Three-dimensional forest structure features extraction based on TomoSAR

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Abstract

Forest structure is an important indicator for evaluating forest ecosystem and an indispensable input parameter for estimating forest carbon sink. Synthetic Aperture Radar (SAR) Tomography (TomoSAR), as a novel microwave remote sensing technique with 3D imaging capability, has been demonstrated to be an valuable tool for accurate inversion of forest structure. At present, the forest vertical structure parameters inversion is almost all concentrated on the forest height estimation. However, the spatial structure of forests is complex, and it is not enough to only use the forest height to express the forest structure. This fails to identify tree canopy, branch layer and underlying vegetation layer, etc., resulting in the partial and inaccurate forest vertical structure information. To solve this problem, this paper constructs 3D structural indices from tomograms, namely Horizontal Structure Index (HS) and Vertical Structure Index (VS). The HS primarily describes canopy density, compensating for the lack of information on the horizontal dimension of forest structure provided by traditional TomoSAR techniques; while VS describes the complexity of canopy distribution in the altitude direction, further enriching information on forest structure vertically. In order to verify their feasibility and validity, HS and VS are extracted using six fully-polarized L-band SAR images covering the Krycklan watershed in Sweden. Moreover, the accuracy is verified by using external high-precision LiDAR data. The results indicate a strong correlation between the structural indices extracted from TomoSAR and those extracted from LiDAR.

1. Introduction

The rapid changes in the global climate in recent years have posed a major threat to human society, and increasing number of countries have elevated "Carbon Neutrality" to a national strategy(Hou et al., 2023; Li et al., 2023; Selivanov et al., 2023). As the largest carbon reservoir in terrestrial ecosystems, it is of great significance to grasp its carbon sink in a timely manner for the realization of "Carbon Neutrality"(Piponiot et al., 2022; Stephenson et al., 2014). Forest structure is an important input parameter in the estimation of forest carbon sinks, therefore, precise forest structure inversion is a prerequisite for accurately estimating forest carbon sinks.

Currently, there are two main techniques for monitoring forest structure: field measurements and remote sensing. The field measurements provide highly accurate data but they are labor-intensive and time-consuming, making it difficult to carry out large-scale monitoring. The remote sensing technique can significantly save labor and material resources as well as time compared with field measurements, among which LiDAR and SAR have developed rapidly in recent years. LiDAR can capture detailed forest structure information, but its high cost limits its ability for large-scale imaging(Awaya and Araki, 2023; Hirschmugl et al., 2023; Lim et al., 2003; Park et al., 2021; Penner et al., 2023). Synthetic Aperture Radar (SAR) technology, on the other hand, can penetrate through the forest canopy to reach the ground surface, effectively obtaining forest structural parameters. Among them, Synthetic Aperture Radar Tomography (TomoSAR) technology, as a 3D SAR imaging technique, effectively addresses the problem of layover in traditional SAR technology. It has been demonstrated to achieve the effective separation of internal scatterers within forest in the vertical direction, obtaining 3D structural profiles of forest(Pardini et al., 2021; Peng et al., 2021; Peng et al., 2018; Wang et al., 2022). In recent years, many scholars have been committed to extracting features related to forest structure from tomographic profiles, and then establishing a new way to express forest structure in a refined way by TomoSAR.

TomoSAR can obtain the vertical backscattering power curve of target objects. The scattering mechanisms in forest areas are complex, but the phase center of the resulting backscattered energy is concentrated in the ground and canopy. Therefore, using peak extraction functions can extract the height of canopy and ground scattering centers(Peng et al., 2018). After power compensation, basic forest structural indices such as underlying topography and forest height can be obtained(Luo et al., 2023; Peng et al., 2021; Wang et al., 2022; Zhang et al., 2023). Underlying topography is the basis of height information in forest structure, and forest height directly affects tree crown area and branch quality. Therefore, these two parameters are widely used to express forest structure. In reality, forest spatial structure is complex and variable with diverse vertical layering of canopies; using only these parameters is not sufficient to fully characterize their vertical structural characteristics. Additionally, forests are distributed in three dimensions; they not only have vertical structural information but also horizontal structural information related to tree distribution including branches and leaves. Therefore, using only these parameters is insufficient for a detailed description of the three-dimensional structure of forests.

