

# The Potential of HT-1 Spaceborne InSAR for Forest Vertical Structure Inversion

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## Abstract

Spaceborne multi-baseline interferometric synthetic aperture radar (InSAR) provides an effective solution for large-scale forest vertical structure inversion. The Hongtu-1 (HT-1) satellite, using a four-satellite cartwheel formation, enables single-pass multi-baseline acquisition and avoids temporal decorrelation. In this study, a complete interferometric processing workflow for HT-1 data is developed, including orbit correction, interferometric registration, phase correction, and tomographic calibration. Forest vertical structure is reconstructed using Capon-based tomography and compared with the single-baseline Phase Histogram (PH) technique. Experiments are conducted in Gabon using four HT-1 SAR images, with airborne LiDAR data for validation. The results show that both methods can retrieve forest vertical structure, while Capon provides more continuous profiles and higher accuracy. Capon achieves an RMSE of 5.43 m, outperforming the 6.49 m of PH. This confirms the feasibility of HT-1 for spaceborne tomography and its potential for forest vertical structure inversion, suggesting that such multi-baseline systems are worth promoting in future satellite missions.

## 1. Introduction

Forests play a critical role in the global carbon cycle, acting as both carbon sources and sinks within the Earth's biosphere. As a core parameter describing ecosystem function and health, forest vertical structure is essential for biomass estimation, carbon cycle modelling and ecological conservation. Therefore, achieving high-precision, large-scale inversion and dynamic monitoring of forest vertical structure is of significant research value. Compared with optical imagery, which has limited penetration, and LiDAR, which provides discrete sampling, interferometric synthetic aperture radar (InSAR) offers several advantages. Its all-weather, all-day observation capability, strong penetration, and wide-swath coverage make it a powerful tool for forest vertical structure inversion.

Current inversion methods mainly include the single-baseline Phase Histogram (PH) technique and multi-baseline TomoSAR. The PH technique approximates vertical backscattering profiles by assigning pixels to discrete height layers based on phase-to-height conversion (Shiroma and Laval 2020). However, it is only an approximation and has difficulty getting continuous, high-resolution vertical structure. In contrast, TomoSAR uses multi-baseline observations to form a synthetic aperture in the elevation direction, enabling the retrieval of continuous vertical reflectivity profiles and fine three-dimensional reconstruction (Reigber, Moreira et al. 1999). Although PH has been validated with both airborne and spaceborne LT-1 SAR data, its agreement with LiDAR waveforms is still limited, and its profiles lack continuity (Wu, Tebaldini et al. 2024). TomoSAR achieves higher inversion accuracy, but most existing studies are based on airborne platforms, which limits its application to large-scale forest structure and biomass mapping. Therefore, developing TomoSAR methods suitable for spaceborne platforms is important.

Spaceborne TomoSAR is one of the most promising techniques for large-scale forest structure and biomass mapping. Traditional spaceborne TomoSAR typically relies on repeat-pass observations to acquire multi-baseline data. However, this mode faces significant challenges in forest areas. Temporal

decorrelation reduces interferometric coherence, which may defocus tomographic spectra or even lead to failure in vertical structure reconstruction. In addition, atmospheric delay differences between acquisitions will further reduce imaging accuracy and affect the reliability of inversion results. Therefore, conventional repeat-pass TomoSAR is difficult to apply in forest areas with significant temporal changes.

In contrast, the HT-1 spaceborne SAR system employs a four-satellite cartwheel formation to enable simultaneous multi-baseline data acquisition in a single-transmit and multiple-receive mode (Deng, Zhang et al. 2025), as shown in Figure 1. This configuration offers two key advantages. First, simultaneous multi-station observations remove temporal decorrelation, thereby significantly improving interferometric coherence. Second, since all satellites image at the same time, atmospheric delays are effectively cancelled during interferometry, which enhances tomographic accuracy. These features provide favourable data conditions for applying spaceborne TomoSAR to forest vertical structure inversion.

