

Article

Sub-Canopy Topography Inversion Using Multi-Baseline Bistatic InSAR Without External Vegetation-Related Data

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Highlights

What are the main findings?

- This study demonstrates that the proposed multi-baseline InSAR framework for sub-canopy topography inversion successfully extends the RVoG model to single-polarization interferometric cases, supporting large-scale terrain mapping using globally available single-polarization InSAR data.
- This study confirms the feasibility of using the RVoG model to extract the height of the scattering phase center.

What is the implication of the main findings?

- This study can get rid of reliance on external datasets (e.g., ICESat-2 and GEDI) by developing and introducing a SAR-based dimidiate pixel model and a coherence-driven penetration depth model to initialize key parameters in RVoG model.
- This study quantifies the effects of interferometric geometry, scattering contributions, and fractional vegetation cover (FVC) on the proposed method in sub-canopy topography retrieval, clarifying the applicability of the proposed method.

Abstract

Previous studies on single-polarized InSAR-based sub-canopy topography inversion have mainly relied on simplified or empirical models that only consider the volume scattering process. In a boreal forest area, the canopy layer is often discontinuous. In such a case, the radar backscattering echoes are mainly dominated by ground surface and volume scattering processes. However, interferometric scattering models like Random Volume over Ground (RVoG) have been little utilized in the case of single-polarized InSAR. In this study, we propose a novel method for retrieving sub-canopy topography by combining the RVoG model with multi-baseline InSAR data. Prior to the RVoG model inversion, a SAR-based dimidiate pixel model and a coherence-based penetration depth model are introduced to quantify the initial values of the unknown parameters, thereby minimizing the reliance on external vegetation datasets. Building on this, a nonlinear least-squares algorithm is employed. Then, we estimate the scattering phase center height and subsequently derive the sub-canopy topography. Two frames of multi-baseline TanDEM-X co-registered single-look slant-range complex (CoSSC) data (resampled to 10 m × 10 m) over the Krycklan catchment in northern Sweden are used for the inversion. Validation from airborne light detection and ranging (LiDAR) data shows that the root-mean-square error (RMSE) for the



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two test sites is 3.82 m and 3.47 m, respectively, demonstrating a significant improvement over the InSAR phase-measured digital elevation model (DEM). Furthermore, diverse interferometric baseline geometries and different initial values are identified as key factors influencing retrieval performance. In summary, our work effectively addresses the limitations of the traditional RVoG model and provides an advanced and practical tool for sub-canopy topography mapping in forested areas.

Keywords: digital elevation model (DEM); Random Volume over Ground (RVoG); TanDEM-X; InSAR; sub-canopy topography

1. Introduction

The Digital Terrain Model (DTM) is an essential element of national geospatial databases, depicting the three-dimensional topography of the bare earth [1]. Within forest ecosystems, accurate sub-canopy topography (i.e., DTM) is critical for forest resource management, ecological land use, disaster mitigation, and water resource regulation [2–4]. Despite the critical significance of the sub-canopy topography in various applications, accurately mapping the sub-canopy topography remains a substantial challenge due to vegetation occlusion. At present, the optical remote sensing technique, while cost-effective and capable of extensive geographical coverage, is limited to capturing only the elevation of the vegetation surface [5]. Airborne light detection and ranging (LiDAR) can deliver high-quality, high-resolution ground surface elevation from point cloud data through gaps in the forest canopy. However, its high cost and data redundancy often preclude large-scale, cost-effective applications [6]. Spaceborne LiDAR can offer extensive coverage, but the collected data have low spatial resolution. Consequently, developing robust and efficient methods for deriving high-quality vegetation obstruction-free sub-canopy topography is of paramount significance.

Interferometric Synthetic Aperture Radar (InSAR) exploits the penetration capability of microwave signals in vegetated media, together with their sensitivity to the geometric structure of scattering elements, making it an important technique for providing a feasible means for terrain measurement in forest environments [7,8]. However, when generating a DEM in forest areas, conventional InSAR methods face a fundamental challenge: InSAR topography measurement reflects the elevation of the scattering phase center position, which often differs from the actual ground surface due to the signal interaction with the vegetation layer (see Figure 1). This bias is referred to as the scattering phase center height, which is caused by the forest scattering mechanism. Obviously, the scattering phase center height must be accurately estimated and removed to retrieve the underlying topography. Currently, methodologies for single-polarized InSAR-based sub-canopy topography retrieval fall into two categories. The first category concentrates on the volume scattering process between the radar signal and the forest canopy. It uses simplified interferometric scattering models like the original and improved SINC models that only consider the volume scattering within a homogeneous canopy and neglect the contribution of ground surface scattering [9]. The original and improved SINC models that only assume the volume scattering within a homogeneous canopy and neglect the potential ground surface scattering contribution. In such a case, the aforementioned models can retrieve the sub-canopy topography with a root mean square error (RMSE) of about 2.5 to 4.5 m by combining with the single-baseline InSAR observation, but they require the external data (such as ICESat-2 or GEDI) to calibrate the uncertainties caused by the model simplification [9]. Furthermore, the inversion accuracy may also be affected by the in-

terferometric geometry of the single-baseline observation and by temporal discrepancies of the selected external data, particularly in heterogeneous boreal forest environments. The second category uses empirical models that depend on external information. These models calibrate the scattering phase center height using auxiliary vegetation-related data, such as vegetation height, canopy coverage [10,11]. These approaches, however, encounter limitations in the boreal forest area, where heterogeneous canopy density and structure lead to complex wave-ground interaction. Moreover, sparse or low-resolution external datasets fail to adequately represent the regional diversity of phase center heights.

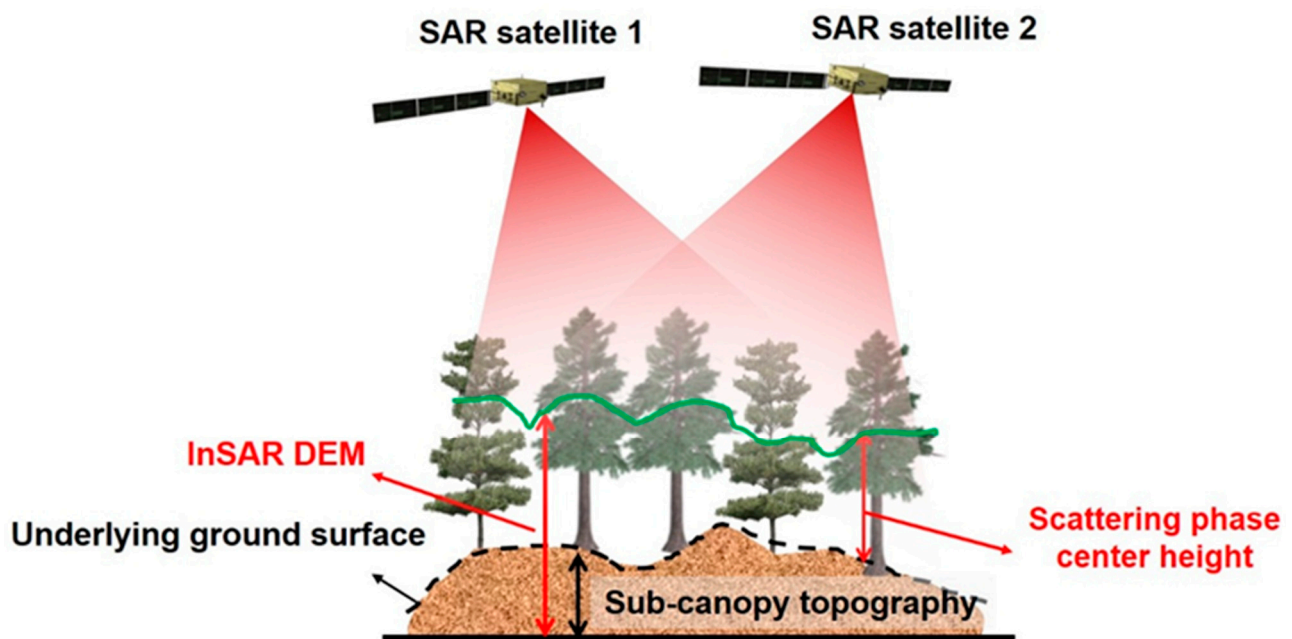


Figure 1. A schematic diagram of the InSAR digital elevation model (DEM) and sub-canopy topography in the forest area.