In view of this, this paper introduces the Forest Three-Dimensional Structure Indices: Horizontal Structure Index (HS) and Vertical Structure Index (VS), and applies them to the inversion of forest three-dimensional structure characteristics. HS mainly describes the denseness of the canopy, which compensates for the lack of information on the horizontal dimension of forest structure in the traditional TomoSAR inversion, while VS describes the complexity of the canopy stratification in the height direction, which further enriches the information on forest structure in the height direction. Therefore, the Three-Dimensional Structure Indices have the potential to finely describe the three-dimensional structure of forest(Pardini et al., 2018; Pardini et al., 2018; Tello et al., 2018).

The rest of the paper is organized as follows. Section 2 briefly describes the principles of TomoSAR imaging and outlines the principles and construction process of the 3D structure indices. Section 3 describes the study area and dataset information, and presents and analyzes the experimental results. Finally, the paper is concluded in Section 4.

2. Methodology

2.1 SAR tomographic model

The basic idea of SAR tomography is to acquire multiple observations of the same area at different heights. In addition to synthesizing apertures in the azimuth direction, it also forms another synthetic aperture in the third dimension, the elevation direction. This enables the differentiation of scattering objects at different elevations for the same slant range. Assuming the radar sensor observes the same target area N times, after imaging focusing, N single-look complex images can be obtained, the imaging geometry is shown in Figure 1. Preprocessing steps such as selecting the master image, image registration, flat earth phase removal, and phase error calibration are performed on this dataset to obtain the SAR tomography dataset(Zhang et al., 2023). For computational convenience, if the radar echo signal is discretely sampled along the elevation direction D times (where D >> N), then the SAR tomography continuous model can be discretized as follows(Peng et al., 2018):

$$g_n = \sum_{d=1}^{D} \beta_{z_d}(x, y, z) \cdot \exp\big(jk_z(n)\big)\, z_d \tag{1}$$

Where β_{z_d} = the reflectivity function at height z_d
$k_z(n)$ = the vertical wavenumber of the nth slave image relative to the master image, $k_z(n) = \frac{4\pi b_{\perp n}}{\lambda r \sin\theta}$.

For N observations, the relationship between the echo signal and the reflectivity function can be expressed as:

$$\begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_N \end{bmatrix} = \begin{bmatrix} \exp(jk_z(1)z_1) & \cdots & \exp(jk_z(1)z_D) \\ \exp(jk_z(2)z_1) & \cdots & \exp(jk_z(2)z_D) \\ \vdots & \vdots & \vdots \\ \exp(jk_z(N)z_1) & \cdots & \exp(jk_z(N)z_D) \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_D \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_N \end{bmatrix} \tag{2}$$

Simplify Equation (2) into matrix form:

$$G = A\beta + e \tag{3}$$

Where G = the observation vector composed of N images
A = the $N \times D$ dimensional guiding matrix, $A = [a(z_1), a(z_2) \cdots a(z_D)]$
$a(z_D)$ = the d-th mapping vector of the mapping matrix A
β = the unknown parameter vector
e = the noise vector.

For forest with distributed multiple scattering targets, the number of acquired images is generally smaller than the number of unknown parameters. However, what TomoSAR technology requires is the distribution of reflectivity function in the height direction, i.e., the power spectrum in the height direction, expressed as:

$$P = E(|\beta|^2) \tag{4}$$

Where P = the backscattered power, solving equation (4) can be regarded as a spectral estimation problem.

At present, many spectral estimation methods have been applied to SAR tomography, among which Adaptive Beamforming (Capon) can perform SAR tomography without any prior information, and has high computational efficiency and vertical resolution(Lu et al., 2022). Therefore, this paper chooses Capon algorithm to obtain forest 3D profile information. The power spectrum of reflectivity function estimated by Capon algorithm can be expressed as(Peng et al., 2021):

$$P_{CP} = \frac{1}{a^H(z_d)\hat{R}^{-1}a(z_d)} \tag{5}$$

Where $a(z_d)$ = the array steering matrix
$\hat{R}$ = the sample covariance matrix obtained by multi-view averaging.