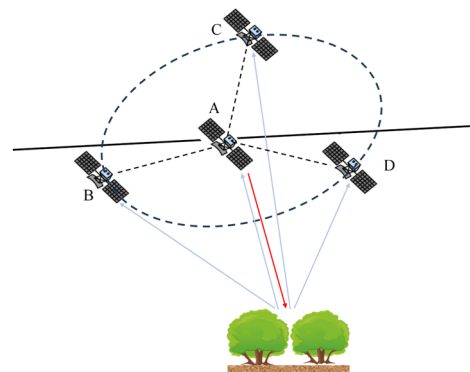


Figure 1. Configuration of HT-1 Cartwheel satellite system

Based on these features, this study uses HT-1 multi-baseline data and builds a complete interferometric processing workflow for spaceborne multi-baseline SAR. Tomographic processing is then applied to spaceborne data to achieve high-precision forest vertical structure inversion. The results are compared with those

obtained using the PH technique to evaluate tomographic performance of HT-1 and provide a technical reference for large-scale forest vertical structure inversion using spaceborne SAR.

## 2. Theoretical Foundation

### 2.1 HT-1 Multi-baseline Data Processing

The HT-1 constellation was successfully launched on March 30, 2023, from Taiyuan. It consists of four X-band SAR satellites arranged in a cartwheel formation. The primary satellite (HT-1A), handles both transmission and reception, while the three auxiliary satellites (HT-1B, HT-1C, and HT-1D) operate only as receivers. With a near-zero temporal baseline between the primary and auxiliary images, this configuration effectively minimizes atmospheric disturbances and temporal decorrelation, thereby improving inversion accuracy for forest vertical structure. The processing workflow for HT-1 data can be organized into four main stages based on the procedures shown in Figure 2.

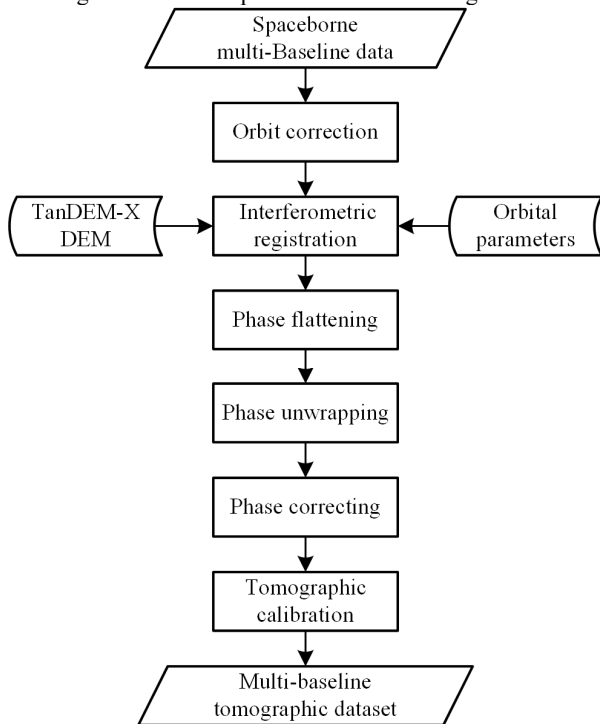


Figure 2. Process of HT-1 multi-baseline data

#### Step 1: Orbit correction and interferometric registration.

Since the original single-look complex (SLC) data have coarse orbits, orbit correction is first performed using external high-resolution optical imagery to improve geometric positioning accuracy. A coarse-to-fine registration strategy is employed: initial offsets are estimated from orbital parameters for coarse registration, followed by fine registration based on coherence coefficients to estimate sub-pixel offsets. The coherence coefficient is calculated as:

$$|v| = \frac{\left| \sum_{p=1}^N M_p S_p^* \right|}{\sqrt{\sum_{p=1}^N |M_p|^2 \sum_{p=1}^N |S_p|^2}} \quad (1)$$

where  $M_p$  and  $S_p$  are the pixel values of the master and slave images within the estimation window. The slave images are then

resampled to align with the master image at the same ground locations, completing the registration process.

#### Step 2: Phase flattening and unwrapping.

Following registration, interferograms are generated through conjugate multiplication. An external digital elevation model (DEM), such as the TanDEM-X 30 m product, is then used to construct a topographic phase model. The DEM is transformed from geographic to radar coordinates based on rigorous geometric relationships to obtain the topographic interferometric phase. Differential processing then removes the flat-earth and topographic phases, getting an interferometric phase that contains primarily forest scattering contributions. Finally, a coherence-based minimum cost flow phase unwrapping algorithm is applied to obtain continuous phase information.