In boreal forest environments, significant variations in forest density lead to complex radar–target interactions. Since the SAR signals, even the short-wavelength SAR signal (such as the X-band microwave), penetrate the canopy, they interact with both the vegetation layer and the ground surface [12–14]. Consequently, a comprehensive interferometric scattering model is required to extract the sub-canopy topography. The Random Volume over Ground (RVoG) model, which combines both ground surface and vegetation volume scattering, provides a more precise representation of electromagnetic scattering processes in forested areas [15]. At present, the RVoG model has become one of the most widely adopted physical models for estimating forest parameters and sub-canopy topography [16,17]. However, the applications of the RVoG model for estimating the sub-canopy topography have been largely dependent on full-polarization SAR data based on the polarimetric interferometry theory [18–21]. Such data have primarily been acquired from airborne campaigns, which are often limited in spatial coverage and restricted to specific test sites globally [22,23]. In addition, the available spaceborne full-polarization SAR data are also limited. In contrast, the TerraSAR-X add-on for Digital Elevation Measurement (TanDEM-X) project has provided a large amount of high-quality single-polarization interferometric data with near-global coverage. Additionally, bistatic TanDEM-X InSAR data have been widely applied to global digital elevation model (DEM) generation. However, as mentioned above, an InSAR-derived DEM in forest areas cannot represent the true subcanopy topography [23,24]. The multi-baseline InSAR technique introduces diverse independent measurements to

overcome the underdetermined problem with single-baseline InSAR observation, thereby significantly enhancing the stability and accuracy of the inversion [25,26].

This paper proposes a new framework for reconstructing sub-canopy topography from multi-baseline bistatic InSAR data without using external data (e.g., ICESat-2 or GEDI) in boreal forest environments. The proposed approach adopts the RVoG model to indirectly estimate the scattering phase center height. A key issue is the positive solution of the RVoG model. Since the model has multiple unknown parameters and a high degree of nonlinearity, it is difficult to converge during parameter inversion. To address this, multi-baseline bistatic InSAR data are utilized to improve model robustness and inversion precision by effectively constraining and balancing the RVoG inversion function, hence resolving the rank-deficiency problem. Furthermore, radar signal scattering in forested areas is predominantly governed by volume scattering in dense canopy regions and surface scattering in canopy gaps. Based on this premise, a dimidiate pixel model for SAR amplitude information is developed to quantitatively determine the initial ground-to-volume amplitude ratio in the RVoG model, thereby largely reducing the reliance on external prior datasets (e.g., ICESat-2 or GEDI). In addition, a coherence-based penetration depth model is introduced to fix the initial values of other parameters. To test its effectiveness, the proposed method was evaluated in the Krycklan of northern Sweden. Two frames of multi-baseline TanDEM-X co-registered single-look slant-range complex (CoSSC) data (resampled to $10\text{ m} \times 10\text{ m}$) were used for inversion. Further, ICESat-2 and airborne LiDAR datasets were used to assess the inverted sub-canopy topography.

2. Test Area and Data

2.1. Test Area

Figure 2 shows the location of the two experimental regions within the Krycklan in northern Sweden. These areas are situated between latitudes $63^{\circ}8'N$ and $64^{\circ}28'N$ and longitudes $19^{\circ}E$ and $20^{\circ}6'E$, with elevations ranging from around 100 m to 400 m. The area experiences a subarctic climate, characterized by long winters and persistent seasonal snow cover. The Krycklan is predominantly composed of boreal forests, wetlands, streams, and lakes, forming a typical boreal mixed forest ecosystem. Forests cover roughly 85% of the area, with Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) as the dominant species, accompanied by smaller proportions of broadleaf species such as *Betula* spp. and others. The measured forest height is approximately 18 m. Forest density varies considerably across the region. Owing to its diverse ecosystem composition, the Krycklan serves as an ideal location for testing sub-canopy topography retrieval methods.

2.2. Data

The TanDEM-X project consists of two X-band SAR satellites that operate in close formation to simultaneously image the Earth's surface from differing perspectives. Data are collected in a bistatic mode, where one satellite transmits the signal and both satellites receive the reflected signal, thereby mitigating the impacts of temporal decorrelation. The experimental data utilized in this study were systematically acquired over the area demarcated by the red solid line in Figure 2b, with the key acquisition parameters detailed in Table 1.

The Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) was launched by NASA in September 2018. It features a single-photon LiDAR system that accurately measures the height of ice sheets, plants, land surfaces, and bodies of water on Earth [27,28]. For this study, the ATL08 product is employed, which provides independent canopy height measurements. In addition, the terrain elevation measurements contained in ATL08 serve as complementary reference data for evaluating the sub-canopy topography inversion results,

particularly in areas where LiDAR coverage is unavailable. Through this complementarity, both forest height and the final ground elevation can be independently validated. As shown in Figure 2b, the blue dots indicate the spatial distribution of the ATL08 observations.

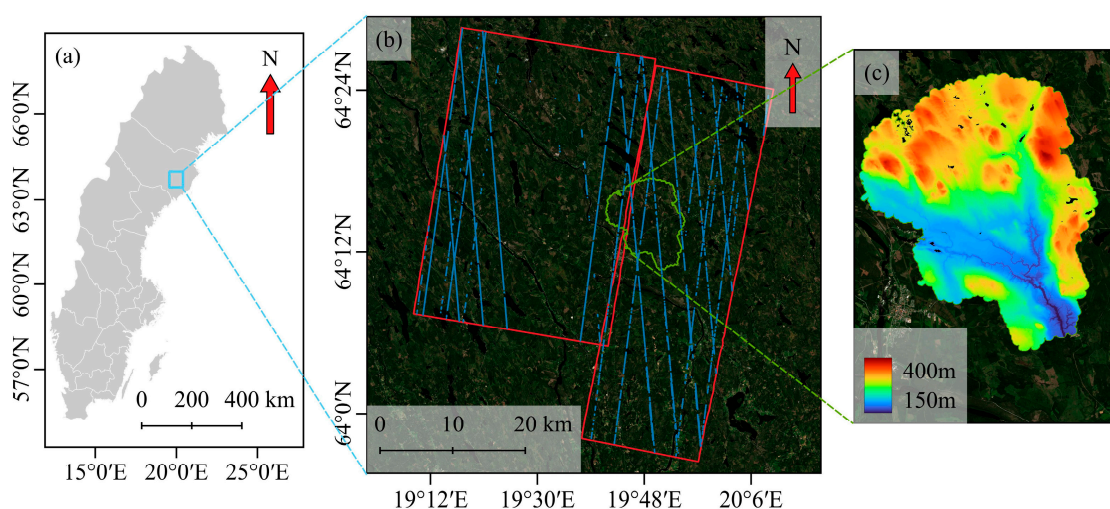


Figure 2. (a) Location of the study area in Sweden; (b) red frames indicate Test Area 1 (left) and Test Area 2 (right), the green line delineates the airborne LiDAR coverage, blue dots represent ICESat-2 data points; (c) airborne LiDAR DTM.

Table 1. Geometric parameters of TanDEM X CoSSC data.

Test Area	Test Area 1	Test Area 2
Acquisition date	21 June 2022, 2 July 2022, 24 July 2022, 4 August 2022	4 June 2022, 26 June 2022, 7 July 2022, 18 July 2022
Effective baseline (m)	157.21, 147.49, 130.31, 130.90	173.70, 143.87, 134.23, 130.38
Incidence angle (°)	51.67	44.12
Polarization mode	HH	HH

Airborne LiDAR sub-canopy topography data acquired by the Swedish Defence Research Agency (FOI) in 2006 were used as reference data for validation, with a spatial resolution of $12\text{ m} \times 12\text{ m}$. The spatial extent of this dataset is outlined by the green box in Figure 2b. Although the LiDAR dataset predates the TanDEM-X acquisitions (2022) by approximately 16 years, this temporal mismatch of ground surface is minor. This is mainly because the Krycklan catchment is located in a boreal forest environment characterized by slow geomorphological processes, limited soil disturbance, and low erosion rates, leading to a largely stable bare-earth surface over decadal timescales [29]. Consequently, the 2006 LiDAR dataset remains a reliable source for validating the sub-canopy topography. To conduct the pixel-by-pixel comparison, both the InSAR-derived sub-canopy topography and the original InSAR DEM are resampled to a spatial resolution of $12\text{ m} \times 12\text{ m}$.