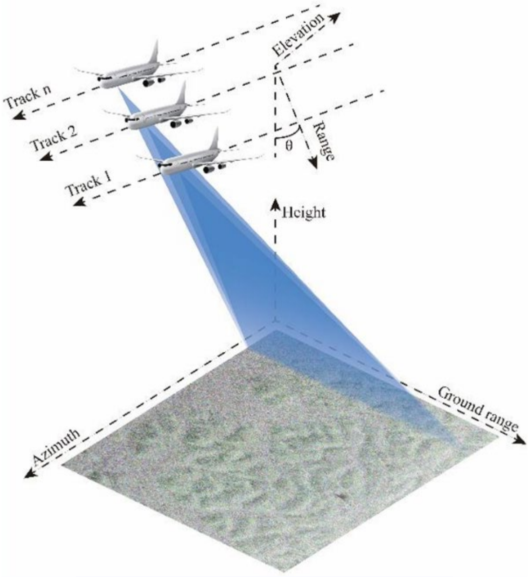

Figure 1. TomoSAR imaging geometry

2.2 Construction of forest 3D structure indices

The spatial structure of tropical forests is complex, with obvious canopy stratification in vertical direction and varying density in horizontal direction. The spatial structure characteristics of tropical forests cannot be fully characterized by only partial vertical structural features. Therefore, this paper introduces a set of indices based on SAR tomography to quantitatively describe the 3D structure of forest, derived from structural indices established in forest ecology. The forest 3D structure indices consist of horizontal structure index and vertical structure index, providing comprehensive descriptions of forest structure from both horizontal and vertical perspectives(Pardini et al., 2018).

2.2.1 Horizontal structure index: In forest ecology, the Stand Density Index (SDI) is used to describe the crowding level of stands. The crowding level depends not only on the distribution density of trees but also on the average tree size. It is defined as:

$$SDI = N\left(\frac{D_g}{D_0}\right)^{\beta} \tag{6}$$

Where N = stand density
D_g = the average diameter at breast height(DBH) of the stand
D_0 = the standard average DBH
β = the stand's natural sparse slope

It is obvious that it is built on the basis of individual trees, limited by the spatial resolution of SAR images, TomoSAR is almost impossible to obtain information at the individual tree level. However, through SAR tomography imaging, it is possible to obtain the radar backscattering power intensity variation curve from the top of the canopy to the ground. As shown in Figure 2, it contains scattering information from both the canopy and the ground. By obtaining the reflection peaks, one can acquire the scattering phase centers of the ground and the canopy. Based on this, the height of the canopy phase center relative to the ground can be calculated. Subsequently, the number of canopy phase centers above a specific threshold in a structural unit can be computed to derive canopy density information, i.e., HS, expressed as:

$$HS = \frac{n(P_{canopy})}{S} \tag{7}$$

Where $n(P_{canopy})$ = the number of canopy scattering centers above the threshold within the structural unit
S = the actual ground area corresponding to the structural unit.

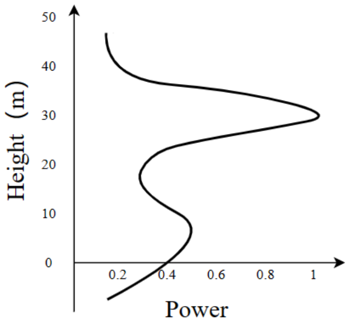

Figure 2. TomoSAR single pixel reflectivity profile

2.2.2 Vertical structure index: In forest ecology, the variance of DBH of all trees in the structural unit is usually used to describe the vertical structure of the stand, because DBH is easier to measure than tree height, and the DBH of tree is usually proportional to tree height, so the complexity of tree DBH determines the complexity of tree height to some extent. TomoSAR can obtain the heights of canopy scattering centers and ground scattering centers. Further differencing can yield canopy height (canopy phase center height, not tree height). Therefore, the description of forest vertical structure can adopt the variance of canopy height. To enhance its ability to describe the complexity of forest canopy, the canopy heights set within the structural unit is first deduplicated, and the vertical structure index is constructed as the product of the variance and quantity of the canopy heights set after deduplicated within the structural unit, namely:

$$VS = n'_{canopy} var(H'_{canopy}) \tag{8}$$

Where n'_{canopy} = the number of canopy heights after deduplication
H'_{canopy} = the set of deduplicated canopy heights.

2.3 Accuracy verification

The pulse signal emitted by LiDAR can penetrate the vegetation canopy and receive the laser energy reflected from the forest canopy, tree trunks, ground surface and other ground objects, which can accurately obtain the 3D structural information of the forest, but it is commonly used to validate the accuracy of TomoSAR-related imaging because of its high cost of acquiring the data and difficulty in wide-area imaging. In order to quantitatively investigate the expression ability of forest 3D structure indices on forest structure, this paper uses external LiDAR data to verify the accuracy of TomoSAR 3D structure indices.

