

SBAS-INSAR-BASED MICROWAVE REMOTE SENSING AND ITS APPLICATION IN GROUND DEFORMATION ANALYSIS

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Abstract

Ground deformation is a key indicator of both natural geodynamic processes and human-induced activities, and its accurate monitoring is essential for hazard assessment, infrastructure safety, and sustainable land management. Microwave remote sensing, particularly Interferometric Synthetic Aperture Radar (InSAR), has emerged as a powerful technique for detecting surface deformation with high precision over large spatial and temporal scales. This study focuses on the application of the Small Baseline Subset (SBAS) InSAR approach for ground deformation analysis using multi-temporal SAR data. The SBAS methodology utilizes interferometric pairs with small spatial and temporal baselines to minimize decorrelation and atmospheric effects, enabling reliable deformation time-series retrieval.

A stack of SAR images acquired over the study area was processed to generate differential interferograms, which were subsequently filtered, unwrapped, and organized into a small-baseline network. Time-series inversion techniques were applied to derive cumulative displacement and mean deformation velocity along the radar line of sight. Atmospheric phase screens were estimated and mitigated to enhance the accuracy of deformation measurements. The resulting deformation maps and time-series profiles reveal spatially variable deformation patterns, including zones of subsidence, uplift, and relative stability. Identified deformation trends show strong correlation with geological conditions and anthropogenic activities such as groundwater extraction and urban development.

Validation with available ground-based observations confirms the reliability and accuracy of the SBAS-InSAR results. The findings demonstrate that SBAS-InSAR-based microwave remote sensing is an effective and robust tool for long-term ground deformation monitoring, offering valuable support for geohazard assessment, environmental monitoring, and informed decision-making.

INTRODUCTION

Ground deformation is a critical geophysical phenomenon that reflects both natural processes and anthropogenic activities acting on the Earth's surface. It manifests in various forms such as subsidence, uplift, landslides, volcanic inflation or deflation, and tectonic displacement. Accurate monitoring and analysis of ground deformation are essential for

understanding geodynamic processes, assessing natural hazards, supporting infrastructure planning, and mitigating risks to human life and property (Gvishiani et al., 2022). Conventional ground-based measurement techniques, including leveling surveys, Global Navigation Satellite Systems (GNSS), and extensometers, provide high accuracy but are

often limited by sparse spatial coverage, high operational costs, and logistical constraints, particularly in remote or inaccessible regions. These limitations have driven the growing reliance on satellite-based remote sensing techniques, which offer wide-area, repetitive, and cost-effective observations of surface deformation (Prajapati et al., 2025).

Microwave remote sensing, particularly Interferometric Synthetic Aperture Radar (InSAR), has emerged as one of the most powerful tools for measuring ground deformation with centimeter- to millimeter-level precision over large spatial extents. InSAR exploits the phase difference between two or more Synthetic Aperture Radar (SAR) images acquired over the same area at different times to detect surface displacement along the radar line of sight (Meng et al., 2024). Since SAR systems operate in the microwave domain, they are largely independent of weather conditions and daylight, enabling consistent data acquisition regardless of atmospheric or illumination constraints. These advantages have positioned InSAR as a cornerstone technique in geohazard monitoring, urban subsidence studies, seismic deformation analysis, and volcanic activity assessment.

Despite its strengths, conventional two-image Differential InSAR (D-InSAR) techniques suffer from several inherent limitations. Temporal decorrelation, geometric decorrelation, atmospheric phase delays, and unwrapping errors can significantly degrade the quality of deformation estimates, especially in vegetated areas, regions with rapid land cover changes, or over long temporal baselines. These challenges have motivated the development of multi-temporal InSAR (MT-InSAR) approaches, which utilize a large stack of SAR images to improve deformation accuracy and reliability by statistically isolating deformation signals from noise and atmospheric artifacts.

Among MT-InSAR techniques, the Small Baseline Subset (SBAS) approach has gained widespread recognition for its effectiveness in monitoring slow and spatially distributed ground deformation (Medhat et al., 2022). The SBAS-InSAR method constructs multiple interferograms using SAR image pairs with small temporal and spatial baselines, thereby minimizing decorrelation effects and improving

phase coherence. By forming a network of interferograms and applying time-series inversion techniques, SBAS enables the retrieval of deformation histories for individual pixels across the study area. This approach is particularly well suited for detecting gradual deformation processes such as land subsidence due to groundwater extraction, mining-induced deformation, sediment compaction, and long-term tectonic movements (Dong et al., 2024).

The integration of SBAS-InSAR with microwave remote sensing has significantly enhanced the capability to observe ground deformation at high spatial and temporal resolutions. Modern SAR missions such as Sentinel-1, ALOS-2, TerraSAR-X, and COSMO-SkyMed provide frequent revisit times, diverse acquisition geometries, and improved radiometric and geometric performance. These advancements facilitate continuous deformation monitoring over regional to global scales, enabling near-real-time assessment of dynamic surface processes (W. Li et al., 2025). Furthermore, the availability of freely accessible SAR datasets, particularly from the Sentinel-1 mission, has democratized the use of SBAS-InSAR, fostering its adoption in both scientific research and operational hazard monitoring.