3. Sub-Canopy Topography Inversion Method Based on Multi-Baseline TanDEM-X InSAR Observations

3.1. RVoG Model

The Random Volume over Ground (RVoG) model has been widely adopted for characterizing forest structures using PolInSAR data. It interprets forest parameters by complex coherence coefficients and has been effectively validated across a variety of forest types and environment conditions [25]. As shown in Figure 3, the RVoG model is basically a two-layer

scattering model. One layer represents a uniform, gapless forest canopy, and the other layer represents an impermeable ground layer [30,31]. It describes the wave scattering within the canopy using an exponential structure function with an attenuation coefficient that governs the signal penetration depth. For the X-band signals, the penetration distance through the canopy is small. As a result, the radar energy primarily reaches the ground through geometric gaps in the canopy rather than by volumetric penetration.



Figure 3. RVoG model for sub-canopy topography retrieval using InSAR. (a) Forest scenario; (b) Forest volume medium modeled by RVoG model; (c) Vertical structure function. In (b), the forest structure is modeled as a two-layer scattering volume, where z_0 denotes the ground elevation and $z_0 + h_v$ represents the height of the scattering volume. $f(z)$ indicates the radar reflectivity at different scattering heights, whose attenuation is governed by the extinction coefficient σ .

Based on the scattering principles of the model, it can be expressed as:

$$\tilde{\gamma} = e^{i\varphi_0} \frac{\tilde{\gamma}_v + \mu}{1 + \mu} \quad (1)$$

where $\tilde{\gamma}$ denotes the complex coherence; φ_0 is the ground surface phase; μ is the ground-to-volume amplitude ratio; and $\tilde{\gamma}_v$ represents the vegetation volume scattering decorrelation, which can be described by the Fourier relationship between the radar reflectivity vertical profile $f(z)$ and the vegetation height h_v :

$$\tilde{\gamma}_v = \frac{\int_0^{h_v} f(z) e^{ik_z z} dz}{\int_0^{h_v} f(z) dz} \quad (2)$$

$$f(z) = e^{\frac{2\sigma z}{\cos\theta}} \quad (3)$$

where θ denotes the incidence angle of radar wave, σ signifies the extinction coefficient, indicating the attenuation of radar waves within the vegetation canopy. During inversion, to align the forest parameters and enhance the intuitiveness of the attenuation process, the extinction coefficient can be transformed into the appropriate attenuation coefficient α . Therefore, $\tilde{\gamma}_v$ can be rewritten as:

$$\tilde{\gamma}_v = \frac{\alpha}{\alpha + ik_z} \frac{e^{\alpha h_v + ik_z h_v} - 1}{e^{\alpha h_v} - 1} \quad (4)$$

where k_z is the vertical effective wavenumber, which is expressed as:

$$k_z = \frac{4\pi B_{\perp}}{\lambda R \sin\theta} \quad (5)$$

where $B_{\perp}$ denotes the length of the perpendicular baseline, λ represents the radar wavelength, and R signifies the slant range.

3.2. Model Parameter Estimation

Inverting the parameters of the RVoG model using single-baseline data results in a rank deficit in the model solution due to inadequate observational information. To address this, a multi-baseline inversion technique is employed, wherein the model's unknowns are determined using the nonlinear least squares criterion:

$$F(\alpha, h_v, \mu) = \min_{\alpha, h_v, \mu} \sum_{i=1}^N \left\| \left| \tilde{\gamma}_{obs} \right|_i - \left| \tilde{\gamma}(\alpha, h_v, \mu) \right|_i \right\|^2 \quad (6)$$

where $F(\alpha, h_v, \mu)$ represents the objective function, with α, h_v, μ as the unknown parameters to be estimated; N denotes the number of interferometric baselines; $\left| \tilde{\gamma}_{obs} \right|_i$ signifies the coherence value measured for a specific baseline; and $\left| \tilde{\gamma}(\alpha, h_v, \mu) \right|_i$ is the coherence coefficient established by the RVoG model.

3.3. Initialization of Model Parameters

The ground-to-volume amplitude ratio, which measures the strength of surface scattering compared to vegetation volume scattering, critically impacts the performance of the RVoG model in retrieving sub-canopy topography. This study introduces a dimidiate pixel model to the SAR amplitude image to quantify the initial value of the ground-to-volume amplitude ratio. This approach assumes that the backscattering amplitude within each SAR pixel is characterized as a linear weighting combination of two distinct components ($\delta_{gr}^0, \delta_{veg}^0$) from vegetation canopy and bare ground. Note that the vegetation canopy and bare ground are two pure scenarios in a forest scene, and the corresponding backscattering intensities are also two end values of all radar returns. The magnitude of volume scattering intensity is related to the proportion (i.e., δ_η) of the canopy in a pixel, besides the SAR backscattering return from dense canopy. As a result, the ground-to-volume amplitude ratio is initially determined by the ratio of ground surface scattering amplitude (i.e., $\delta_{gr}^0 \cdot (1 - \delta_\eta)$) to volume scattering amplitude (i.e., $\delta_{veg}^0 \cdot \delta_\eta$), as shown in Equation (7). The proportion (i.e., δ_η) of the canopy can be approximately determined by two end values from the SAR-based dimidiate pixel model (i.e., Equation (8)).

$$\mu = \frac{\delta_{gr}^0}{\delta_{veg}^0} \cdot \frac{1 - \delta_\eta}{\delta_\eta} = \mu_0 \cdot \frac{1 - \delta_\eta}{\delta_\eta} \quad (7)$$

$$\delta_\eta = \frac{\delta_i - \delta_{gr}^0}{\delta_{veg}^0 - \delta_{gr}^0} \quad (8)$$

where δ_{gr}^0 represents pure surface scattering intensity, δ_{veg}^0 denotes pure vegetation volume scattering intensity, and δ_i refers to the SAR amplitude information. The intermediate variable μ_0 in Equation (7) describes the ratio of pure ground surface scattering intensity to the pure volume scattering intensity.

Meanwhile, a penetration depth model [32] is employed to estimate the initial values of forest height and attenuation coefficient.

$$\left| \tilde{\gamma} \right| = \left| \frac{1}{1 + ik_z d} \right| \quad (9)$$

where d represents the penetration depth, which characterizes the effective penetration capability of the radar signal through the vegetation layer [32].

To enable an effective inversion of forest parameters, reasonable initial values of the forest height (h_v) and the attenuation coefficient (α) must first be obtained. In this study, the radar wave penetration depth is used as the basis for estimating the initial values of h_v and

α . Theoretically, when the ratio of forest height to penetration depth is greater than or equal to 2, the forest volume layer can be considered as a semi-infinite medium [33,34]. In the boreal forest area, the sparse canopy allows the radar signal to propagate more deeply, and ground surface and volume scattering often coexist, resulting in a greater penetration depth. This study empirically adopts $1.5d$ as a more realistic initial estimate of forest height [26,32]. In addition, $\alpha = 1/d$ is set as the initial value for the attenuation coefficient.

The above three initial values are then substituted into Equation (6), and a nonlinear least-squares optimization is performed to solve model parameters.

3.4. Sub-Canopy Topography Inversion Method

Due to the penetration capability of the SAR signal and its interaction with multiple scatterers distributed throughout the forest canopy, InSAR measures the elevation of the scattering phase center, which represents the integrated backscattering contribution from multiple scatterers inside the forest. This elevation corresponds to the InSAR-derived DEM product. Therefore, retrieving the actual sub-canopy topography information requires the removal of the forest scattering contribution from the InSAR DEM. At the X-band frequencies, the radar signal exhibits a limited penetration depth within the canopy, corresponding to a high extinction coefficient. Under this condition, the scattering phase center model can be simplified as follows:

$$h_{pch} = \frac{\arg(\tilde{\gamma})}{k_z} \quad (10)$$

For X-band InSAR measurements, the scattering phase center is located near the top of the forest canopy, as the backscattered signal is dominated by contributions from the canopy layer. This phenomenon is consistent with the Random Volume over Ground (RVoG) model under the condition of negligible ground penetration, where the canopy is treated as a random volume. By substituting the forest parameters obtained from the nonlinear least-squares criterion into the backscattering model (Equation (10)), the height of the scattering phase center can be derived.

The actual sub-canopy topography is obtained as follows:

$$h_{sct} = h_{InSAR\ DEM} - h_{pch} \quad (11)$$

where $h_{InSAR\ DEM}$ denotes the InSAR-derived DEM elevation and h_{pch} is the scattering phase center height.