3 Experiments and results

In order to explore the feasibility and validity of forest 3D structure indices to refine the description of forest structure, this paper utilizes L-band airborne dataset in the northern forest area to extract forest 3D structure features based on TomoSAR and verify the accuracy.

3.1 Study area and dataset

A boreal forest in the Krycklan watershed was selected as the study area for this experiment (the black boxed portion of Fig. 3), which has a rolling topography, the forest stand consisting mainly of pine and spruce, and low year-round temperatures.

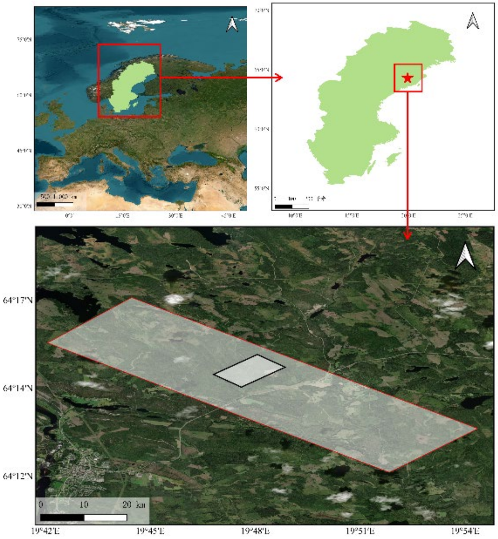

Figure 3. Overview of the Krycklan study area.

Figure 4. Krycklan area ground real trees photos

To quantitatively explore the ability of 3D structure indices to describe forest structure, this paper uses 6-scene L-band full-polarization SAR images obtained by airborne BioSAR2008 campaign for 3D tomography, and extracts structure indices. Radar system parameters and vertical baseline information are listed in Table 1.

Platform Parameters.	Numerical values
Center slant distance	3900m
Wavelength	0.23m
Incidence angle	25º- 55º
Range resolution	2.12m
Azimuth resolution	1.2m
Polarization mode	HH+HV+HV

Table 1. Imaging parameters of the L-band E-SAR system

To validate the TomoSAR imaging accuracy, on August 5 and August 6, 2008, the airborne LiDAR S/N425TopEye system was applied to the area. Both DTM and Canopy Height Model CHM can be generated from these point cloud data.

3.2 Experimental results and analysis

It has been shown that the backscattered power from the ground is mainly contained in the HH polarization channel, and the backscattered power from the HV polarization channel is dominated by the canopy body scattering. At the same time, Capon tomography algorithm does not require any prior information and has high imaging accuracy. Therefore, the Capon algorithm with high accuracy is adopted in this paper. HH polarization is used to extract the ground height, and HV polarization is used to extract the canopy height. Then, the relative ground height of the canopy (height of the canopy phase center) is obtained by difference, which provides necessary conditions for the subsequent extraction of 3D structure indices. As shown in Fig. 5, the vegetation distribution in this area is relatively regular, and the stands are concentrated in the form of community, but the division between adjacent stands is obvious. Moreover, the canopy height distribution is complex and the stand structure is diverse, which is suitable for exploring the feasibility and effectiveness of forest 3D structure indices describing forest structure.

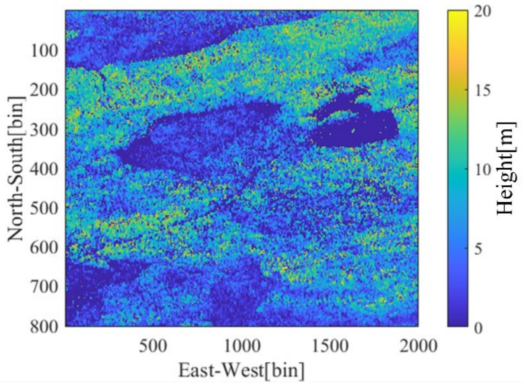

Figure 5. DTM extracted by TomoSAR

3.2.1 Extraction of 3D structure indices:

On the basis of using TomoSAR to extract the relative ground height of the canopy, the 3D forest structure indices were extracted through the formula introduced in Section 2.2, and the final results are shown in Figure 6 and 7. The results showed that the canopy density is higher in most areas of the study area, and the HS value is greater than 0.5. At the same time, the canopy density distribution is uniform and the horizontal structure complexity is low, indicating that the forest stand in this area is less artificially intervened, and only a small area have extremely low HS (close to 0), for the water body in this area.. If the horizontal structure index of two stands is similar, then VS will be used as supplementary information to characterize the 3D structure of the forest. VS is higher in most areas (greater than 0.6), and less than 0.2 in few areas, indicating that the distribution of stands in height is more complex and the canopy complexity is higher in this area.