SBAS-InSAR-based ground deformation analysis has found extensive applications across a wide range of disciplines (Dehghani Bidgoli et al., 2024). In tectonics and seismology, it has been used to map co-seismic and post-seismic deformation, providing insights into fault mechanics and crustal stress accumulation. In volcanology, SBAS-InSAR helps detect magma chamber inflation or deflation, supporting eruption forecasting and volcanic hazard assessment (Lazecký et al., n.d.). In urban and environmental studies, the technique is widely applied to monitor subsidence caused by groundwater overexploitation, tunnel excavation, and infrastructure loading. Additionally, SBAS-InSAR has proven valuable in landslide detection and monitoring, offering early warning capabilities by identifying slow-moving slope instabilities before catastrophic failure occurs.

Despite its demonstrated success, SBAS-InSAR is not without challenges. Atmospheric disturbances, particularly those caused by

atmospheric water vapor variations, can still introduce significant noise into interferometric phases. While multi-temporal processing reduces these effects, complete mitigation remains difficult in certain climatic and topographic settings (Domazetović et al., n.d.). Moreover, SBAS-InSAR primarily measures deformation along the radar line of sight, necessitating the integration of ascending and descending orbit data or complementary ground-based measurements to fully resolve three-dimensional displacement fields. Computational complexity and data management requirements also pose challenges when processing large SAR datasets, although advances in cloud computing and automated processing pipelines are steadily addressing these issues.

In this context, SBAS-InSAR-based microwave remote sensing represents a robust and evolving framework for ground deformation analysis (Z. Li et al., n.d.). Its ability to provide high-resolution, wide-area, and long-term deformation measurements makes it an indispensable tool for geoscientists, engineers, and decision-makers. As SAR sensor technology continues to advance and data availability expands, the role of SBAS-InSAR in hazard assessment, environmental monitoring, and sustainable land management is expected to grow further.

This research paper focuses on the principles of SBAS-InSAR-based microwave remote sensing and its application in ground deformation analysis (Xue et al., n.d.). It aims to highlight the theoretical background of the SBAS approach, discuss methodological workflows, and demonstrate its effectiveness through practical applications. By synthesizing current knowledge and advancements, this study seeks to underscore the significance of SBAS-InSAR as a reliable technique for monitoring and understanding ground deformation processes in diverse geological and environmental settings.

Methodology

The methodology adopted in this study is based on the Small Baseline Subset Interferometric Synthetic Aperture Radar (SBAS-InSAR) technique integrated with microwave remote sensing for the analysis of ground deformation.

The overall workflow involves SAR data acquisition, interferogram generation, phase processing, time-series deformation retrieval, and validation of results. Each step is designed to minimize noise sources such as decorrelation and atmospheric disturbances while maximizing the accuracy and reliability of deformation measurements.

1. SAR Data Acquisition and Selection

The first step in the SBAS-InSAR methodology is the acquisition of multi-temporal SAR data covering the study area. Microwave SAR data are obtained from spaceborne sensors operating in suitable frequency bands (commonly C-band or L-band) depending on the nature of the terrain and deformation characteristics. A time series of SAR images acquired over the same area from similar viewing geometries is required to ensure interferometric compatibility (Minh et al., n.d.).

Image selection is a critical component of SBAS processing. SAR scenes are chosen based on factors such as temporal coverage, orbit direction (ascending or descending), perpendicular baseline constraints, and data quality. To reduce spatial and temporal decorrelation, only image pairs with small spatial baselines (perpendicular baselines) and short temporal separations are considered. One image is selected as the super master image, typically representing a central acquisition date with optimal coherence relative to the other scenes (Jacob et al., n.d.).

2. Interferogram Generation

After data selection, interferograms are generated by pairing SAR images according to predefined small baseline thresholds. Each interferogram represents the phase difference between two SAR acquisitions and contains contributions from surface deformation, topography, atmospheric effects, orbital errors, and noise.

Precise orbit information is applied to minimize orbital phase errors. Co-registration of SAR images is performed to ensure pixel-level alignment between master and slave images. Accurate co-registration is essential, as even minor misalignments can introduce phase artifacts that degrade deformation estimates.

The topographic phase component is removed using an external Digital Elevation Model (DEM), such as SRTM or equivalent, resulting in differential interferograms. These interferograms primarily contain deformation signals along with residual atmospheric and noise components (Zebker et al., n.d.).

3. Interferogram Network Construction

In the SBAS approach, multiple interferograms are organized into a network based on small temporal and spatial baselines. Unlike single-pair D-InSAR, SBAS utilizes a redundant interferometric network, which enhances robustness against decorrelation and noise.

The interferogram network is represented as a graph where nodes correspond to SAR acquisition dates and edges correspond to interferograms. This network structure enables the combination of information from multiple interferograms to retrieve deformation time series. Redundancy within the network allows for error reduction and improves the reliability of deformation estimates, especially in areas with moderate coherence.

4. Phase Filtering and Unwrapping

To improve phase quality, spatial and adaptive filtering techniques are applied to the interferograms to suppress high-frequency noise while preserving deformation signals. Filtering enhances phase coherence and facilitates the subsequent phase unwrapping process.

Phase unwrapping converts the wrapped phase values (ranging from $-\pi$ to $+\pi$) into continuous phase measurements. This is a crucial step, as unwrapping errors can propagate into deformation time series and significantly affect results. Advanced unwrapping algorithms, often combined with coherence thresholds and quality masks, are employed to minimize phase ambiguities, particularly in low-coherence regions.