4. Preprocessing, Experimental Results and Analysis

4.1. Preprocessing

To ensure an accurate estimation of the interferometric sensitivity to height, the k_z must be corrected for terrain slope before performing forest parameter inversion. Because the actual ground surface is undulating, the effective vertical wavenumber shifts with changes in the radar incidence angle when terrain slope is present [35]. Accordingly, the slope-corrected vertical wavenumber can be expressed as:

$$k_z^{corr} = \frac{4\pi B_{\perp}}{\lambda R \sin(\theta - \beta_s)} \quad (12)$$

where β_s is the terrain slope angle in the range direction. The slope information is derived from a TanDEM-X DEM with a resolution of $90\text{ m} \times 90\text{ m}$. In practice, a first-order difference operation is applied to the DEM along the range direction to obtain elevation differences between adjacent range pixels. These elevation differences are then converted into the range-direction terrain slope for each pixel. Finally, the slope correction is implemented

by using the range-direction slope to correct the incidence angle in the vertical effective wavenumber k_z [9,32]. By applying slope correction to k_z , the inversion model can more accurately represent the true geometric configuration of each pixel. Using the corrected vertical wavenumber k_z^{corr} not only enhances the physical consistency of the inversion process, but also effectively reduces systematic errors in sub-canopy topography retrieval.

The ground-to-volume amplitude ratio quantifies the comparative intensity of ground surface scattering over vegetation volume scattering. This ratio can be derived from SAR backscattering amplitudes (which refer to the DN value of a SAR image). Accurate initialization of pure ground surface and pure volume scattering contributions is essential for precise parameter retrieval. It is assumed that these pure scattering contributions remain invariant within a given test region. In practice, representative sub-regions of bare ground (dominated by ground surface scattering) and dense forest (dominated by volume scattering) are identified across the study area according to the synchronous optical remote sensing images. The backscattering intensity distributions for these sub-areas are statistically analyzed using a Gaussian statistical distribution. In accordance with the dimidiate pixel model, and to minimize the impact of outliers, the pure surface scattering contribution is set as the mean minus two standard deviations (i.e., $\rho - 2\delta$) of the fitted Gaussian distribution [26]. In contrast, the pure volume scattering contribution is defined as the mean plus two standard deviations (i.e., $\rho + 2\delta$), as depicted in Figure 4. This method encompasses roughly 95% of the data, thereby augmenting the reliability of the estimation.

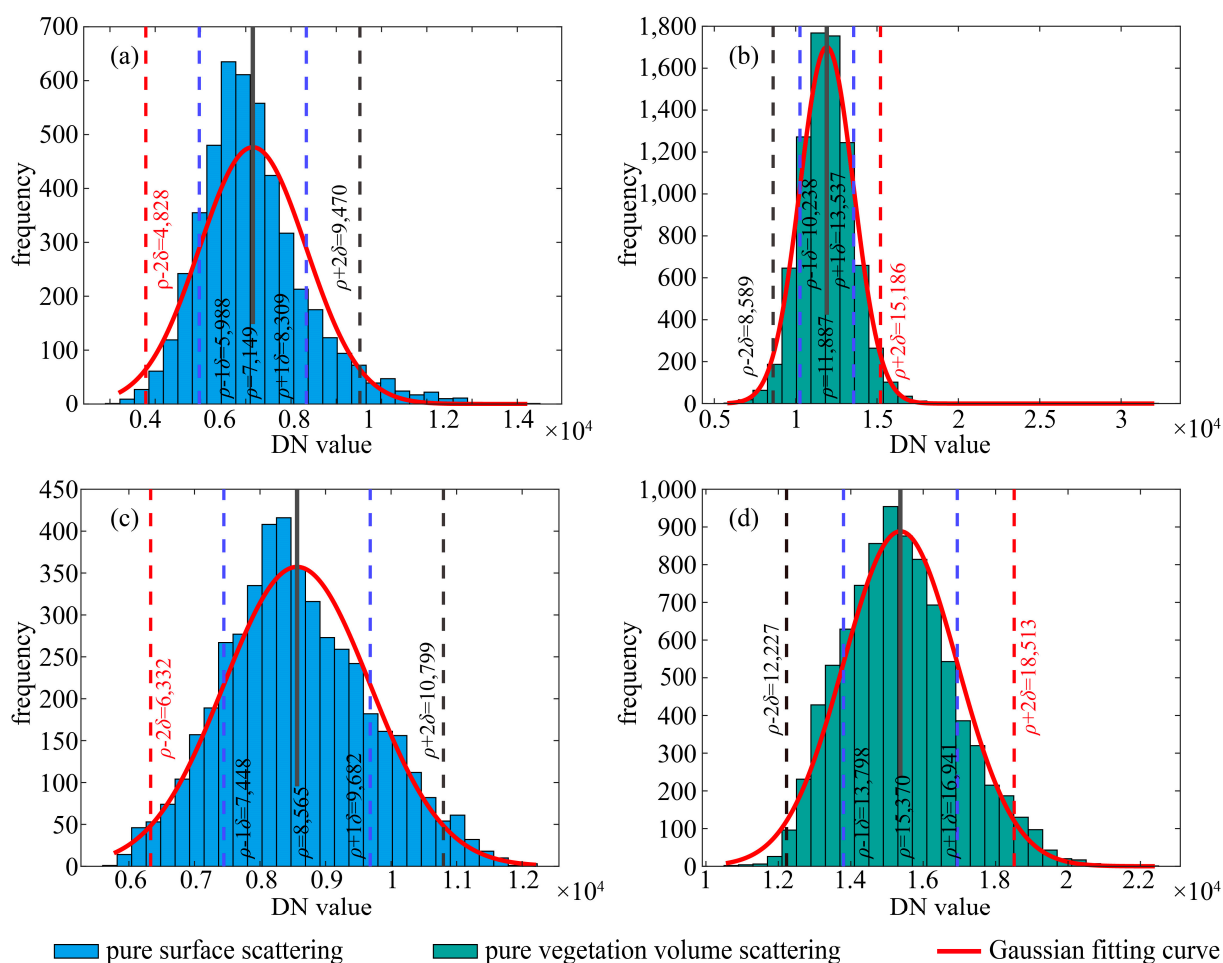


Figure 4. Gaussian distributions of the backscattering amplitudes for pure surface scattering and pure volume scattering. (a) Pure surface scattering in Test Site 1; (b) Pure volume scattering in Test Site 1; (c) Pure surface scattering in Test Site 2; (d) Pure volume scattering in Test Site 2.

4.2. Forest Canopy Height Inversion Results

The estimated forest canopy height in the two test sites is shown in Figure 5a. Herein, the fractional vegetation cover (FVC) map (see Figure 5b) is also provided to illustrate the heterogeneity of the vegetation distribution. Through visual inspection, we found that there is a certain correlation between the estimated forest distribution and the extent of FVC. But it is worth noting that, due to the presence of young forests and crops, a higher value of FVC does not necessarily mean that the corresponding forest height is also higher.

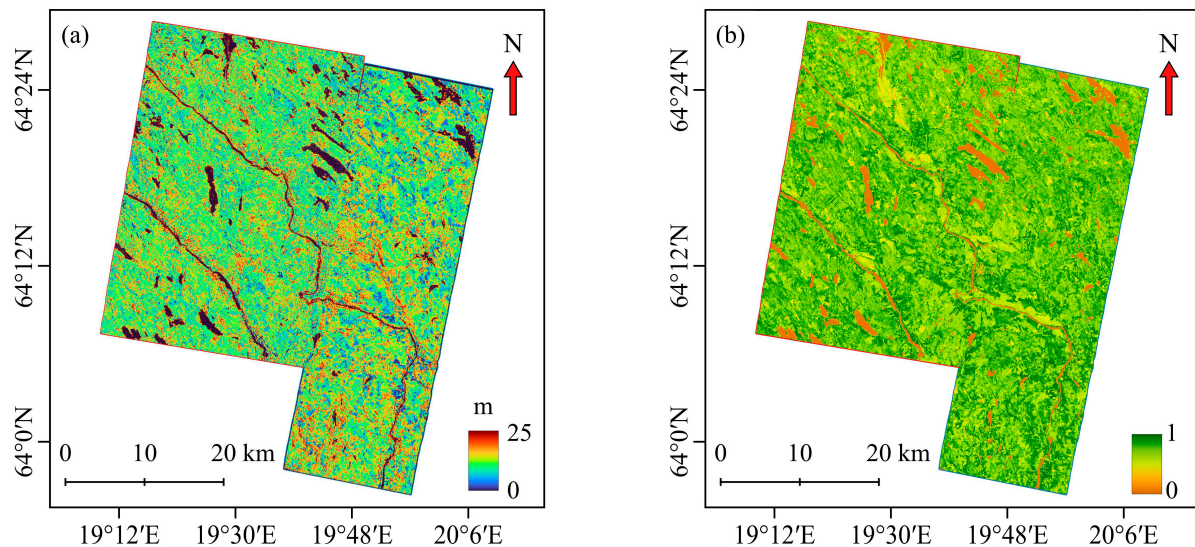


Figure 5. (a) Estimated forest canopy height map in the two test sites. (b) Fractional vegetation cover map (calculated by the Sentinel-2 image acquired on 23 July 2022) in the two test sites.