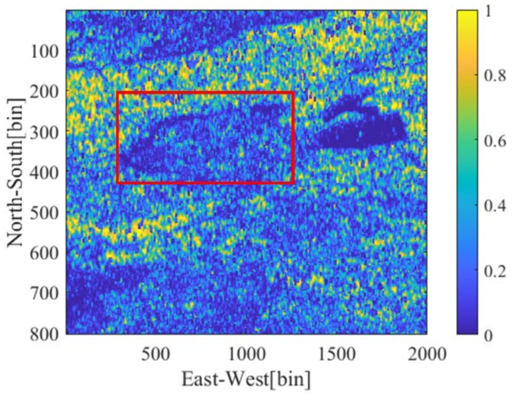

Figure 6. Horizontal structure index obtained by TomoSAR

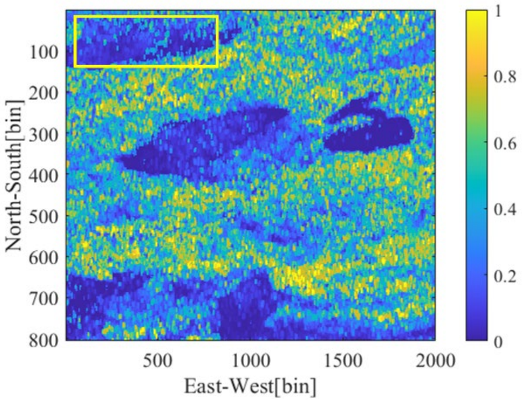

Figure 7. Vertical structure index obtained by TomoSAR

3.2.2 Accuracy Verification: LiDAR has high-precision 3D imaging capability to acquire 3D scene point cloud datasets, and the forest 3D structural indices are also applicable to LiDAR data. Therefore, this paper uses the high-precision CHM data acquired by LiDAR to verify the accuracy of the above experiments. In order to unify the horizontal resolution of the two data sources, the CHM is first filtered, and the filtering result is shown in Fig. 8. Then, the three-dimensional structural indices are used for feature extraction, the results are shown in Figures 9, 10. And correlation analyses are carried out with the corresponding results of TomoSAR in order to quantitatively assess its accuracy.