#### Step 3: Phase correction.

Spaceborne SAR orbits are generally stable, and the trajectories can be considered as linear over short acquisition intervals. However, due to limited positioning accuracy and slight baseline perturbations in the four-satellite formation, residual trend errors may still exist in the unwrapped phase. These errors can be approximated as a linear function of the azimuth and range pixel coordinates:

$$\Phi(x, y) = ax + by + c \quad (2)$$

where  $x$  and  $y$  represent the azimuth and range pixel coordinates, and  $a, b, c$  are parameters to be estimated. High-coherence pixels are then selected from the coherence map as control points and parameters are estimated using least-squares method. The resulting error surface is then used to compensate the phase. Residual low-frequency periodic errors can be further suppressed in the frequency domain to improve phase quality.

#### Step 4: Tomographic calibration.

After completing the above interferometric processing and error removal, phase errors between interferometric pairs are calculated with the vertical wavenumber. These phase errors are then used to compensate the interferograms, and ground points are set as the phase reference zero. This process constructs a tomographic dataset with a unified height reference, providing the foundation for later 3D forest structure inversion.

### 2.2 Tomography Imaging

Tomography is similar to synthetic aperture in the azimuth direction. It achieves high resolution in the elevation direction by forming an equivalent aperture from multiple near-parallel passes, thereby enabling 3D imaging of the observed target.

After the data have undergone registration, interferometry, flattening, filtering and unwrapping, the multi-baseline SAR observation dataset can be expressed as:

$$I_n^{TC}(r, x) = \int p(z) \exp(jk_z(n)z) dz \quad (3)$$

where  $I_n^{TC}(r, x)$  represents the multi-baseline SAR data after topographic phase removal,  $z$  represents the elevation coordinate,  $p(z)$  is the reflectivity function along the elevation direction, and  $k_z$  is the vertical wavenumber, defined as:

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

where  $b_{\perp}(n)$  is the perpendicular baseline of each interferometric pair,  $\lambda$  is the radar wavelength,  $R$  is the slant range, and  $\theta$  is the incidence angle. For tomographic imaging of multi-baseline observations, the standard TomoSAR model can be expressed as:

$$T(z) = \left\langle \left| \sum_n I_n^{TC} \exp(-jk_z(n)z) \right|^2 \right\rangle_w \quad (5)$$

To mitigate coherent noise in forest areas, multi-baseline SAR data are commonly represented in matrix form, enabling the backscatter power spectrum to be estimated. Moreover, due to the limited number and uneven distribution of interferometric pairs in HT-1 data, conventional spectral estimation methods tend to exhibit low resolution. Therefore, the Capon algorithm is employed in this study for tomographic inversion:

$$P_{\text{capon}} = \frac{1}{a(z)^H R^{-1} a(z)} \quad (6)$$

where  $P_{\text{capon}}$  represents the scattering intensity along the elevation direction and  $R$  is the covariance matrix. This method effectively suppresses sidelobes and improves vertical resolution, enabling a more accurate description of forest vertical structure (Lombardini and Reigber 2003).

### 2.3 PH technique

To validate the TomoSAR inversion results, the Phase Histogram (PH) technique is introduced as a single-baseline comparison method. The PH technique estimates phase heights of each pixel within a local window based on phase-to-height conversion, and assigns them to the right elevation layers, thereby approximating a vertical backscattering energy profile. The PH technique can be expressed as:

$$P_H(z_n) = \sum_{m=1}^M f_m \cdot \text{rect}(\phi_m, z_n) \quad (7)$$

where  $P_H(z_n)$  is the phase histogram value at height layer  $z_n$ ,  $f_m$  is the interferogram amplitude,  $\phi_m$  is the interferometric phase. The rect function determines whether a pixel is assigned to height layer  $z_n$ :

$$\text{rect}(\phi_m, z_n) = \begin{cases} 1, & \text{if } \left| \frac{\phi_m}{k_z} - z_n \right| < \frac{\Delta z}{2} \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

Where  $\Delta z$  is the height sampling interval, set to 1 m in this study. The inversion accuracy of the PH technique is related to the vertical wavenumber  $k_z$ . To mitigate the influence of height ambiguity, interferometric pairs with an ambiguity height approximately twice the forest height are typically selected (Chuanjun, Peng et al. 2025). The ambiguity height is defined as:

$$H_{\text{amb}} = \frac{2\pi}{k_z} \quad (9)$$

## 3. Dataset and Experiments Results

### 3.1 Dataset

This study uses four SLC images acquired by the HT-1 distributed satellite system on August 12, 2024, over a test site in Gabon, Africa (Figure 3). These images form three interferometric pairs to participate in this study. This area includes dense evergreen broadleaf forest with canopy heights mainly ranging from 10 to 30 m and reaching up to 50 m at maximum. Validation data are airborne LiDAR (LVIS) data, including waveform, elevation, and relative height product. The RH98 relative height metric is selected as the reference for forest height, representing the height at which 98% of the returned energy is reached.