The cross-validation scatter plot in Figure 6 compares the estimated forest height (from Test Areas 1 and 2) against ICESat-2 canopy height measurements. Overall, the scatter points are primarily distributed near the diagonal, indicating a certain level of consistency between the two datasets. However, the points also exhibit noticeable dispersion, reflecting residual variability between the estimates. The mean error (MEAN) in Test Area 1 is 0.19 m, the RMSE is 5.45 m, and the coefficient of determination (R^2) is 0.444. The corresponding values in Test Area 2 are 0.65 m, 4.44 m, and 0.637, respectively. These results provide further evidence supporting the applicability of the RVoG-based multi-baseline method in the Krycklan test area. The accuracy statistics demonstrate the method's capability for reliable forest height estimation, which serves as a critical foundation for the subsequent retrieval of sub-canopy topography.

4.3. Sub-Canopy Topography Inversion Results

Estimated sub-canopy topography in the two test sites is displayed in Figure 7. The uneven terrain and small hills are clearly visible. To further demonstrate the removal efficiency of the scattering phase center height and the reliability of the estimated sub-canopy topography, four profiles were selected, as shown in Figure 7a,b. High-resolution airborne LiDAR terrain elevation data were utilized for localized accuracy assessment. Figure 8 shows four selected elevation profile maps from InSAR DEM (including the scattering phase center height) and estimated and airborne LiDAR-measured sub-canopy topography. Obviously, significant differences between the InSAR-derived sub-canopy topography (or airborne LiDAR-measured sub-canopy topography) and the original InSAR DEM are found, demonstrating the feasibility of subtracting the scattering phase center height from the InSAR DEM. In addition, the sub-canopy topography retrieved by the

proposed method shows close agreement with the airborne LiDAR terrain measurements in most areas. This indicates that the proposed method is effective for reconstructing sub-canopy topography.

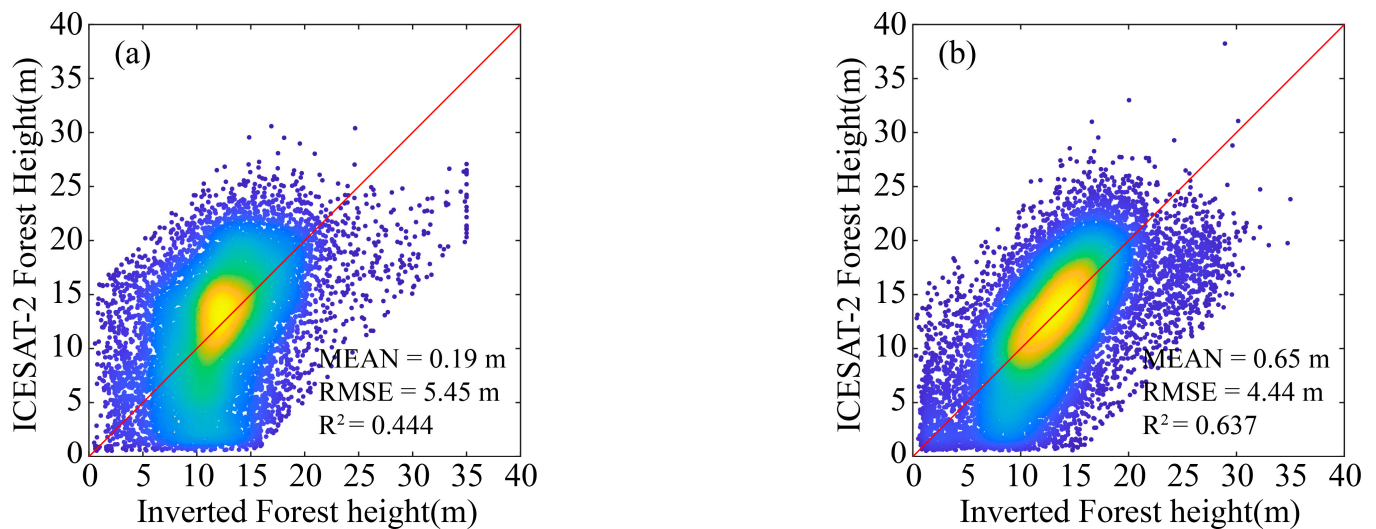


Figure 6. Cross-validation between RVoG-modeled forest height and ICESat-2 canopy height measurements: (a) Test Area 1. (b) Test Area 2. The solid red line denotes the 1:1 reference line.

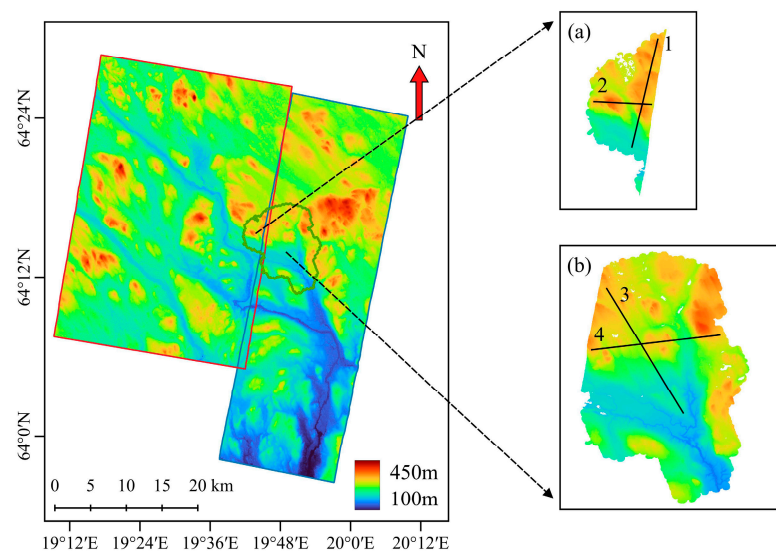


Figure 7. Sub-canopy Topography inversion results and the airborne LiDAR-covered area delineated by the green line. (a) Airborne LiDAR-covered area in Test Area 1; (b) airborne LiDAR-covered area in Test Area 2. Black lines in the two sub-figures are the selected elevation profiles.

To evaluate the accuracy of the estimated sub-canopy topography, the inversion results were validated against reference ground elevations derived from ICESat-2 and airborne LiDAR, as shown in Figure 9. The correlation coefficients between the inversion results and both reference datasets are 0.99, indicating highly consistent topographic representation. Figure 9 shows that the sub-canopy topography inversion results in Test Area 1 and Test Area 2 are more accurate than the original InSAR DEM. This confirms that the proposed multi-baseline InSAR method effectively eliminates the scattering phase center height, obtaining elevation information that more closely approximates the actual ground.

