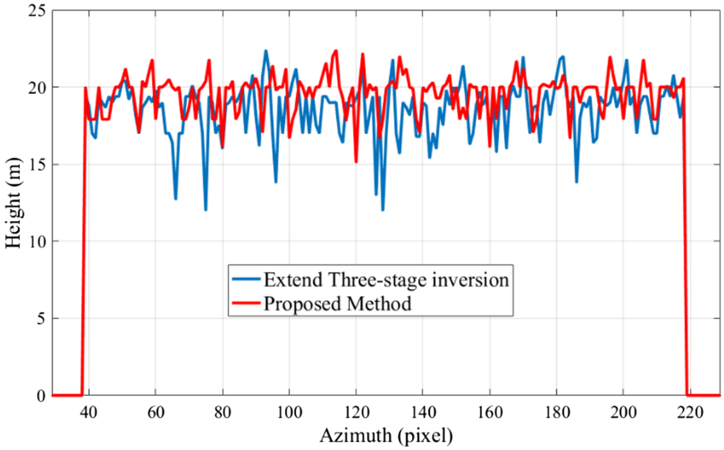

Fig. 4. A graph comparing the height of forest estimated by 2 methods. (Color figure online)

accuracy of the forest height estimated by the two methods is the root mean square error (RMSE). That are of 3,062 m and 1,582 m, respectively. The value of the suggested approach is smaller, meaning that the efficiency of volume height estimation of this method is higher than the extended 3-stage inversion method. Furthermore, the other parameters in Table 1, including the surface phase and the mean extinction coefficient estimated by the suggested approach, also show high accuracy and are close to these values of the system.

Table 1. Forest height estimation for two approaches.

Parameters	True values	Extended 3-stage inversion	Proposed manner
h_V [m]	20	18.696	19.629
ϕ_0 [rad]	0.0875	0.1343	0.0948
Mean extinction σ [dB/m]	0.156	0.264	0.185
RMSE [m]	0	3.062	1.582
Accuracy [%]	100	93.480	98.145
h_V [m]	20	18.696	19.629

Figure 5 (a) is a 2D image and Fig. 5 (b) is a 3D image describing the wood height in the entire surveyed forest detected from the suggested approach. It can be seen that the pixels are shown in 2D and 3D, they are mostly concentrated at 20 m approximately (there are some pixels higher than 20 m but not significant). From the results shown in Fig. 5, the suggested approach is relatively accurate and reliable.

After that, to analyze the influence of tree species on the accurate forest height retrieval of the suggested manner, we apply the proposed manner and the extended 3-stage inversion method with the simulated forest areas having different tree species

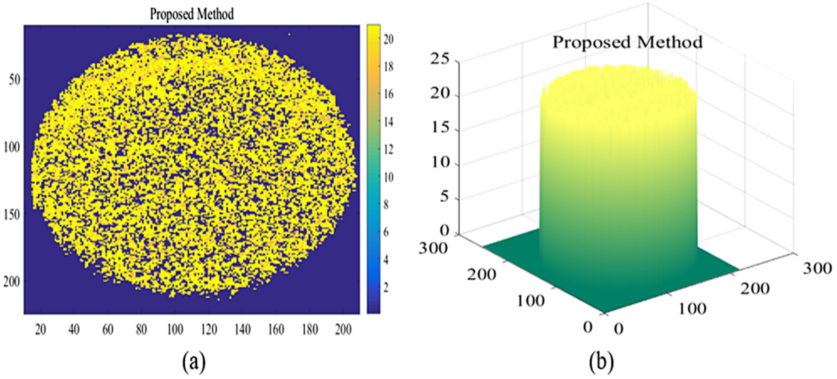

Fig. 5. Forest height is estimated by the suggested approach.

(coniferous forests, mixed forests and broadleaf forests). In the simulation data, we only change the tree types, the other parameters remain unchanged. Figure 6 describes the forest height estimated by two methods with three different tree species. We can see that the forest tree species of the conifer family (Pine) often cause large errors for the estimated results in both methods. The main reason is that with the forest trees belonging to the conifer family, scattering waves easily penetrate to the ground and then the central phase of ground scattering and mass scattering components are relatively close together.