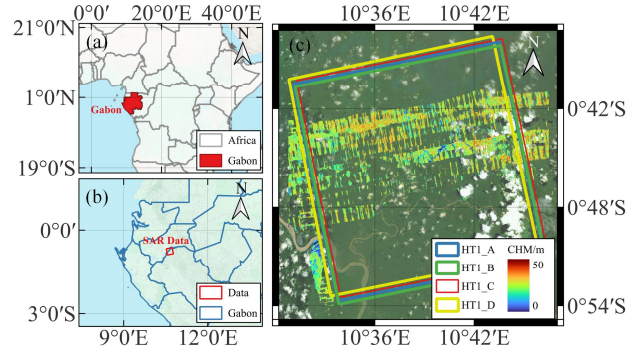


Figure 3. Study area in Gabon, Africa. (a)-(b) Location of the study area; (c) Position distribution of the four SAR images and the LiDAR canopy height model (CHM).

As shown in Figure 4, the left column presents coherence maps for each interferometric pair, while the middle and right columns show interferograms before and after phase correction. Significant trend and periodic errors are observed in the interferograms before correction. After phase refinement, these errors are effectively removed, and phase continuity is substantially improved, thereby providing high-quality input for later tomographic inversion.

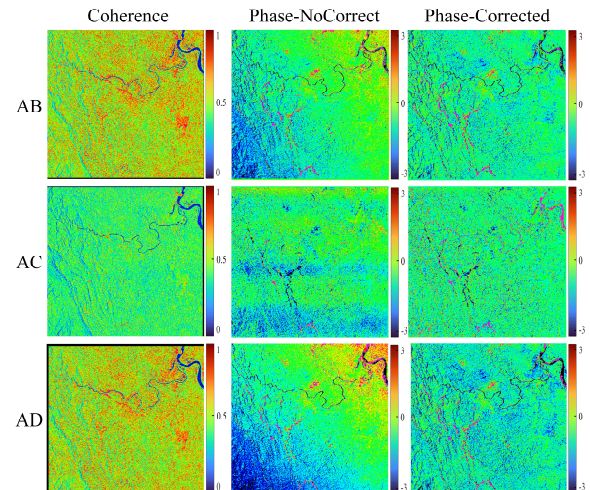


Figure 4. Coherence maps of three interferometric pairs (left column), and interferograms before (middle column) and after phase correction (right column).

### 3.2 Analysis of Experiments Results

The single-baseline PH technique is introduced as a comparison method to evaluate the effectiveness of HT-1 multi-baseline data for vertical structure inversion. Airborne LiDAR data are used for validation. Comparisons are conducted in terms of canopy



| InSAR pairs    | A-B | A-C | A-D |
|----------------|-----|-----|-----|
| $b_{\perp}(n)$ | 168 | 284 | 165 |

Table 1. Baseline length of three pairs

height, vertical structure, and backscattering profiles to comprehensively assess the capability of HT-1 tomography for vertical structure inversion.

A typical range-direction profile is selected to analyze the PH inversion results under different vertical baseline conditions, as shown in Figure 5. Different pairs have different vertical baseline distributions, which directly affect the ambiguity height and inversion performance. The baselines of all three pairs fall within a suitable range, with no extreme values. However, the AC pair, affected by a relatively small ambiguity height, exhibits lower coherence, resulting in poor phase unwrapping quality and low spectral continuity. The AD pair performs better than the AC pair but still shows low degree of energy focusing. In contrast, the AB

pair has high coherence, a suitable ambiguity height, and a clear, continuous spectral profile. Considering both coherence and spectral distribution, the AB pair outperforms the other two pairs. Therefore, later method analyses are based on this pair.