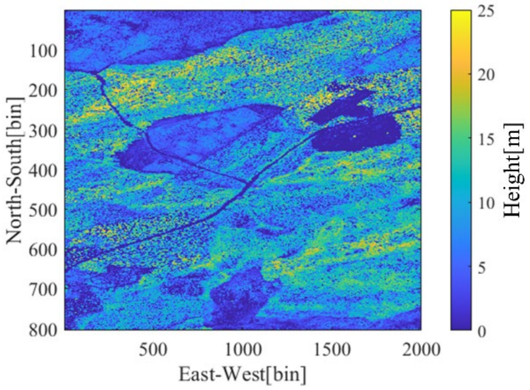

Figure 8. CHM obtained by LiDAR

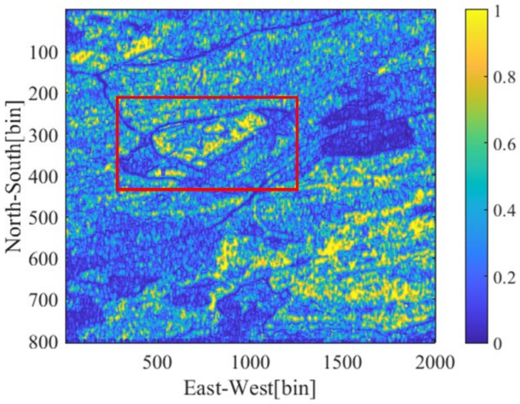

Figure 9. Horizontal structure index obtained by LiDAR

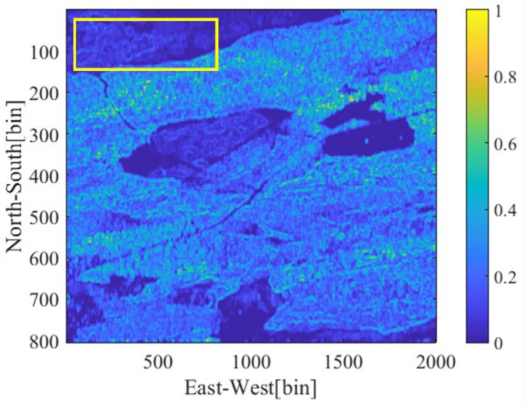

Figure 10. Vertical structure index obtained by LiDAR

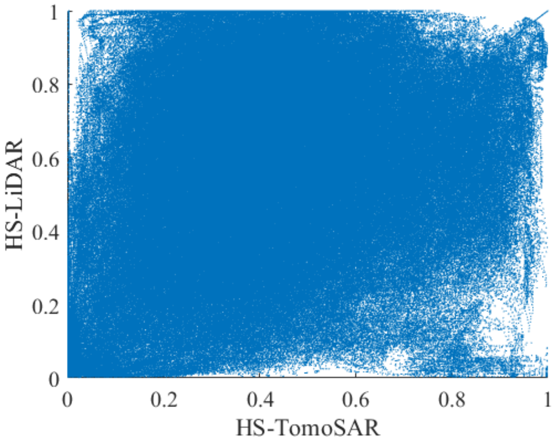

Figure 11. Two-dimensional joint distribution map between HS-TomoSAR and HS-LiDAR

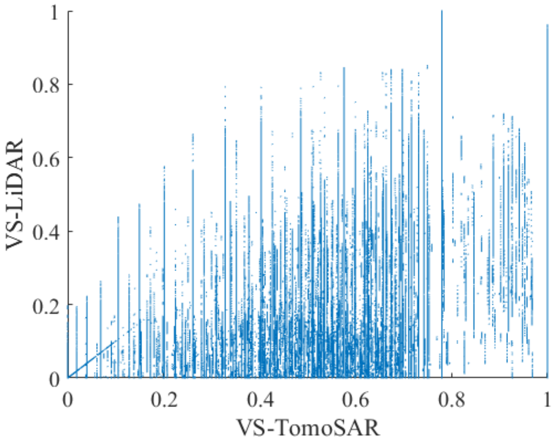

Figure 12. Two-dimensional joint distribution map between VS-TomoSAR and VS-LiDAR

Comparison of the structural indices extracted from the two data sources reveals that TomoSAR-HS is overall lower than LiDAR-HS, especially in the area marked by the red boxes in Figs. 6 and 9, because the vertical resolution of TomoSAR is not as good as that of LiDAR, and the red boxed area has a lower forest stand, whose scattering information is masked by the ground scattering information. While TomoSAR-VS is overall higher than LiDAR-VS, especially the plot marked by yellow boxes in Figures 7 and 10, this is because TomoSAR is affected by noise resulting in inaccurate extracted ground heights, which in turn causes misclassification of canopy, whereas VS mainly describes the canopy height information, and therefore exhibits a greater difference than HS. On the basis of the above qualitative analysis, quantitative accuracy is assessed using correlation analysis, which shows that the correlation of the structure indices extracted from the two data sources is high, with the horizontal structure index correlation of 0.5877 and the vertical structure index correlation of 0.6278, the accuracy verification results are shown in Fig 11 and 12, and that the reason for the VS to have higher accuracy is because of the removal of the repetitive height-scattering peaks from the ground. The above experimental results show that TomoSAR has the ability to refine the description of forest 3D structure

4 Conclusion

This paper mainly focuses on using TomoSAR to extract 3D structural indices to refine the description of forest structure.

Aiming at the problem that the traditional structural indices do not adequately describe the vertical structure of the forest and hardly describe the horizontal structure, we introduce 3D structural indices to quantitatively describe the forest structure, and then explore the feasibility and effectiveness of TomoSAR to refine the description of the 3D structure of the forest. The experimental results show that the structure indices extracted from TomoSAR and LiDAR have high correlation, and TomoSAR has the ability to express the 3D structure of forest in a refined way similar to LiDAR. The research results of this paper provide a new idea for TomoSAR to estimate forest structure, and it is proposed to verify the transportability of 3D structure indices in other areas and apply it to forest AGB estimation.

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