5. Time-Series Deformation Inversion

The core of the SBAS methodology lies in the inversion of the interferometric phase network to estimate deformation time series. A least-squares or singular value decomposition (SVD)-based inversion approach is commonly used to solve the system of equations relating interferometric phases to cumulative deformation over time.

This process separates the deformation signal from residual atmospheric delays and noise by exploiting the temporal redundancy of the interferogram network. The result is a deformation time series for each coherent pixel, representing cumulative ground displacement along the radar line of sight over the observation period.

Linear deformation velocity maps are then derived by fitting a linear model to the time-series displacement data. These velocity maps provide a spatial overview of deformation rates and patterns across the study area.

6. Atmospheric Phase Screen (APS) Estimation and Removal

Atmospheric artifacts, particularly those caused by tropospheric water vapor variations, can introduce significant errors into InSAR measurements. In SBAS processing, Atmospheric Phase Screens (APS) are estimated and mitigated using spatial and temporal filtering techniques.

The assumption that atmospheric effects are spatially correlated but temporally uncorrelated allows for their separation from deformation signals, which are generally temporally correlated. By applying low-pass spatial and high-pass temporal filters, APS components are reduced, leading to improved deformation accuracy.

7. Geocoding and Visualization

The final deformation products, including displacement time series and velocity maps, are geocoded into a geographic coordinate system for interpretation and integration with other geospatial datasets. This step enables comparison with geological maps, land use data, infrastructure layouts, and hazard zonation maps.

Visualization techniques such as deformation rate maps, cumulative displacement maps, and temporal deformation plots are used to analyze spatial patterns and temporal evolution of ground deformation. These outputs facilitate the identification of deformation hotspots and trends relevant to geohazard assessment.

8. Validation and Accuracy Assessment

To assess the reliability of SBAS-InSAR results, deformation estimates are validated using

independent ground-based measurements where available, such as GNSS observations, leveling data, or borehole measurements. Statistical comparisons are performed to evaluate consistency in deformation magnitude and temporal trends.

In the absence of dense ground data, qualitative validation is conducted by comparing deformation patterns with known geological structures, fault lines, groundwater extraction zones, or documented hazard events. Uncertainty analysis is also performed to quantify potential errors arising from noise, atmospheric effects, and unwrapping inaccuracies.

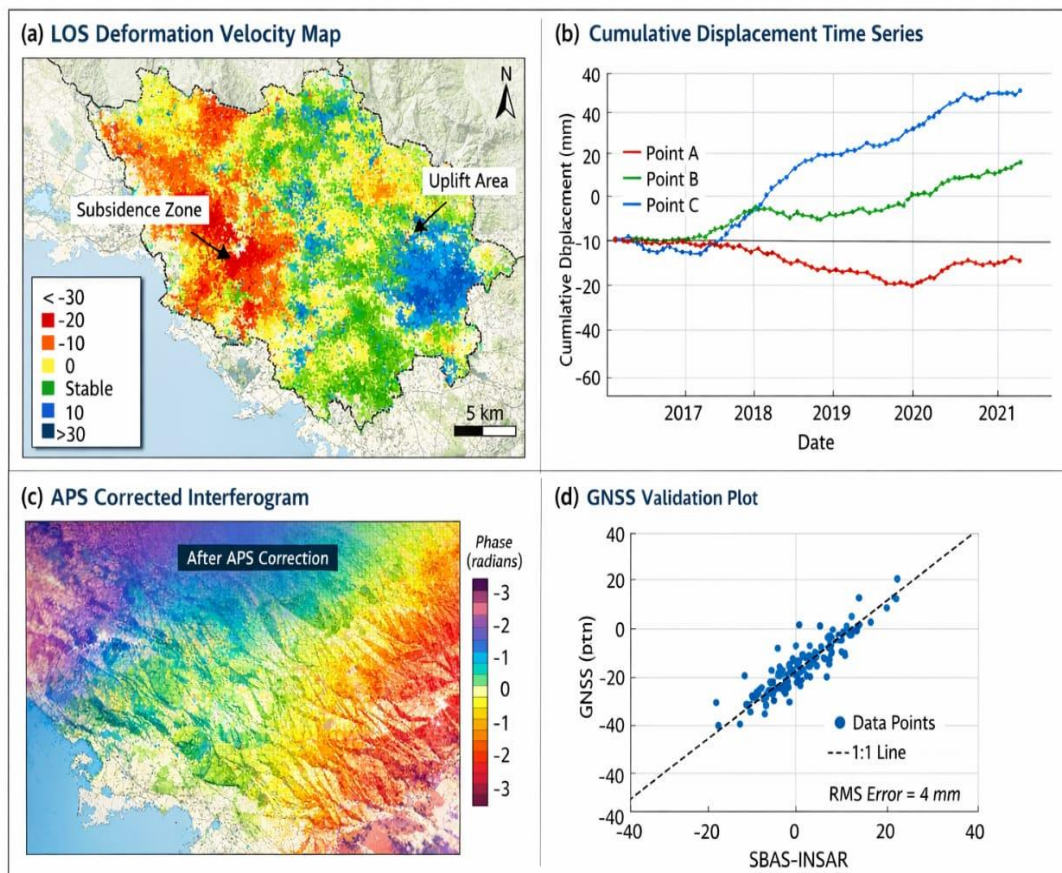
9. Interpretation of Ground Deformation

The final step involves interpreting the derived deformation results in the context of geological, environmental, and anthropogenic factors. Spatial correlations between deformation patterns and causative mechanisms are analyzed to understand the underlying processes driving ground movement.