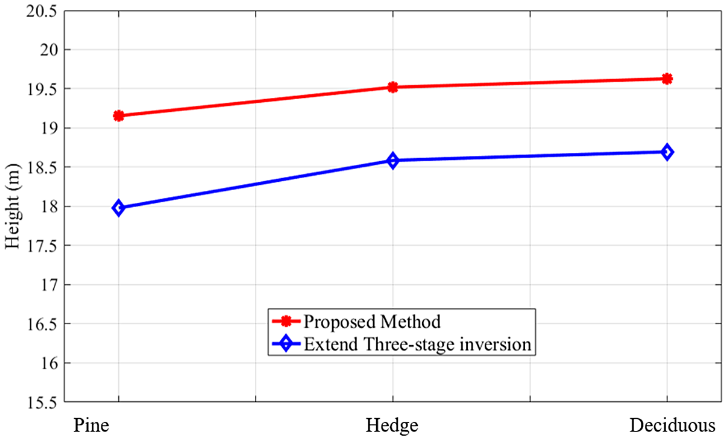

Fig. 6. The chart compares the forest height estimated by two methods with different tree species.

In contrast, with the forest area consisting of mixed trees (Hedge) and broad canopy trees (Deciduous), the radar waves are almost difficult to penetrate the canopy to affect the ground. That mean, the most radar microwaves scatter at the peak of the foliage so the center phase of these two scattering components is relatively far apart. However, in this case, the density of selected forest trees for simulation data is 900 trees/Ha. At that time, radar microwaves will not only be able to penetrate to the surface but also scatter on the canopy. Therefore, the backscattering signals will be received well and the center phase deviation of the volume alone scattering and surface scattering is not too close or too far, and it ensures that the calculation of the forest parameters is correctly. From the above analysis, it can be concluded that the forest tree species is also a parameter that has an effect on the effectiveness of the estimated forest height. Figure 6 presents the results of estimating forest height of the two methods with changes corresponding to the simulation data of each different tree species. However, because the density set for the initial simulation data was 900 trees/Ha, it was relatively favorable with the backscattering of radar waves. Therefore, the estimated forest height results in this case are not much changed. From this figure, it is again shown that the estimated forest height of the proposed algorithm is always more accurate and flexible than the extended 3-stage manner.

4 Conclusion

The paper has researched and developed an accurate method for estimating forest height from dual-polarization PolInSAR images. In the suggested approach, the terrain phase is first determined based on the mean coherence set theory. Then a comprehensive polarization channel search method is proposed to extract forest height and average wave penetration factor. The experiment results indicate that the accuracy of forest height detected by the suggested approach was enhanced by around 4.65% in comparison with the extended 3-state one. In the incoming years, the suggested approach can possibly be applied to different types of data and in different forest areas to optimize the efficiency of suggested approach.

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References

1. Mette, T., Papathanassiou, K.P., Hajnsek, I., Pretzsch, H., Biber, P.: Applying a common allometric equation to convert forest height from Pol-InSAR data to forest biomass. In: Proceedings of the IGARSS, Anchorage, AK, USA, pp. 272–276 (2004)
2. Cai, H., Zou, B., Lin, M.: Parameter inversion model base on PolInSAR images. In: Proceedings of APSAR 2007, Huangshan, 5–9 November 2007, pp. 751–754 (2007)
3. Papathanssiou, K.P., Cloud, S.R.: Single baseline polarimetric SAR interferometry. IEEE Trans. Geosci. Remote Sens. **39**(11), 2352–2363 (2001)
4. Cloud, S.R., Papathanssiou, K.P.: Three-stage inversion process for polarimetric SAR interferometry. IEE Proc. - Radar Sonar Navig. **150**(3), 125–134 (2003)
5. Wenxue, F., Huadong, G., Xinwu, L., Bangsen, T., Zhongchang, S.: Extended three-stage polarimetric SAR interferometry algorithm by dual-polarization data. IEEE Trans. Geosci. Remote Sens. **54**(5), 2792–2802 (2016)
6. Xie, Y., Fu, H., Zhu, J., Wang, C., Xie, Q.: A LiDAR-aided multibaseline PolInSAR method for forest height estimation: with emphasis on dual-baseline selection. IEEE Trans. Geosci. Remote Sens. **17**(10), 1807–1811 (2019)

7. Treuhaft, R.N., Cloude, S.R.: The structure of oriented vegetation from polarimetric interferometry. IEEE Trans. Geosci. Remote Sens. **37**(5), 2620–2624 (1999)
8. Managhebi, T., Maghsoudi, Y., Zoej, M.J.V.: A volume optimization method to improve the three-stage inversion algorithm for forest height estimation using PolInSAR data. IEEE Geosci. Remote Sens. Lett. **15**(3), 1214–1218 (2018)
9. Managhebi, T., Maghsoudi, Y., Zoej, M.J.V.: An improved three-stage inversion algorithm in forest height estimation using single-baseline polarimetric SAR interferometry data. IEEE Geosci. Remote Sens. Lett. **15**(6), 887–891 (2018)
10. Williams, M.L.: PolSARproSim: A Coherent, Polarimetric SAR Simulation of Forest for PolSARProSim (2006). http://earth.eo.esa.int/polsarpro/SimulatedDataSources.html