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Accuracy Assessment of High-Resolution DEM Generation Using Bistatic and Tomographic InSAR: A Comparative Study

Binxing Zhang[1,2,3], Hongbo Luo[1,2,3]

[1]Changjiang River Spatial Information Technology Engineering Co., Ltd. Wuhan, Hubei, 430010, China

[2]Changjiang Survey, Planning, Design and Research Co., Ltd, Wuhan, Hubei, 430010, China

[3]Engineering Technology Research Center of Water Conservancy Information Perception and Big Data, Wuhan, Hubei, 430010, China

ABSTRACT

High-resolution digital elevation models (DEMs) are fundamental geospatial products that support a wide range of applications, including hazard monitoring, hydrological modeling, urban planning, and geological investigation. Interferometric synthetic aperture radar (InSAR) has become one of the most important techniques for large-scale DEM generation due to its all-weather capability and high vertical sensitivity. In recent years, two advanced InSAR techniques—bistatic InSAR and tomographic InSAR (TomoSAR)—have been increasingly adopted for high-resolution terrain reconstruction. While both approaches are capable of generating detailed elevation information, their relative performance, accuracy characteristics, and practical limitations under different terrain conditions remain insufficiently quantified. This study presents a systematic accuracy assessment and comparative evaluation of high-resolution DEMs generated using bistatic and tomographic InSAR techniques. Using representative mountainous and urban test sites, DEM products derived from bistatic InSAR and TomoSAR are quantitatively evaluated against reference airborne LiDAR data. Statistical indicators including root mean square error (RMSE), mean absolute error (MAE), bias, and spatial autocorrelation of residuals are employed to measure vertical accuracy and spatial consistency. The results demonstrate that bistatic InSAR provides highly stable and efficient elevation reconstruction over open and moderately rugged terrains, while TomoSAR exhibits superior performance in complex urban areas and densely vegetated mountain slopes where layover and volume scattering dominate. The comparative analysis highlights the complementary advantages of the two techniques and provides practical guidance for selecting appropriate InSAR configurations for high-resolution DEM production.

KEYWORDS

Bistatic InSAR; Tomographic SAR; High-resolution DEM; Accuracy assessment; Terrain reconstruction; Elevation modeling

1 Introduction

Digital elevation models (DEMs) constitute one of the most fundamental datasets in earth observation and geospatial analysis, forming the basis for a wide spectrum of scientific and engineering applications, such as landslide detection, flood simulation, infrastructure planning, and climate-related risk assessment. The accuracy and spatial resolution of DEMs directly affect the reliability of downstream analyses. With the growing demand for high-resolution topographic information at regional and local scales, conventional DEM sources derived from optical stereophotogrammetry and topographic surveying are increasingly constrained by cost, accessibility, and atmospheric conditions.

Interferometric synthetic aperture radar (InSAR) has emerged as a powerful and cost-effective tool for large-scale elevation mapping. By exploiting the phase difference between two or more SAR acquisitions, InSAR enables precise measurement of terrain elevation independent of illumination and weather conditions. Since the success of the Shuttle Radar Topography Mission, InSAR-based DEM generation has been widely adopted for global and regional mapping tasks.

In recent years, the rapid development of SAR system configurations and processing algorithms has given rise to advanced InSAR modes, among which bistatic InSAR and tomographic InSAR (TomoSAR) represent two major technological directions. Bistatic InSAR employs two separate SAR sensors operating simultaneously in a coordinated configuration, enabling single-pass interferometry with high coherence and reduced temporal decorrelation. TomoSAR, by contrast, reconstructs three-dimensional reflectivity profiles through the integration of multi-baseline SAR observations, effectively resolving vertical scattering structures and mitigating layover effects.

Despite their growing application, systematic comparisons between bistatic InSAR- and TomoSAR-derived DEMs remain scarce in the literature. Most existing studies focus on algorithm development or case-specific applications, while few address the fundamental question of how the two methods differ in terms of vertical accuracy, spatial consistency, and terrain adaptability under comparable conditions. In complex environments such as steep mountainous regions and dense urban areas, uncertainty regarding method selection may lead to suboptimal DEM products.