For the same profile, the inversion results obtained using Capon tomography and PH techniques are compared in the left column of Figure 6. Both methods show general consistency with LiDAR CHM in the range-direction profile. However, the PH technique exhibits poorer profile continuity, while Capon produces smoother and more continuous results.

Two representative points, A and B, are selected along the profile for backscattering profile comparison, as shown in the right column of Figure 6. At point B, both methods show good agreement with the LiDAR waveform. At point A, Capon still has a close match to the LiDAR waveform, while PH technique shows significant sidelobe interference and poorer agreement.

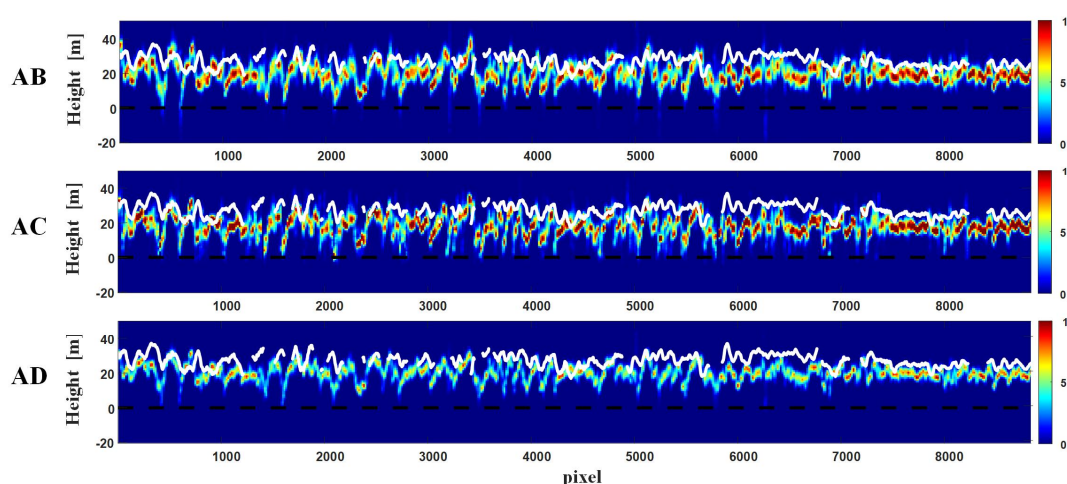


Figure 5. Comparison of PH-based forest vertical structure inversion results using different interferometric pairs.

