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Earth Observation for Tracking Surface Dynamics

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Earth Observation for Tracking Surface Dynamics

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DEDICATION

To My Favorite Chapter - the Erasmus Mundus GeoTech Journey,

This thesis honors a dream I once held quietly, until life allowed me to live it. Against the odds, I learned early that endings are not stops, but directions. It was curiosity that led me here, and curiosity that will keep me going.

The chapter is closing, but the vision remains.

With all that remains true. 🖤

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Earth Observation for Tracking Surface Dynamics

ABSTRACT

Large urban construction projects can cause small ground movements that may affect buildings and infrastructure but often go unnoticed in early stages. Traditional ground-based monitoring methods are limited in coverage and costly. This study investigates the use of satellite radar data to monitor ground deformation over an active construction site in the Central Business District (CBD) of Lahore, Pakistan. Sentinel-1 satellite data from November 2023 to November 2024 were analyzed using two time-series Interferometric Synthetic Aperture Radar (InSAR) techniques: Persistent Scatterer InSAR (PS-InSAR) and Small Baseline Subset (SBAS). The data were processed with the PyGMTSAR framework to generate ground displacement time series and Line-of-Sight (LOS) velocity maps. The results reveal clear spatial variations in ground movement, including stable areas and localized subsidence linked to construction activities. PS-InSAR provided detailed measurements over stable urban structures, while SBAS captured broader deformation patterns across the site. The combined approach demonstrates that Sentinel-1 time-series InSAR is a reliable and low-cost solution for monitoring construction-related ground deformation, supporting safer and more informed urban infrastructure planning.

KEYWORDS

Sentinel-1; Time-Series InSAR; PS-InSAR; SBAS; Urban Construction; Ground Deformation

Sustainable Development Goals (SGD):