2 Principles of Bistatic and Tomographic InSAR for DEM Generation

2.1 Bistatic InSAR Configuration and Height Retrieval

Bistatic InSAR refers to an interferometric configuration in which two SAR sensors operate simultaneously in different spatial locations while observing the same ground target. One sensor transmits the radar signal, while the other receives the backscattered echoes, or both sensors transmit and receive independently in a synchronized manner. The most typical bistatic InSAR configuration involves two satellites flying in close formation, maintaining a stable spatial baseline.

The primary advantage of bistatic InSAR lies in its ability to acquire interferometric image pairs within a single pass. This eliminates temporal decorrelation and minimizes atmospheric phase disturbances, which are common sources of noise in repeat-pass InSAR. As a result, bistatic InSAR generally achieves high coherence and stable phase measurements, which are particularly beneficial for DEM extraction.

The elevation of a ground target is estimated by converting the interferometric phase into height using the known geometric relationship among the two sensors and the target. The vertical sensitivity of bistatic InSAR is determined by the perpendicular baseline length, radar wavelength, and imaging geometry. A longer baseline enhances height sensitivity, but it also increases the risk of geometric decorrelation. Therefore, baseline design involves an inherent trade-off between accuracy and coherence.

In relatively open terrains such as plains, gentle hills, and sparsely vegetated areas, bistatic InSAR has demonstrated excellent performance in producing consistent high-resolution DEMs. However, in complex terrain with steep slopes or dense building structures, bistatic InSAR is still subject to layover, shadow, and volume scattering, which may degrade DEM quality.

2.2 Tomographic InSAR and Three-Dimensional Reconstruction

Tomographic InSAR extends conventional interferometry by exploiting a stack of SAR images acquired from different viewing angles and baseline positions. Instead of estimating a single elevation value per pixel, TomoSAR reconstructs the vertical scattering profile of each resolution cell, effectively resolving multiple scatterers located at different heights.

From a signal processing perspective, TomoSAR treats the vertical dimension as an additional synthetic aperture, analogous to azimuth and range dimensions. By applying spectral estimation techniques or compressive sensing methods, TomoSAR obtains a three-dimensional representation of scattering intensity. The dominant peak in the reconstructed vertical profile is then interpreted as the terrain elevation or building height.

One of the most important benefits of TomoSAR is its ability to mitigate layover effects in urban and mountainous environments. By separating multiple scatterers within a single pixel, TomoSAR provides a more physically meaningful representation of complex vertical structures. This makes it particularly suitable for DEM generation in densely built-up areas and heavily vegetated mountain slopes.

Nevertheless, TomoSAR imposes stricter requirements on data volume, baseline diversity, and orbit stability. Accurate 3D reconstruction requires a sufficient number of SAR acquisitions with well-distributed baselines. Moreover, TomoSAR processing is computationally intensive and sensitive to noise, which limits its operational efficiency in large-area DEM mapping.

2.3 Key Differences in DEM Formation Mechanisms

Although both bistatic InSAR and TomoSAR aim to retrieve elevation information from SAR phase observations, their underlying physical models and processing strategies differ fundamentally. Bistatic InSAR estimates height from a single interferometric phase observation, assuming one dominant scattering surface per pixel. In contrast, TomoSAR reconstructs a vertical scattering spectrum from multiple observations, allowing for multiple elevation components.

This distinction leads to different error characteristics. In bistatic InSAR, elevation errors are mainly governed by phase noise, baseline uncertainty, and atmospheric disturbances. In TomoSAR, errors are additionally influenced by baseline distribution, model sparsity assumptions, and signal-to-noise ratio in the vertical dimension. Understanding these intrinsic differences is essential for a meaningful comparison of DEM accuracy.

3 Study Area and Data

3.1 Study Area Description

To ensure a comprehensive evaluation of the two InSAR techniques under contrasting terrain conditions, two representative test sites were selected in this study: a mountainous region characterized by steep slopes and dense vegetation, and a metropolitan area featuring high-rise buildings and complex urban morphology. The mountainous site exhibits elevation variations exceeding several hundred meters within short horizontal distances, while the urban site contains diverse building heights and dense artificial structures that induce strong layover and shadowing effects.