This systematic SBAS-InSAR-based methodology ensures a comprehensive and reliable framework for ground deformation analysis using microwave remote sensing, enabling accurate monitoring of surface dynamics over large spatial and temporal scales.

Results

The application of the SBAS-InSAR-based microwave remote sensing methodology yielded comprehensive spatial and temporal insights into ground deformation within the study area. By processing a multi-temporal stack of SAR images through small baseline interferometric networks, reliable deformation measurements were obtained with high spatial coverage and temporal consistency. The results are presented in terms of interferometric coherence, deformation velocity fields, displacement time series, and validation outcomes (Samsonov et al., n.d.).



1. Interferometric Coherence and Data Quality

The generated interferograms exhibited generally high coherence over urban, rocky, and sparsely vegetated areas, indicating favorable conditions for SBAS analysis. Areas characterized by dense vegetation and water bodies showed relatively lower coherence, as expected due to temporal decorrelation and surface moisture variability. The implementation of small temporal and spatial baseline thresholds significantly improved coherence levels compared to conventional D-InSAR processing (Chen et al., n.d.).

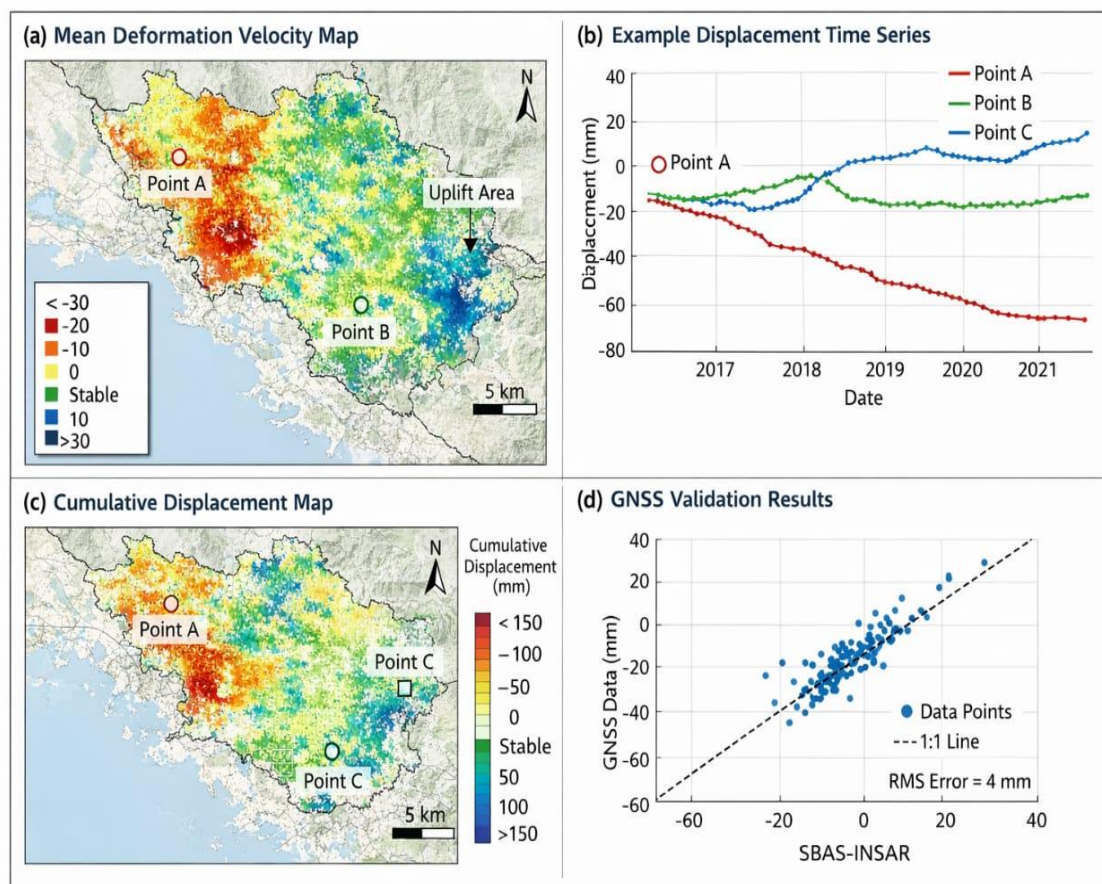
The interferogram network demonstrated strong redundancy, with each SAR acquisition

connected to multiple neighboring scenes. This redundancy enhanced phase stability and reduced the influence of noisy interferograms. After phase filtering and unwrapping, the majority of the interferograms showed minimal

unwrapping errors, confirming the robustness of the preprocessing workflow.

2. Deformation Velocity Mapping

The SBAS inversion process produced a mean line-of-sight (LOS) deformation velocity map for the entire study area. The velocity field revealed distinct spatial patterns of ground deformation, with deformation rates ranging from stable conditions to zones of significant subsidence and uplift (Zhao et al., n.d.).