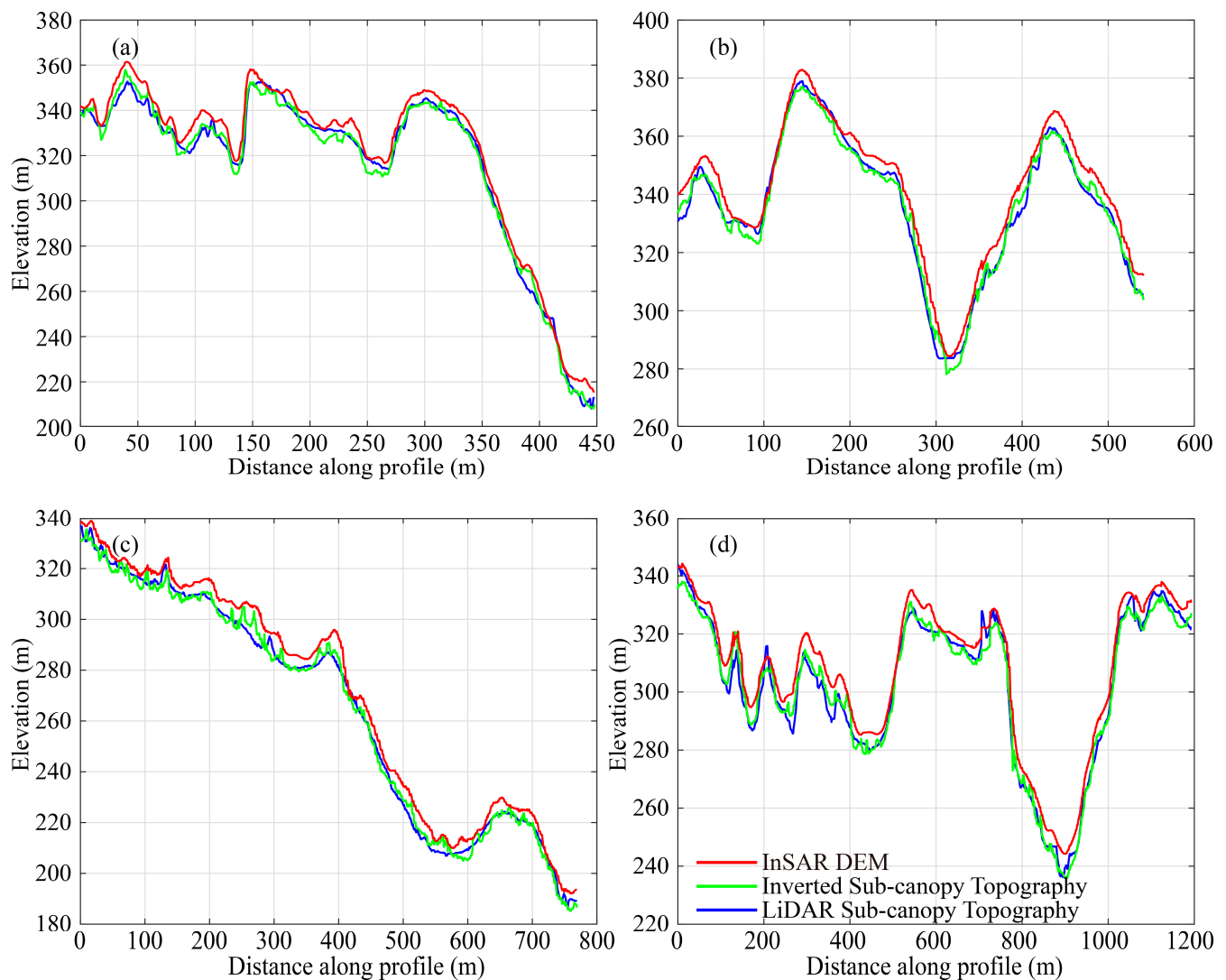


Figure 8. Elevation profiles including InSAR DEM, inverted sub-canopy topography and airborne LiDAR sub-canopy topography. (a–d) Profiles 1–4.

To quantitatively assess the efficacy of the proposed sub-canopy topography inversion technique, as seen in Figure 9a,b,e,f, the InSAR DEM was cross-validated against two validation datasets. The proposed inversion method markedly enhanced the accuracy of the results compared to the ICESat-2 surface elevation. For the two test sites, the MEAN error decreases from 3.32 m to −1.50 m and from 3.74 m to −0.76 m, respectively. The RMSE is reduced from 5.01 m to 3.94 m and from 4.74 m to 3.13 m, corresponding to improvements of 21.4% and 34.0%. Relative to the airborne LiDAR ground elevations, the inversion results also exhibit significantly improved accuracy: the MEAN error decreases from 3.78 m to −0.88 m and from 4.62 m to 0.13 m, while the RMSE decreases from 5.43 m to 3.82 m and from 5.72 m to 3.47 m, yielding improvements of 29.6% and 39.3%, respectively. These results indicate that the proposed sub-canopy topography inversion method demonstrates the method's efficacy in mitigating elevation biases induced by vegetation scattering and its strong capability to recover accurate sub-canopy topography.

In addition, an examination of the validation datasets shows that ICESat-2 ground elevations are, on average, approximately 0.6 to 0.9 m higher than those derived from airborne LiDAR. This systematic bias primarily arises from differences in data acquisition characteristics and canopy-penetration capability [36,37].

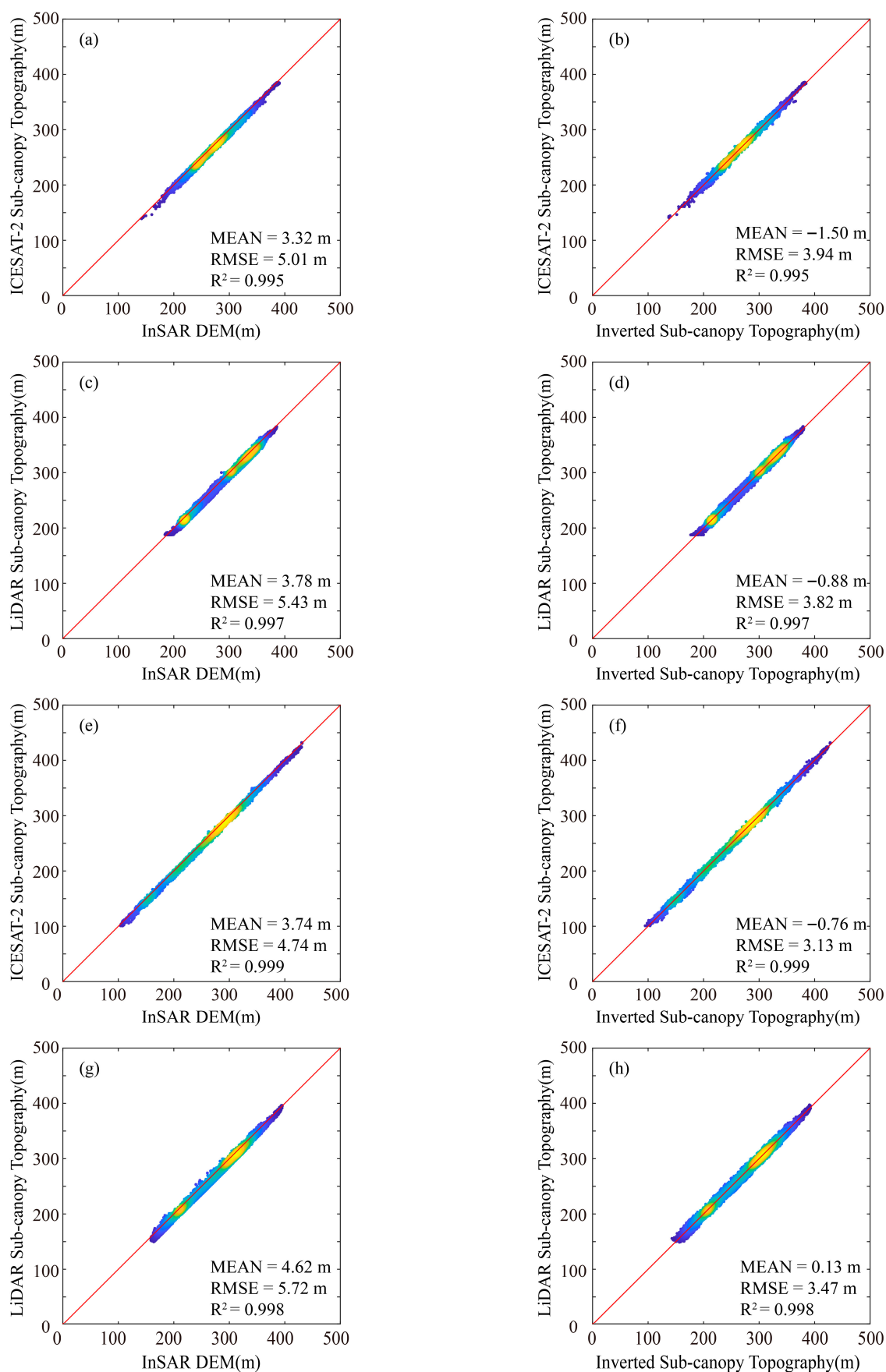


Figure 9. Cross-validation of InSAR DEM and sub-canopy topography inversion results using ICESat-2 and airborne LiDAR surface elevation. (a–d) Test Area 1. (e–h) Test Area 2.

5. Discussion

5.1. Impact of Baseline Configuration on Sub-Canopy Topography Inversion

As mentioned above, the multi-baseline technique can enhance the convergence and reliability of model inversion by providing multiple observations [25,26]. However, we aim to investigate the influence of different interferometric combinations on the inversion results under the condition of limited observations. In our proposed method, three parameters (i.e., forest height, ground-to-volume amplitude ratio, and attenuation coefficient) must be initially determined. During the parameter estimation, at least three independent equations must be formulated, necessitating three interferometric observations. To address this, this study utilized four available interferometric configurations in Test Areas 1 and 2, conducting inversions across five different baseline combinations (or groups) for each area to ensure robustness. L1–L5 and R1–R5 denote different multi-baseline configurations for Test Area 1 and Test Area 2, respectively, as listed in Table 2.

Table 2. Different multi-baseline combinations in two test areas.