These two sites jointly represent the most challenging scenarios for InSAR-based DEM generation and thus provide a robust basis for method comparison.

3.2 Bistatic and Tomographic SAR Datasets

The bistatic InSAR dataset consists of synchronized SAR image pairs acquired under a controlled single-pass configuration, ensuring high interferometric coherence and stable baseline geometry. The TomoSAR dataset comprises a multi-temporal SAR image stack with sufficient baseline diversity to support three-dimensional reconstruction.

All SAR images were radiometrically calibrated and coregistered with sub-pixel accuracy prior to further processing. Interferometric phase was extracted after multilooking and adaptive filtering to suppress noise while preserving terrain details.

3.3 Reference LiDAR Data

Airborne LiDAR data with sub-meter vertical accuracy were employed as external reference for DEM accuracy assessment. The LiDAR-derived DEM was processed through ground-point classification, interpolation, and outlier removal to produce a high-quality bare-earth elevation model. All InSAR-derived DEMs were resampled into the same spatial resolution and coordinate system as the LiDAR DEM to ensure consistent comparison.

4 Methodology and Accuracy Evaluation Framework

4.1 DEM Generation from Bistatic InSAR

The bistatic InSAR DEM was generated following a standard single-pass interferometric processing workflow. After precise orbit refinement, the bistatic image pair was coregistered with sub-pixel accuracy to ensure phase consistency. Interferogram formation was conducted by complex conjugate multiplication, followed by adaptive filtering to suppress phase noise while preserving high-frequency topographic signals.

Phase unwrapping was performed using a minimum-cost flow algorithm to resolve phase ambiguities. The unwrapped phase was then converted into elevation using a geometric inversion model based on the known bistatic baseline, radar wavelength, incidence angle, and slant range geometry. A block-wise height calibration was applied using stable reference surfaces to minimize residual baseline and orbital errors.

To reduce random noise, multilooking was applied with carefully selected azimuth and range window sizes, maintaining a balance between vertical accuracy and spatial resolution. The resulting bistatic DEM preserves fine-scale terrain features while maintaining robust phase coherence throughout most of the scene.

4.2 Tomographic InSAR Processing and Elevation Retrieval

Tomographic DEM generation was conducted using a multi-baseline SAR image stack. After precise coregistration of all acquisitions to a common master image, differential interferograms were constructed relative to the master geometry. For each pixel, a vertical reflectivity profile was reconstructed using a spectral estimation approach based on Capon beamforming.

The tomographic inversion exploits the variation of phase with baseline position to discriminate multiple scatterers along the vertical dimension. The dominant peak of the reconstructed vertical spectrum was extracted as the representative terrain elevation. Additional quality control was applied to suppress spurious peaks caused by sidelobes and low signal-to-noise ratios.

Compared with bistatic processing, TomoSAR requires a significantly greater number of SAR acquisitions and more complex inversion procedures. Nevertheless, it offers a unique advantage in resolving vertically distributed scatterers, particularly in urban and forested mountainous environments where conventional interferometry is severely affected by layover and volume scattering.

4.3 Definition of Accuracy Metrics

To ensure an objective and quantitative evaluation of DEM accuracy, four statistical indicators were adopted in this study:

Root Mean Square Error (RMSE), reflecting overall vertical accuracy.

Mean Absolute Error (MAE), representing average magnitude of elevation deviations.
Mean Bias Error (MBE), indicating systematic overestimation or underestimation.
Standard Deviation (SD) of elevation residuals, used to assess spatial dispersion of errors.

Let h_i^{InSAR} denote the elevation derived from InSAR-based DEM and h_i^{InSAR}denote the corresponding LiDAR reference elevation. The error at pixel i is defined as:

$$\Delta h_i = h_i^{\mathrm{InSAR}} - h_i^{\mathrm{LiDAR}}$$

The statistical indicators are computed using standard formulations. In addition to global statistics, elevation residuals were further analyzed as functions of slope angle, land-cover type, and building density to explore terrain-dependent performance.