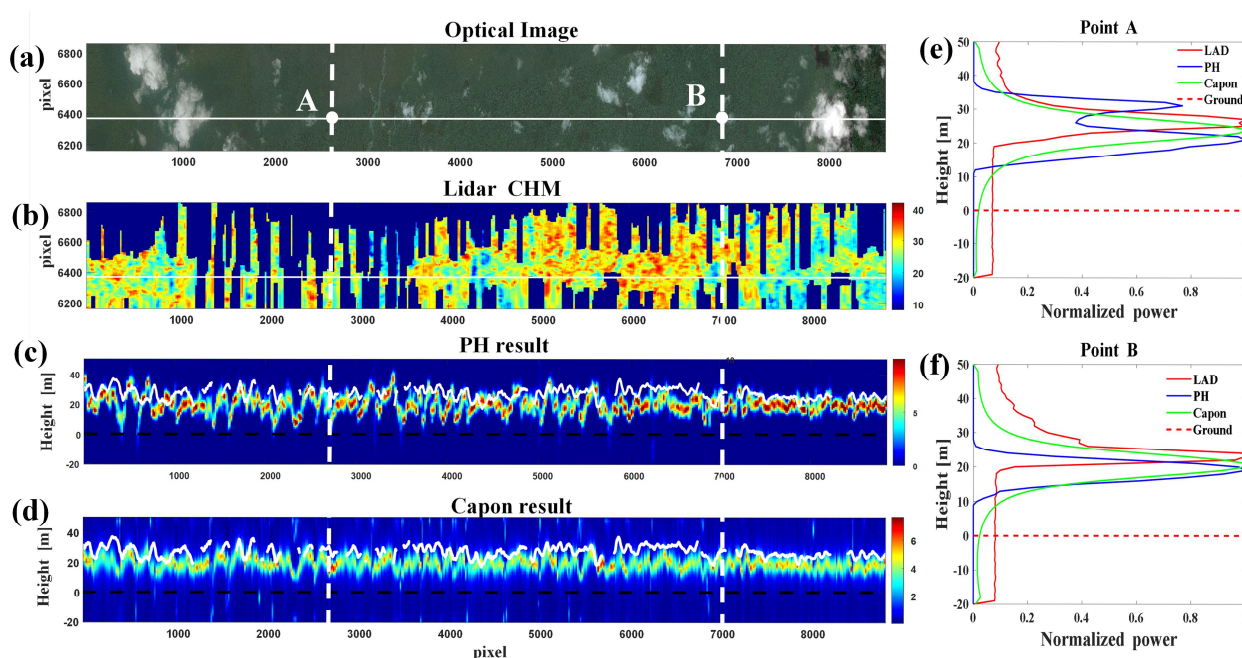


Figure 6. Comparison of Capon and PH for forest vertical structure inversion. (a) Optical image; (b) LiDAR CHM; (c)-(d) Vertical profile from PH and Capon along white solid line in (a); (e)-(f) Normalized vertical backscattered power profile of the point A and B.



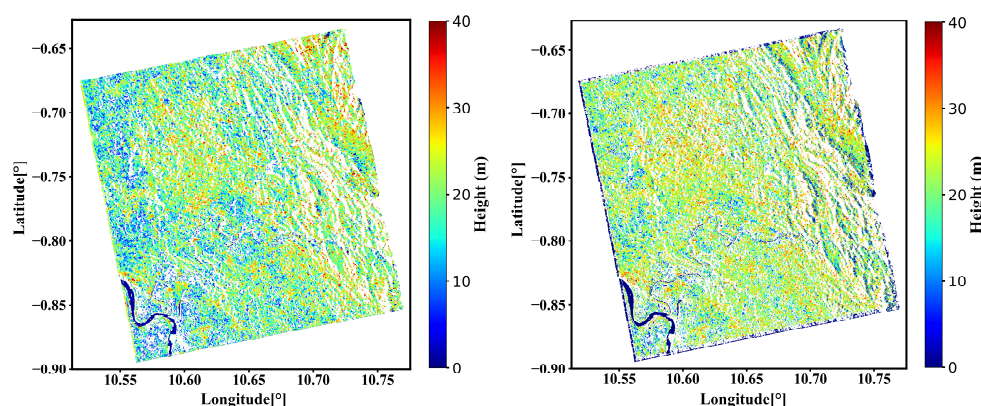


Figure 7. Forest height map in geographic coordinates derived from PH (left column) and Capon (right column).

In addition, it is worth noting that both methods share a common limitation: they are unable to effectively obtain ground information. This is partly because the study area consists of dense tropical forest with limited radar penetration, and partly because the X-band HT-1 system has weak penetration through forests, with scattering centers mainly concentrated near the canopy. Consequently, the tomographic results cannot directly separate ground scattering peaks, and forest height estimation therefore relies on the accuracy of external DEM.

In areas with a reliable DEM, the power cumulative distribution method is applied, where the height corresponding to 98% cumulative energy in the spectrum is taken as forest height. It is then transformed from radar to geographic coordinates to obtain the full-scene forest height map (Figure 7). To ensure reliability, areas with excessively large or small terrain slopes are removed.

For a clearer representation of the forest height inversion results, the LiDAR CHM and the forest height maps obtained from both

methods are displayed in radar coordinates. Areas not covered by LiDAR are masked, as shown in Figure 8. For the valid regions, the inversion results from the PH and Capon methods are compared with the LiDAR CHM, and density scatterplots are generated.

The results show that both methods exhibit a certain degree of underestimation, mainly due to systematic bias introduced by the external DEM, which does not fully remove forest height contributions. The PH technique shows more severe underestimation due to its inherent algorithmic characteristics, and its poor profile continuity results in more outliers.

Quantitatively, the RMSE of the PH technique is 6.49 m, while that of Capon is 5.43 m, indicating that Capon has higher accuracy than the PH technique. Overall, the Capon method outperforms the PH technique in spectral continuity and inversion accuracy, confirming the effectiveness of HT-1 multi-baseline data for forest vertical structure inversion.