Test Area		Group	VBLD
Test Area 1	Three-baseline combination	L1: 21 June 2022, 2 July 2022, 24 July 2022	26.90
		L2: 21 June 2022, 2 July 2022, 4 August 2022	26.31
		L3: 21 June 2022, 24 July 2022, 4 August 2022	26.90
		L4: 2 July 2022, 24 July 2022, 4 August 2022	17.18
	Four-baseline combination	L5: 21 June 2022, 2 July 2022, 24 July 2022, 4 August 2022	26.90
Test Area 2	Three-baseline combination	R1: 4 June 2022, 26 June 2022, 7 July 2022	39.47
		R2: 4 June 2022, 26 June 2022, 18 July 2022	43.32
		R3: 4 June 2022, 7 July 2022, 18 July 2022	43.32
		R4: 26 June 2022, 7 July 2022, 18 July 2022	13.49
	Four-baseline combination	R5: 4 June 2022, 26 June 2022, 7 July 2022, 18 July 2022	43.32

Through constructing multiple baseline combinations (L1–L5 and R1–R5), this study adopted a comparative evaluation strategy using two independent validation datasets (ICESat-2 and airborne LiDAR). As shown in Figure 10, the inversion accuracies (e.g., the MEAN and STD) are relatively close, except for the L4 combination in Test Area 1 and the R4 combination in Test Area 2. Both exhibit notably higher STD values than the other baseline combinations within the same test area. Herein, we calculated the difference between the maximum and minimum vertical baseline length in each interferometric combination, referring to the VBLD in Table 2. We can find that the worst inversion performance from the L4 or R4 combination is probably related to the smaller VBLD, rather than the number of interferometric observations. In addition, two test sites contain almost identical forest scenes and types, and both belong to the Krycklan forest region. The VBLD in Test Area 2 is larger than that in Test Area 1; this can also be regarded as one of the main reasons why the inversion accuracy of the sub-canopy topography in Test Area 2 is higher than that in Test Area 1. Therefore, from the perspective of InSAR geometry, the stability of multi-baseline InSAR RVoG-aided inversion largely depends on the diversity of effective baseline geometries, particularly the difference between the maximum and minimum vertical baseline length. Note that, due to the limited observations or similar interferometric geometry, this study cannot provide the selection criteria for the optimal baseline combination, which needs to be further researched.

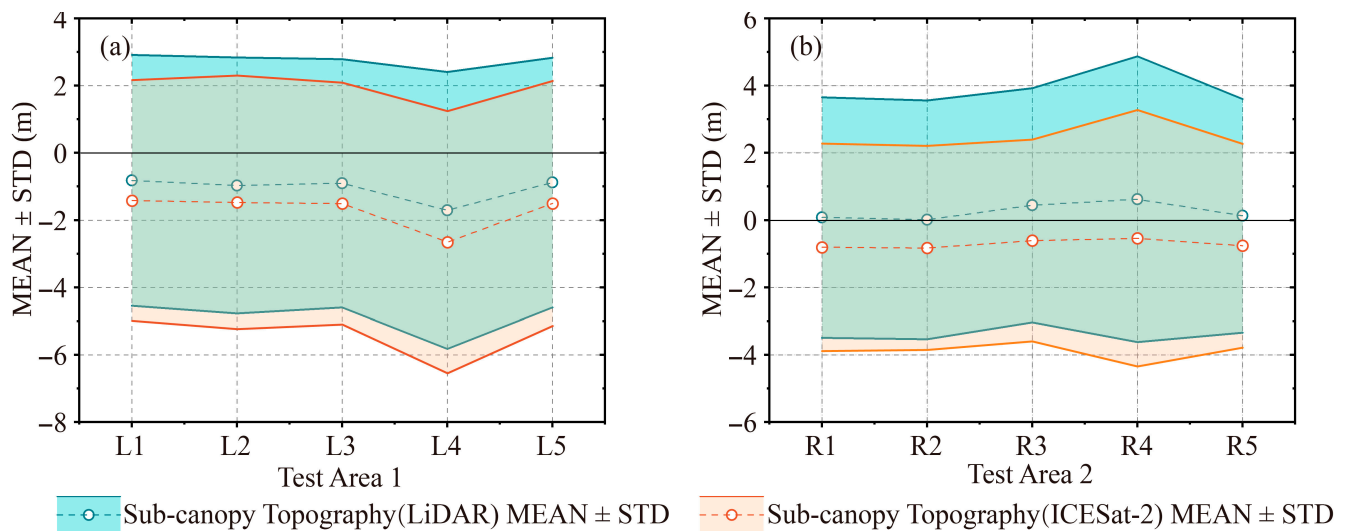


Figure 10. Accuracy evaluation of inverted sub-canopy topography under different baseline combinations: (a) Test Area 1; (b) Test Area 2.

5.2. Influence of Differences Between Pure Surface and Pure Volume Scattering Contributions on Sub-Canopy Topography Retrieval

Due to the influence of factors such as grassland, low vegetation, and water content, selected sub-regions from bare ground (or dense forest) may not be entirely dominated by pure ground surface scattering (or pure volume scattering). As a result, the statistical values (e.g., expectation and standard deviation) of these backscattering amplitudes are biased. To further investigate the potential influence of the bias on the inversion results, this study constructs a simulated dataset by supposing different pure surface scattering and pure volume scattering amplitudes, as shown in Table 3.

According to the analysis in Section 4.1, the scattering contributions were parameterized for simulation by sampling from a Gaussian distribution. The surface scattering contribution was set as $\rho - 2\delta$, whereas the volume scattering contribution was set as $\rho + 2\delta$. Table 3 lists various scattering combination scenarios designed to produce a series of simulated samples with varying scattering contributions. This dataset was subsequently utilized to assess the influence of scattering contribution variation on the precision of estimated sub-canopy topography.

As validated by airborne LiDAR and ICESat-2 data (Figure 11), the inversion accuracy embodies consistent trends in both test areas. The RMSE under diverse scattering settings shows considerable stability, suggesting that variations in scattering contributions do not dramatically elevate the dispersion of results. This indicates that the RVoG model efficiently mitigates scattering noise across various predominant scattering circumstances. The retrieval outcomes exhibit minimal sensitivity to fluctuations in scattering contributions, further validating the model's stability and generalization capacity. In Test Area 1, groups Z9, Z10, and Z11, and in Test Area 2, groups Y1, Y2, and Y3, demonstrate improved mean retrieval accuracy, suggesting that the optimal range of pure surface scattering contributions is between 6500 and 7000 in both test areas. The range of pure volume scattering contributions (i.e., DN values) is approximately 12,000 to 14,000 in Test Area 1 and 15,500 to 17,500 in Test Area 2. Although the two test sites are geographically adjacent, their forest parameters—such as canopy density, vertical vegetation structure, and ground visibility—still present noticeable differences at local scales. These variations result in marked spatial heterogeneity in the optimal ranges of pure scattering contributions.

Table 3. Parameterization and Configuration of Simulated Pure Surface and Pure Volume Scattering Contributions for Sub-canopy Topography Inversion.

Test Area	Group	Pure Surface Scattering Contribution	Pure Volume Scattering Contribution
Test Area 1	Z1	5000	12,000
	Z2	5000	13,000
	Z3	5000	14,000
	Z4	5000	15,000
	Z5	6000	12,000
	Z6	6000	13,000
	Z7	6000	14,000
	Z8	6000	15,000
	Z9	7000	12,000
	Z10	7000	13,000
	Z11	7000	14,000
	Z12	7000	15,000
Test Area 2	Y1	6500	15,500
	Y2	6500	16,500
	Y3	6500	17,500
	Y4	6500	18,500
	Y5	7500	15,500
	Y6	7500	16,500
	Y7	7500	17,500
	Y8	7500	18,500
	Y9	8500	15,500
	Y10	8500	16,500
	Y11	8500	17,500
	Y12	8500	18,500

5.3. Applicability Analysis of RVoG-Based Sub-Canopy Topography Retrieval Under Different Vegetation Densities

The density of the boreal forest environment is considered to be inhomogeneous, which leads to complex electromagnetic scattering processes even though X-band SAR signals are used. As a result, the RVoG model that considers both ground surface and vegetation volume scattering was adopted in this study. However, the applicability of our proposed multi-baseline InSAR method in different forest densities is not explored. For this, the forest density characterized by the FVC values is divided into five intervals with 0.2 for investigation. The validation results from ICESat-2 and airborne LiDAR reference data are listed in Table 4. Note that the evaluation range of ICESat-2 data is the whole test site, while that of airborne LiDAR data is its coverage area.