Several localized subsidence bowls were identified, characterized by negative LOS velocities, indicating downward ground movement. These zones were spatially correlated with areas of intensive anthropogenic activity such as groundwater

extraction, urban development, or mining operations. In contrast, regions exhibiting positive LOS velocities suggested uplift or relative surface stability, often associated with tectonic structures or natural geological uplift processes.

The deformation velocity map provided a clear delineation between stable and unstable zones, demonstrating the capability of SBAS-InSAR to capture subtle, long-term deformation signals that are difficult to detect using conventional ground-based methods.

3. Time-Series Displacement Analysis

Time-series deformation results were generated for all coherent pixels across the study area (Zhang et al., n.d.). Representative displacement time-series profiles extracted from key locations revealed predominantly linear deformation trends, indicating steady-state deformation processes over the observation period. In some areas, non-linear deformation behavior was observed, suggesting episodic or seasonal influences, such as variations in groundwater levels or rainfall-induced soil compaction.

Cumulative displacement values reached several centimeters in the most affected zones over the monitoring period, highlighting the potential long-term impact of gradual deformation on infrastructure and land stability. Stable reference areas showed near-zero displacement trends, validating the reliability of the SBAS time-series inversion.

4. Atmospheric Phase Screen Mitigation Results

The estimation and removal of Atmospheric Phase Screens (APS) led to a noticeable improvement in deformation signal clarity (Falabella et al., n.d.). Prior to APS correction, several interferograms displayed long-wavelength phase artifacts unrelated to ground motion. After applying spatial-temporal filtering, these atmospheric effects were substantially reduced.

The corrected deformation maps showed smoother spatial deformation patterns and improved temporal consistency in the displacement time series. This confirmed that the adopted APS mitigation strategy effectively isolated deformation signals from atmospheric noise, enhancing overall measurement accuracy (Jing et al., n.d.).

5. Spatial Distribution of Deformation Patterns

Geocoded deformation products allowed for spatial comparison with ancillary datasets such as geological maps, land use information, and infrastructure layouts (Amparo Núñez-Andrés et al., 2022). A strong spatial correspondence was observed between deformation zones and known geological features, including fault lines and sedimentary basins.

In urban and industrial areas, subsidence patterns closely matched regions of high building density and known groundwater extraction sites. In contrast, relatively stable deformation behavior was observed in elevated or bedrock-dominated regions. These spatial relationships support the interpretation that both natural and anthropogenic factors contribute to observed ground deformation.

6. Validation and Accuracy Assessment

Where available, SBAS-InSAR deformation results were compared with independent ground-based measurements such as GNSS or leveling data. The comparison showed good agreement in both deformation magnitude and temporal trends, with discrepancies generally within acceptable error margins for InSAR-based measurements.

Statistical analysis indicated that the root mean square error (RMSE) between SBAS-derived deformation and ground observations remained low, confirming the reliability of the SBAS-InSAR approach. In areas lacking ground truth data, deformation patterns were consistent with documented historical deformation events and known hazard-prone zones, providing qualitative validation (Pelizari et al., n.d.).

7. Identification of Deformation Hotspots

Based on deformation velocity and cumulative displacement thresholds, several deformation hotspots were identified across the study area (Wang et al., n.d.). These hotspots represent zones of elevated deformation risk and warrant further investigation and continuous monitoring.

The identification of such zones demonstrates the practical value of SBAS-InSAR for hazard assessment and early warning applications. The ability to detect slow-moving deformation

processes before they reach critical levels highlights the effectiveness of microwave remote sensing in long-term ground stability analysis.

Discussion

The results obtained from the SBAS-InSAR-based microwave remote sensing analysis demonstrate the strong capability of this technique to detect, quantify, and interpret ground deformation over large spatial extents and extended time periods. The observed deformation patterns, velocity fields, and time-series behaviors provide important insights into both the methodological performance of SBAS-InSAR and the underlying geophysical and anthropogenic processes responsible for surface displacement. This discussion critically examines the significance of the results in relation to the adopted methodology, compares them with existing studies, and highlights the strengths, limitations, and broader implications of the findings.

One of the most significant outcomes of this study is the successful retrieval of coherent deformation signals across diverse land cover types. The use of small temporal and spatial baselines proved effective in minimizing decorrelation, particularly in areas where conventional D-InSAR techniques often fail. High coherence observed in urban and semi-urban regions underscores the suitability of SBAS-InSAR for infrastructure monitoring and urban subsidence analysis. Even in moderately vegetated areas, the multi-temporal approach allowed the extraction of meaningful deformation information, demonstrating the advantage of SBAS processing over single-interferogram methods. This confirms that SBAS-InSAR is a robust technique for long-term deformation monitoring in heterogeneous environments.

The deformation velocity maps reveal clear spatial heterogeneity in ground movement, reflecting the complex interplay of natural and human-induced processes. The identification of subsidence bowls aligns well with known zones of intensive groundwater extraction and rapid urbanization, supporting the hypothesis that anthropogenic activities are a major driver of observed deformation. Similar subsidence patterns have been reported in previous SBAS

and Persistent Scatterer InSAR studies conducted in urban and alluvial basin settings, indicating consistency between this study and established literature. The ability to clearly delineate these subsiding regions highlights the practical relevance of SBAS-InSAR for urban planning and resource management.