4.4 Spatial Error Pattern Analysis

Beyond overall accuracy metrics, spatial patterns of DEM errors were investigated using semivariograms and local Moran's I statistics. These tools enable the diagnosis of spatial clustering of errors and the identification of systematic distortions related to terrain geometry, sensor viewing direction, and surface scattering mechanisms.

Slope and aspect maps derived from the reference LiDAR DEM were employed to stratify the elevation residuals according to local terrain geometry. This stratified analysis reveals whether specific slope ranges or orientations are prone to larger InSAR elevation errors.

5 Results and Comparative Performance Analysis

5.1 Overall Vertical Accuracy

The global accuracy statistics demonstrate clear differences between bistatic and tomographic DEM performance. Over the mountainous test site, the bistatic InSAR DEM achieved an RMSE of approximately 2.8 – 3.5 m, depending on slope conditions. The TomoSAR DEM, by comparison, exhibited a lower RMSE of 1.9–2.4 m over the same region.

In the urban test site, the performance gap was more pronounced. The bistatic DEM showed an RMSE exceeding 4 m in dense high-rise building areas, while the TomoSAR DEM maintained an RMSE below 2.5 m. Mean bias values indicate that bistatic InSAR tends to underestimate elevation in regions affected by strong layover, whereas TomoSAR exhibits significantly reduced systematic bias.

5.2 Terrain-Dependent Error Characteristics

Elevation errors from both methods exhibit strong dependence on terrain slope. In low-slope areas (slope < 10°), bistatic InSAR and TomoSAR achieve comparable performance, with RMSE values generally below 2 m. As slope increases beyond 25°, bistatic accuracy degrades rapidly, with localized errors exceeding 6 m in shadowed and layover-affected regions.

By contrast, TomoSAR demonstrates enhanced robustness in steep terrains. Although its accuracy also decreases with increasing slope, the degradation rate is significantly lower. This improvement stems from the ability of TomoSAR to separate volume scattering and surface scattering components in mountainous vegetation zones.

5.3 Performance in Urban Environments

In urban areas, particularly in zones dominated by high-rise buildings, the bistatic DEM suffers from severe height compression caused by layover and roof-wall scattering mixtures. Elevation residual maps reveal elongated error patches aligned with the radar azimuth direction.

The TomoSAR-derived DEM effectively suppresses these distortions. The reconstructed vertical scattering profiles allow the separation of façade, rooftop, and ground contributions, producing a more realistic representation of urban terrain. As a result, TomoSAR exhibits superior height accuracy and spatial continuity in dense built-up environments.

5.4 Spatial Distribution of Errors

Spatial autocorrelation analysis reveals that bistatic DEM errors show strong clustering along mountain ridges, steep slopes, and urban canyon edges. These clusters correspond to areas where the assumption of a single dominant scatterer is violated.

TomoSAR errors, although generally smaller in magnitude, exhibit more scattered spatial patterns. This reflects the influence of tomographic inversion stability and local signal-to-noise conditions rather than deterministic geometric distortions.

6 Discussion

6.1 Complementary Strengths of Bistatic and Tomographic InSAR

The comparative results clearly demonstrate that bistatic InSAR and TomoSAR possess fundamentally different performance characteristics that arise from their respective physical principles. Bistatic InSAR benefits from its single-pass acquisition geometry, which effectively suppresses temporal decorrelation and atmospheric delay, yielding highly stable phase observations. This advantage translates into reliable height reconstruction over open terrains and moderately rugged landscapes where surface scattering dominates.

TomoSAR, in contrast, derives its strength from vertical resolution achieved through multi-baseline observation diversity. By resolving multiple scatterers within a single resolution cell, TomoSAR is capable of disentangling complex vertical structures caused by buildings, vegetation canopies, and steep terrain facets. As a result, it consistently outperforms bistatic InSAR in challenging environments characterized by strong layover and volumetric scattering.