From Table 4, when the FVC is within the range of 0 to 0.6, the validation accuracies of ICESat-2 and airborne LiDAR data embody considerable uncertainties. But when the FVC is within the range of 0.6 to 1, all validation accuracies of ICESat-2 and airborne LiDAR data are better. Especially within the interval of 0.6 to 0.8, their RMSEs range from 3.76 m to 2.92 m, and their MEANs are also smaller with a magnitude of -0.48 m to 0.31 m. This may be related to the assumption and modeling of a uniform and gapless two-layer volume in the RVoG model. When the FVC is less than 0.6, the radar observation scene changes from nearly bare ground areas to vegetated regions with moderate coverage. At this time, although radar–target interactions shift from being dominated by ground surface scattering to the coexistence of surface scattering and volume scattering, the forest layer is not continuous. In such a case, the radar observation scene does not match the RVoG modeling. When the FVC is greater than 0.6 or even larger, the forest layer tends to be continuous, and the RVoG model is more applicable. But noting that, the FVC falls into the

interval of 0.8 to 1, the volume scattering increases, whereas the ground surface scattering gradually weakens. As a result, the inversion results decrease.

In summary, the applicability of the RVoG model for sub-canopy topography retrieval in boreal forests is dependent on different FVC classes. It is a reminder that the uncertainty of inverted sub-canopy topography arises from the combined effects of vegetation structural heterogeneity and the physical penetration limitations of X-band SAR, rather than a single factor.

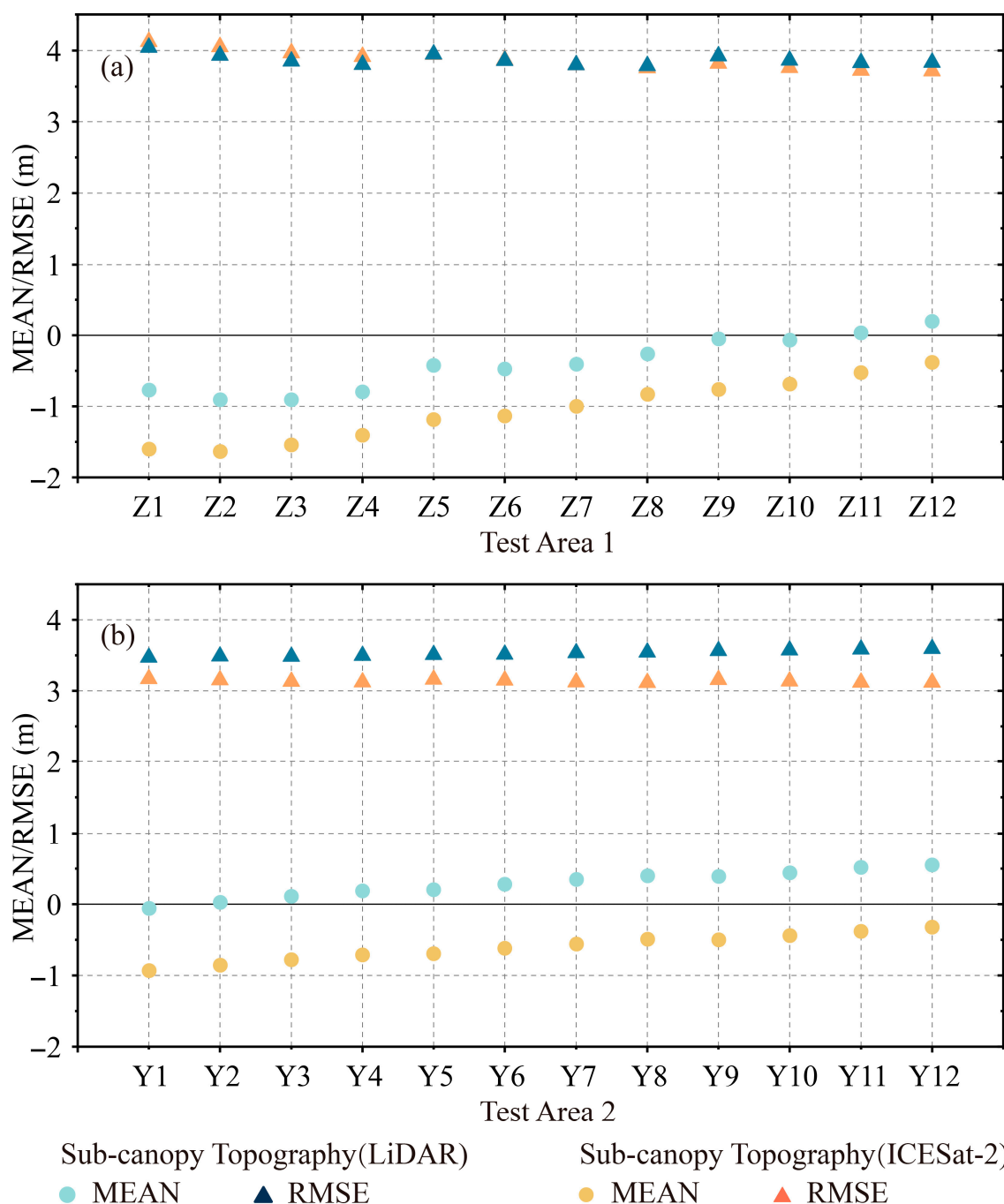


Figure 11. Accuracy assessment of the sub-canopy topography retrieval under different scattering contribution conditions. (a) Test Area 1 and (b) Test Area 2.

Table 4. ICESat-2 and LiDAR validation of estimated sub-canopy topography corresponding to different FVC classes for Test Area 1 and Test Area 2.

Test Area	FVC Class	ICESat-2			LiDAR		
		Numbers	MEAN	RMSE	Numbers	MEAN	RMSE
Test Area 1	[0, 0.2)	81	−3.20	5.76	8264	−0.64	3.14
	[0.2, 0.4)	112	−3.66	4.94	2894	−3.40	5.33
	[0.4, 0.6)	543	−2.47	4.53	19,333	−0.63	4.30
	[0.6, 0.8)	6042	−0.37	3.72	123,230	0.01	3.76
	[0.8, 1]	4853	−2.71	4.08	86,664	−2.13	3.78
Test Area 2	[0, 0.2)	63	−1.08	3.03	3273	−0.33	3.69
	[0.2, 0.4)	88	0.92	3.82	13,376	2.05	4.75
	[0.4, 0.6)	694	0.70	3.77	89,648	2.20	4.54
	[0.6, 0.8)	7663	−0.48	2.92	619,080	0.31	3.47
	[0.8, 1]	7894	−1.11	3.09	414,740	−0.65	3.16

6. Conclusions

This study proposes a multi-baseline InSAR framework for sub-canopy topography retrieval, extending the applicability of the RVoG model to bistatic single-polarization observations. Unlike conventional RVoG-based approaches, which typically rely on fully polarimetric SAR data and external vegetation products, the proposed method enables sub-canopy terrain extraction by reformulating the parameter initialization and constraint strategy within the RVoG inversion process. Specifically, a SAR-based dimidiate pixel model is introduced to initialize the ground-to-volume scattering ratio, while a coherence-driven penetration depth model is employed to estimate the initial forest structural parameters. As a result, all initial RVoG parameters are derived solely from the intrinsic InSAR observations, substantially reducing the dependence on auxiliary external datasets. Moreover, the use of multi-baseline interferometric observations effectively compensates for the lack of polarimetric information in single-polarization data, while alleviating the rank-deficiency problem inherent in single-baseline RVoG inversion through enhanced geometric diversity.

Experimental results over the Krycklan boreal forest test site suggest that the proposed method can achieve stable sub-canopy topography retrieval, with the derived results exhibiting good agreement with both ICESat-2 and airborne LiDAR reference data. The analysis further indicates that baseline geometric diversity contributes to improved inversion accuracy and robustness. Nevertheless, the performance in extremely dense forest areas is still constrained by the limited penetration capability of X-band SAR, and the empirical separation of surface and volume scattering may introduce additional uncertainties in complex forest structures. Overall, this study provides an alternative framework for terrain mapping in forested environments, while further enhancing the accuracy of sub-canopy topography retrieval remains an important topic for future research.

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Data Availability Statement: Data Availability Statement: The ICESat-2 data used in this article can be downloaded for free or ordered through the following link: <https://nsidc.org/data/data-access-tool/ATL08/versions/6> (accessed on 3 June 2025). The TanDEM-X data can be obtained from the German Aerospace Center (DLR). The LiDAR data can be obtained from the Swedish Defence Research Agency (FOI).

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