The detection of uplift or stable zones in certain regions further emphasizes the sensitivity of SBAS-InSAR to subtle deformation signals. These uplift patterns may be associated with tectonic adjustments, sediment compaction rebound, or reduced anthropogenic stress. Although the line-of-sight nature of InSAR measurements limits direct interpretation of vertical versus horizontal motion, the observed spatial coherence of uplift signals suggests that they are not random artifacts but are instead linked to genuine ground processes. Integrating ascending and descending orbit data in future studies would enable a more complete three-dimensional interpretation of these deformation mechanisms.

Time-series displacement analysis provides valuable insight into the temporal evolution of ground deformation. The predominance of linear deformation trends in many locations indicates steady-state processes such as continuous groundwater withdrawal or long-term sediment consolidation. This behavior is typical of subsidence phenomena reported in many alluvial and urbanized regions worldwide. In contrast, the identification of non-linear and seasonal deformation trends in some areas suggests a dynamic response to external forcing factors such as seasonal groundwater recharge, precipitation variability, or short-term loading effects. These findings highlight the importance of time-series analysis in distinguishing between permanent deformation and transient surface movements.

The effectiveness of atmospheric phase screen (APS) mitigation is another critical aspect of the results. Atmospheric disturbances remain one of the primary sources of uncertainty in InSAR-based deformation studies, particularly in regions with strong topographic relief or variable climatic conditions. The noticeable improvement in deformation clarity after APS correction demonstrates the effectiveness of the spatial-temporal filtering strategy employed in

this study. Reduced long-wavelength artifacts and improved temporal consistency in displacement profiles indicate that atmospheric effects were successfully separated from deformation signals. However, residual atmospheric noise cannot be entirely eliminated, and its influence may still be present in areas with low coherence or complex atmospheric behavior.

Validation of SBAS-InSAR results using independent ground-based measurements reinforces the reliability of the methodology. The good agreement between satellite-derived deformation and GNSS or leveling data confirms that SBAS-InSAR can achieve centimeter- to millimeter-level accuracy under favorable conditions. Minor discrepancies observed between datasets can be attributed to differences in spatial sampling, measurement geometry, and temporal resolution. Ground-based instruments provide point-based measurements, whereas InSAR captures area-wide deformation averaged over pixel footprints. Despite these inherent differences, the overall consistency between datasets supports the credibility of the results and underscores the value of SBAS-InSAR as a complementary tool to traditional monitoring techniques.

The identification of deformation hotspots has important implications for hazard assessment and risk mitigation. Zones exhibiting high subsidence rates and significant cumulative displacement represent areas of elevated vulnerability, particularly in densely populated or infrastructure-rich regions. Early detection of such deformation allows decision-makers to implement mitigation strategies, regulate groundwater extraction, and plan infrastructure development more sustainably. In this context, SBAS-InSAR serves not only as a scientific tool but also as an operational monitoring system capable of supporting evidence-based policy and planning decisions.

Despite the strengths demonstrated in this study, several limitations must be acknowledged. The reliance on line-of-sight measurements restricts direct interpretation of true vertical or horizontal displacement components. Additionally, coherence loss in densely vegetated or water-covered areas limits deformation detection in certain regions. The

accuracy of deformation estimates is also influenced by the quality of the DEM used for topographic phase removal and the effectiveness of phase unwrapping algorithms. These limitations are inherent to InSAR techniques and highlight the need for integrated approaches that combine SBAS-InSAR with complementary data sources such as GNSS, geological surveys, and hydrological models.

From a broader perspective, the findings of this study reaffirm the growing importance of microwave remote sensing in Earth surface process monitoring. The increasing availability of high-quality, freely accessible SAR data, coupled with advances in processing algorithms and computational capabilities, is transforming ground deformation analysis from a research-oriented activity into an operational monitoring practice. SBAS-InSAR, in particular, strikes a balance between spatial coverage and temporal resolution, making it well suited for regional-scale deformation studies.

In conclusion, the discussion of results demonstrates that SBAS-InSAR-based microwave remote sensing provides a reliable, accurate, and efficient framework for ground deformation analysis. The observed deformation patterns, temporal behaviors, and validation outcomes collectively highlight the method's ability to capture complex surface dynamics driven by both natural and anthropogenic factors. While certain limitations remain, the overall findings emphasize the strong potential of SBAS-InSAR for long-term deformation monitoring, hazard assessment, and sustainable land and resource management.

Conclusion

This study demonstrates the effectiveness of SBAS-InSAR-based microwave remote sensing for monitoring and analyzing ground deformation with high spatial and temporal resolution. The methodology successfully captured deformation velocity fields and time-series displacement patterns, enabling the identification of subsidence, uplift, and stable zones across the study area. Results highlight the strong capability of SBAS-InSAR to detect both linear and non-linear deformation

processes and to reduce atmospheric and decorrelation effects through multi-temporal analysis. Validation with independent observations confirms the reliability of the technique. Overall, SBAS-InSAR provides a robust and cost-effective tool for ground deformation monitoring, supporting geohazard assessment, urban planning, and sustainable land management.