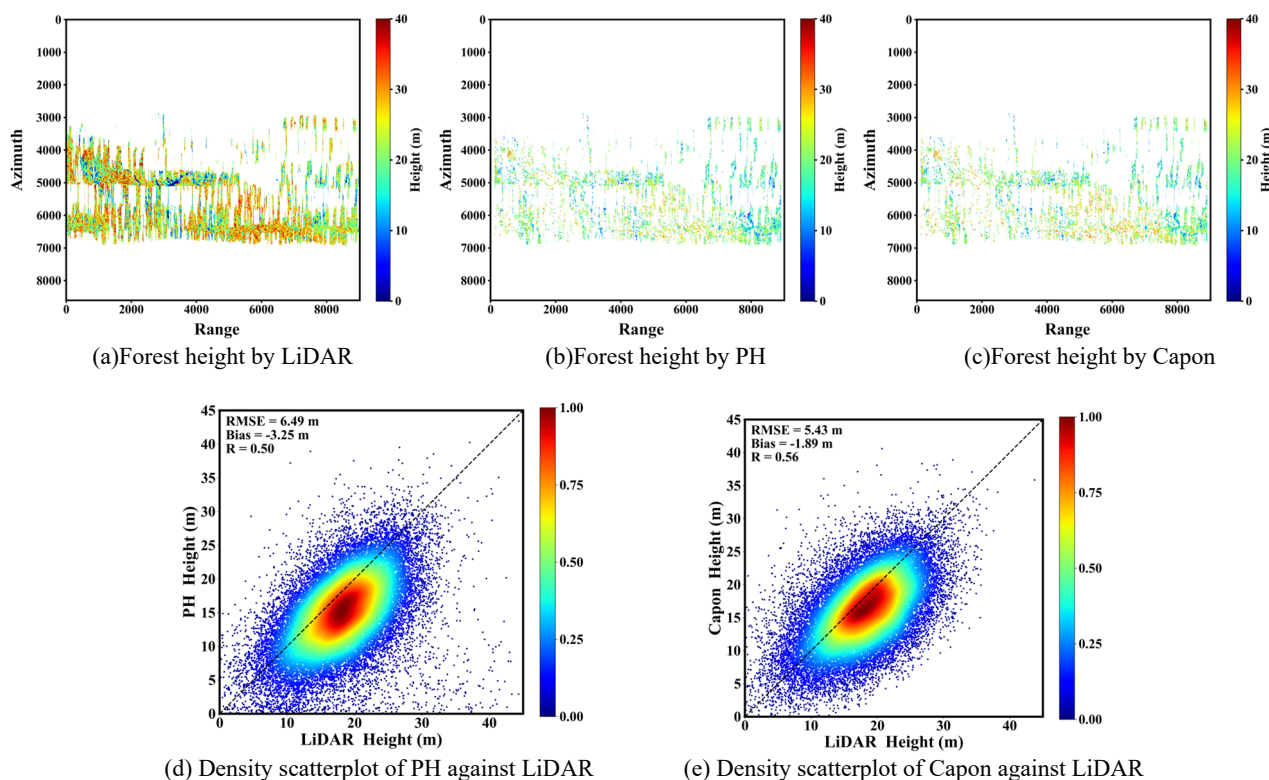


Figure 8. Comparison of Capon and PH in forest CHM inversion against LiDAR CHM.

| Method | Single line(s) | Full image(h) |
|--------|----------------|---------------|
| PH     | 3              | ~ 0.3         |
| Capon  | 12             | ~ 6           |

Table 2. Computational efficiency of PH and Capon

However, the improvement in accuracy comes at the cost of computational efficiency. As shown in Table 2, PH takes about 3 seconds for a single range-line profile, while Capon requires approximately 12 seconds. For a full image, PH completes inversion within minutes, while Capon demands hours. Therefore, improving the computational efficiency of tomography imaging is an important direction for future research, especially for large-scale applications.

#### 4. Conclusion

This paper develops a complete interferometric processing workflow for HT-1 multi-baseline data. By applying tomography to spaceborne SAR data, forest vertical structure profiles and canopy heights are obtained over the test site, showing good agreement with LiDAR data. Compared with the single-baseline PH technique, Capon-based tomography achieves higher accuracy and better profile continuity. These results confirm the feasibility of HT-1 for tomography and show the potential of multi-baseline satellites for future missions. At the same time, the limitations of X-band SAR in penetrating dense forest canopies are also highlighted. Based on these findings, future work may explore integrating multi-band data to improve ground information retrieval and complete the vertical structure from canopy to ground. In addition, improving the computational efficiency of tomography methods is another direction worth pursuing for large-scale applications.

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