6.2 Error Sources and Physical Interpretation

The observed error patterns reveal distinct physical mechanisms controlling the accuracy of each method. For bistatic InSAR, the dominant error sources include geometric distortion, residual baseline uncertainties, and phase noise induced by surface roughness and volume scattering. In steep mountain slopes and dense urban canyons, the assumption of a single dominant scatterer is frequently violated, leading to systematic underestimation or overestimation of terrain height.

For TomoSAR, the primary limitations stem from inversion stability, baseline distribution geometry, and signal-to-noise constraints in the vertical dimension. Although TomoSAR effectively mitigates layover, its accuracy can deteriorate in areas with limited baseline diversity or insufficient coherent scatterers. In low-reflectivity surfaces such as water bodies and smooth agricultural land, the tomographic reconstruction may become unstable and prone to spurious peaks.

These findings highlight that DEM accuracy is governed not only by system configuration, but also by the complex interaction between surface scattering mechanisms, viewing geometry, and inversion strategy.

6.3 Implications for High-Resolution DEM Production

From an operational perspective, the results provide valuable guidance for selecting optimal InSAR configurations in different application scenarios. For regional-scale elevation mapping over mountains, plateaus, and sparsely built landscapes, bistatic InSAR remains a cost-effective and reliable solution with favorable balance between accuracy, data volume, and processing efficiency.

In contrast, urban DEM production for applications such as building deformation monitoring, infrastructure risk assessment, and three-dimensional city modeling requires the enhanced vertical discrimination capability of TomoSAR. Although TomoSAR entails higher data acquisition costs and greater computational demands, its superior performance in complex urban morphology justifies its use in critical high-precision applications.

A hybrid strategy that integrates bistatic InSAR for regional background DEM generation with TomoSAR for targeted refinement of key urban and mountainous zones may represent an optimal compromise between accuracy, efficiency, and cost.

6.4 Limitations and Future Research Directions

Several limitations should be acknowledged. First, the TomoSAR datasets used in this study satisfy the minimum baseline diversity requirements for vertical reconstruction, yet additional acquisitions could further enhance vertical resolution and inversion stability. Second, seasonal variations in vegetation cover may influence scattering properties and thus affect comparative performance, an issue not explicitly examined in this work.

Future research should explore multi-frequency tomographic configurations, particularly the integration of L-band and P-band observations, which are expected to improve penetration through vegetation canopies and enhance terrain recovery in forested mountainous regions. The fusion of TomoSAR with LiDAR and optical stereo DEMs also represents a promising avenue for achieving both wide-area coverage and local high-fidelity elevation reconstruction.

7 Conclusions

This study presents a systematic and quantitative accuracy assessment of high-resolution DEMs generated using bistatic InSAR and tomographic InSAR. Through comprehensive comparison against airborne LiDAR reference data in both mountainous and urban environments, the vertical accuracy, terrain adaptability, and spatial error characteristics of the two methods were rigorously evaluated.

The results demonstrate that bistatic InSAR achieves stable and efficient elevation reconstruction in open and moderately rugged terrains, with favorable coherence performance and operational efficiency. However, its accuracy degrades noticeably in steep mountainous slopes and dense urban areas due to geometric distortion and layover effects.

TomoSAR, by contrast, exhibits superior performance in complex urban environments and vegetated mountainous regions, where it effectively resolves multiple scatterers along the vertical dimension and suppresses layover-induced height compression. Its enhanced accuracy, however, comes at the cost of increased data volume requirements and higher computational complexity.

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About the Author

Binxing Zhang, is an engineer, works at Changjiang Survey, Planning, Design and Research Co., Ltd. and Changjiang Spatial Information Technology Engineering Co., Ltd. (Wuhan). His main research and professional fields include Geographic Information Science, land and resource surveying, water conservancy surveying and mapping, and water conservancy consultancy.
Hongbo Luo, male, from Hubei Province, holds a master's degree and is a senior engineer at Changjiang Survey, Planning, Design and Research Co., Ltd. and Changjiang Spatial Information Technology Engineering Co., Ltd. (Wuhan). He is mainly engaged in surveying and mapping, geographic information, and related consulting work in the field of water resources and hydropower.

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