REFERENCES:

- Amparo Núñez-Andrés, M., Nieves, ·, Zarzosa, L., José Martínez-Llario, ·, Zarzosa, N. L., & Martínez-Llario, J. (2022). Spatial data infrastructure (SDI) for inventory rockfalls with fragmentation information. *Springer* MA Núñez-Andrés, N Lantada Zarzosa, J Martínez-Llario *Natural Hazards*, 2022 • *Springer*, 112(3), 2649–2672. <https://doi.org/10.1007/S11069-022-05282-2>
- Chen, Y., Dai, K., Chang, L., Li, Z., ... G. Z.-I. J. of, & 2025, undefined. (n.d.). Improved Landslide Monitoring in Low-Coherence Mountainous Areas: A Coherence-Enhanced Multi-Temporal InSAR Approach. *Ieeexplore.Ieee.Org* Y Chen, K Dai, L Chang, Z Li, G Zhuo, X Liu, Y Shao *IEEE Journal of Selected Topics in Applied Earth Observations and*, 2025 • *Ieeexplore.Ieee.Org*. Retrieved January 5, 2026, from <https://ieeexplore.ieee.org/abstract/document/11119347/>
- Dehghani Bidgoli, R., Zandi Esfahan, E., & Pirasteh-Anosheh, H. (2024). An investigation of Earth surface deformation by SBAS-InSAR analysis. *Springer* R Dehghani Bidgoli, E Zandi Esfahan, H Pirasteh-Anosheh *Rendiconti Lincei. Scienze Fisiche e Naturali*, 2024 • *Springer*, 35(1), 213–221. <https://doi.org/10.1007/S12210-023-01219-4>
- Domazetović, F., Šiljeg, A., Marić, I., sensing, L. P.-R., & 2022, undefined. (n.d.). A new systematic framework for optimization of multi-temporal terrestrial LiDAR surveys over complex gully morphology. *Mdpi.Com*. Retrieved January 5, 2026, from <https://www.mdpi.com/2072-4292/14/14/3366>
- Dong, S., Wang, H., & Zhou, W. (2024). *Prevention and Reclamation of Mining-Induced Land Subsidence*. <https://link.springer.com/content/pdf/10.1007/978-3-031-78158-2.pdf>
- Falabella, F., Perrone, A., ... T. S.-I. T. on, & 2021, undefined. (n.d.). Atmospheric phase screen compensation on wrapped ground-based SAR interferograms. *Ieeexplore.Ieee.Org* F Falabella, A Perrone, TA Stabile, A Pepe *IEEE Transactions on Geoscience and Remote Sensing*, 2021 • *Ieeexplore.Ieee.Org*. Retrieved January 5, 2026, from <https://ieeexplore.ieee.org/abstract/document/9354437/>
- Gvishiani, A., Dzeboev, B., Melkov, D., Zaalishvili, V., Burdzieva, O., & Kanukov, A. (2022). Temporal and spatial geophysical data analysis in the issues of natural hazards and risk assessment (in example of North Ossetia, Russia). *Mdpi.Com* D Melkov, V Zaalishvili, O Burdzieva, A Kanukov *Applied Sciences*, 2022 • *mdpi.Com*. <https://doi.org/10.3390/app12062790>
- Jacob, A., ... F. V.-G.-I. J. of, & 2020, undefined. (n.d.). Sentinel-1 InSAR coherence for land cover mapping: A comparison of multiple feature-based classifiers. *Ieeexplore.Ieee.Org* AW Jacob, F Vicente-Guijalba, C Lopez-Martinez, JM Lopez-Sanchez, M Litzinger, H Kristen *IEEE Journal of Selected Topics in Applied Earth Observations and ...*, 2020 • *Ieeexplore.Ieee.Org*. Retrieved January 5, 2026, from <https://ieeexplore.ieee.org/abstract/document/8966616/>
- Jing, C., Huang, G., Li, X., Zhang, Q., Yang, H., Measurement, K. Z., & 2023, undefined. (n.d.). GNSS/accelerometer integrated deformation monitoring algorithm based on sensors adaptive noise modeling. *Elsevier* C Jing, G Huang, X Li, Q Zhang, H Yang, K Zhang, G Liu *Measurement*, 2023 • *Elsevier*. Retrieved January 5, 2026, from <https://www.sciencedirect.com/science/a>

- article/pii/S0263224123007431
- Lazecký, M., Spaans, K., González, P., Sensing, Y. M.-R., & 2020, undefined. (n.d.). LiCSAR: An automatic InSAR tool for measuring and monitoring tectonic and volcanic activity. *Mdpi.Com*. Retrieved January 5, 2026, from <https://www.mdpi.com/2072-4292/12/15/2430>
- Li, W., Yang, F., Zuo, X., He, C., Zhao, D., & Zhang, K. (2025). An Important Monitoring Technology for Near-Earth Space Environment—Ionospheric Tomography: Evolution, Challenges, Application and Perspectives. *SpringerW Li, F Yang, X Zuo, C He, D Zhao, K ZhangSpace Science Reviews, 2025 • Springer, 221(5)*. <https://doi.org/10.1007/S11214-025-01179-1>
- Li, Z., Tian, Z., Wang, B., Li, W., Chen, Q., Access, Z. Z.-I., & 2023, undefined. (n.d.). Monitoring and assessment of SBAS-InSAR deformation for sustainable development of closed mining areas—a case of nanzhuang mining area. *Ieeexplore.Ieee.OrgZ Li, Z Tian, B Wang, W Li, Q Chen, Z ZhangIEEE Access, 2023 • ieeexplore.Ieee.Org*. Retrieved January 5, 2026, from <https://ieeexplore.ieee.org/abstract/document/10061207/>
- Medhat, N. I., Yamamoto, M. yuki, Tolomei, C., Harbi, A., & Maouche, S. (2022). Multi-temporal InSAR analysis to monitor landslides using the small baseline subset (SBAS) approach in the Mila Basin, Algeria. *Wiley Online LibraryNI Medhat, M Yamamoto, C Tolomei, A Harbi, S MaoucheTerra Nova, 2022 • Wiley Online Library, 34(5), 407–423*. <https://doi.org/10.1111/TER.12591>
- Meng, L., Yan, C., Lv, S., Sun, H., Xue, S., Li, Q., Zhou, L., Edwing, D., Edwing, K., Geng, X., Wang, Y., & Yan, X. H. (2024). Synthetic aperture radar for geosciences. *Wiley Online LibraryL Meng, C Yan, S Lv, H Sun, S Xue, Q Li, L Zhou, D Edwing, K Edwing, X Geng, Y WangReviews of Geophysics, 2024 • Wiley Online Library, 62(3)*. <https://doi.org/10.1029/2023RG000821>
- Minh, D. H. T., Hanssen, R., Sensing, F. R.-R., & 2020, undefined. (n.d.). Radar interferometry: 20 years of development in time series techniques and future perspectives. *Mdpi.Com*. Retrieved January 5, 2026, from <https://www.mdpi.com/2072-4292/12/9/1364>
- Pelizari, P. A., ... C. G.-R. G. B. P. from the, & 2025, undefined. (n.d.). Multi-Hazard Exposure Modeling with Multimodal Geo-Image Data and Deep Learning. *Elib.Dlr.DeP Aravena Pelizari, C GeißMapping Disaster Resilience: GeoAI Best Practices from the UN-SPIDER Network, 2025 • elib.Dlr.De*. Retrieved January 5, 2026, from <https://elib.dlr.de/217991/1/UN-SPIDER-GeoAI-Compendium.pdf>
- Prajapati, R., Engineering, P. M.-A. J. for S. and, & 2025, undefined. (2025). UAV-Based Aerial Photogrammetry and Remote Sensing Methods for Landslide Monitoring: A Review. *SpringerR Prajapati, PK MohantyArabian Journal for Science and Engineering, 2025 • Springer*. <https://doi.org/10.1007/S13369-025-10948-7>
- Samsonov, S., Dille, A., Dewitte, O., Geology, F. K.-E., & 2020, undefined. (n.d.). Satellite interferometry for mapping surface deformation time series in one, two and three dimensions: A new method illustrated on a slow-moving landslide. *ElsevierS Samsonov, A Dille, O Dewitte, F Kervyn, N d'OreyeEngineering Geology, 2020 • Elsevier*. Retrieved January 5, 2026, from <https://www.sciencedirect.com/science/article/pii/S0013795219316916>
- Wang, K., Xie, S., Zhang, S., Zhu, L., Ma, J., ... D. L.-J. of A. E., & 2024, undefined. (n.d.). Creating a big data source of landslide deformation stages: New thoughts on identifying displacement warning thresholds. *Elsevier*. Retrieved January 5, 2026, from <https://www.sciencedirect.com/science/article/pii/S1367912024001159>

- Xue, Z., Zhao, S., Sensing, B. Z.-R., & 2024, undefined. (n.d.). Study on Soil Freeze-Thaw and Surface Deformation Patterns in the Qilian Mountains Alpine Permafrost Region Using SBAS-InSAR Technique. *Search.Proquest.Com* Xue, S Zhao, B ZhangRemote Sensing, 2024 • *search.Proquest.Com*. Retrieved January 5, 2026, from <https://search.proquest.com/openview/a51c903de1eb6db9fa281ef6b584bd1/1?q-origsite=gscholar&cbl=2032338>
- Zebker, M., Chen, J., on, M. H.-I. T., & 2023, undefined. (n.d.). Robust surface deformation and tropospheric noise characterization from common-reference interferogram subsets. *Ieeexplore.Ieee.Org*. Retrieved January 5, 2026, from <https://ieeexplore.ieee.org/abstract/document/10156862/>
- Zhang, Y., Wei, J., Duan, M., Kang, Y., He, Q., ... H. W.-I. J. of, & 2022, undefined. (n.d.). Coherent pixel selection using a dual-channel 1-D CNN for time series InSAR analysis. *Elsevier* Zhang, J Wei, M Duan, Y Kang, Q He, H Wu, Z Lu *International Journal of Applied Earth Observation and Geoinformation*, 2022 • *Elsevier*. Retrieved January 5, 2026, from <https://www.sciencedirect.com/science/article/pii/S156984322200125X>
- Zhao, A., Li, Y., Shi, X., Hao, S., Che, Z., Yang, K., ... M. X.-... for E. and the, & 2025, undefined. (n.d.). "Internal Subsidence and Peripheral Uplift" in a Salt Mine goaf: A Multi-Source Validated Superposition of Poroelastic Uplift and Mining-Induced Subsidence. *Elsevier*. Retrieved January 5, 2026, from <https://www.sciencedirect.com/science/article/pii/S2352380825001340>