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ACRONYMS

AOI – Area of Interest

APS – Atmospheric Phase Screen

CBD – Central Business District

DEM – Digital Elevation Model

DInSAR – Differential Interferometric Synthetic Aperture Radar

GNSS – Global Navigation Satellite System

InSAR – Interferometric Synthetic Aperture Radar

IW – Interferometric Wide

LOS – Line of Sight

MT-InSAR – Multi-Temporal Interferometric Synthetic Aperture Radar

PS – Persistent Scatterer

PSF – Persistent Scatterer Function

RMSE - Root Mean Square Error

SAR – Synthetic Aperture Radar

SBAS – Small Baseline Subset

SLC – Single Look Complex

STL – Seasonal and Trend decomposition using Loess

1. INTRODUCTION

1.1 Background and Motivation

Ground deformation affecting urban areas and construction sites represents a critical risk for infrastructure stability, public safety, and sustainable urban development. In particular, subsidence induced by anthropogenic activities such as construction loading, soil consolidation, and urban expansion can produce slow, spatially heterogeneous displacements that often remain undetected by conventional monitoring techniques until structural damage becomes visible. Traditional geodetic methods, including leveling and GNSS, provide high accuracy but are inherently limited to sparse measurement points and require prior installation of instruments, making them unsuitable for continuous, wide area monitoring of rapidly evolving construction environments.(Bakon et al., 2014; Orellana et al., 2023) Large scale urban development has consequently increased the demand for continuous monitoring of ground deformation, specifically in urban construction sites. If not properly monitored, activities like excavation, tunneling, piling and heavy structural loading can cause surface uplift or subsidence which potentially compromises structural integrity. Although in-situ surveying techniques, like leveling and Global Navigation Satellite System (GNSS) systems, provide highly accurate measurements but are limited to discrete locations. Moreover, ground-based monitoring techniques require substantial logistical and financial investments which makes them less feasible for large scale deformation monitoring for longer term, particularly in areas with underdeveloped geodetic infrastructure. (Hanssen, 2010; Wasowski & Bovenga, 2014) Satellite-based Interferometric Synthetic Aperture Radar (InSAR) has emerged as a powerful alternative for deformation monitoring, offering the ability to detect millimetric ground displacements over large areas without the need for in-situ instrumentation. Thanks to its all-weather, day-and-night acquisition capability, InSAR is particularly well suited for urban and infrastructure monitoring, where accessibility constraints and safety considerations often limit ground-based observations.(Bakon et al., 2016; Montuori et al., 2016) Synthetic Aperture Radar (SAR) Observation is an active remote sensing method that captures high-resolution images in nearly all-weather conditions. Unlike passive methods, SAR actively transmits signals and measures reflections to generate images. One advanced technique within microwave remote sensing is Interferometric Synthetic Aperture Radar, which involves the analysis of two co-registered SAR complex images. This method enables the extraction of geophysical information such as surface topography, deformation, forest cover, canopy height, and the detection of moving objects. InSAR can measure surface deformation with millimeter-level accuracy over wide areas and long temporal intervals. Its ability to operate independently of weather conditions and solar illumination makes it a valuable tool for continuous deformation monitoring, particularly in urban areas. Recent advancements in geolocation and satellite positioning have enabled more precise monitoring of surface deformations. Several multi-temporal InSAR (MT-InSAR) techniques have been developed, enabling robust time-series deformation analysis through the exploitation of large stacks of SAR images. Among various multi temporal InSAR techniques, Persistent Scatterer InSAR (PS-InSAR) and Small Baseline Subset (SBAS) methods are the most frequently employed applied and scientifically proven for deformation analysis. PS-InSAR focuses on identifying stable physical targets which have consistent scattering properties over time, making it advantageous in urban areas because artificial structures provide strong and consistent backscatter. Unlike PS-InSAR, SBAS relies on interferograms generated from SAR image pairs with minimal orbital separation (spatial baselines) and limited time gaps between acquisitions (temporal baselines). This technique minimizes decorrelation and improves deformation detection in areas where radar signal is not dominated by a single strong target. As a result of their distinct properties, the combined use of PS-InSAR and SBAS is highly effective and well suited for construction-related deformation monitoring. Recent studies have demonstrated that MT-InSAR techniques are particularly valuable for investigating subsidence processes related to construction-induced loading and post-construction consolidation. Advanced DInSAR analyses have shown that deformation patterns observed on buildings and infrastructure often reflect the combined effects of geological conditions, construction age, foundation type, and imposed loads, rather than purely natural subsidence processes. These findings highlight the importance of interpreting InSAR-derived deformation time series within the broader context of urban development and construction history to avoid misinterpretation of measured displacements. The Sentinel-1 mission, launched by the European Space Agency (ESA), has substantially expanded the operational applicability of MT-InSAR for ground deformation monitoring. The mission provides free and regularly acquired C-band SAR data with short revisit times and precise orbital information, enabling detailed time-series analysis across regional and local scales. The availability of long-term, freely accessible Sentinel-1 SAR data has significantly enhanced the feasibility of systematic infrastructure and construction-site monitoring using MT-InSAR. Sentinel-1's short revisit time, consistent acquisition strategy, and C-band wavelength provide favorable conditions for time-series deformation analysis in urban settings, enabling the detection of slow, non-linear deformation trends associated with construction activities and soil consolidation processes. As a result, Sentinel-1-based InSAR has been widely adopted for monitoring urban subsidence, infrastructure stability, and construction-related deformation worldwide. While time-series InSAR techniques have advanced considerably, their application to construction-related deformation monitoring in rapidly urbanizing regions of South Asia, including Pakistan, remains underexplored. Lahore, a big metropolitan city in Pakistan has experienced rapid urban expansion and intensive infrastructure development over recent decades. One of the most significant ongoing construction initiatives within the city is the Central Business District (CBD) project, which is located in the centre of Lahore. The project involves the redevelopment of the former Old Walton Airport area into a major commercial and business hub. Covering an area of more than 100 hectares, the CBD project represents a large-scale construction zone that requires systematic deformation monitoring. However, the absence of continuous and comprehensive monitoring increases the risk of undetected ground instability in such construction environments, underscoring the need for remote sensing–based monitoring approaches that can operate independently of in-situ measurements. This study applies Sentinel-1 time-series InSAR techniques, namely PS-InSAR and SBAS, to investigate long-term ground deformation over the Central Business District (CBD) construction site in Lahore, Pakistan. The research is motivated by the need to evaluate the effectiveness of Sentinel-1–based PS and SBAS approaches in detecting and analyzing ground surface dynamics associated with large-scale construction activities. By doing so, the study contributes both methodological insights and region-specific evidence to the growing body of InSAR-based urban deformation monitoring research.

1.2 Area of Interest

The Area of Interest (AOI) selected for this study corresponds to a major urban redevelopment zone located in the central part of Lahore, Pakistan. The site occupies the area of a former airport that is currently undergoing large-scale transformation into a central business district characterized by dense construction activity, including high-rise buildings, transportation infrastructure, and underground utilities. The scale and intensity of ongoing construction make the area particularly susceptible to ground deformation processes related to surface loading and subsurface disturbance. The AOI lies within an alluvial geological setting typical of the Indo-Gangetic plain, where unconsolidated to semi-consolidated sediments dominate the subsurface. Such geological conditions are known to be sensitive to construction-induced loading and consolidation, potentially leading to gradual surface deformation. The combination of geotechnical susceptibility and extensive construction activity provides a suitable context for investigating deformation processes using satellite-based monitoring techniques. From a remote sensing perspective, the urban character of the AOI provides favorable conditions for time-series InSAR analysis. The presence of numerous buildings and engineered structures ensures a high density of coherent radar targets suitable for Persistent Scatterer analysis, while the spatial extent of the redevelopment area allows the application of Small Baseline Subset techniques to capture distributed deformation patterns. The AOI therefore represents an appropriate and representative case study for evaluating Sentinel-1 time-series InSAR methods for construction-related deformation monitoring in a rapidly urbanizing urban environment.

1.3 Problem Statement

Monitoring construction-induced ground deformation requires the capability to detect subtle, often millimetric, surface displacements that evolve gradually over time. While optical remote sensing data, including freely available multispectral imagery, are widely used for land-cover mapping and change detection, they are fundamentally limited in their ability to measure small-scale vertical ground deformation. Optical techniques primarily rely on radiometric or geometric changes in surface features and are therefore more suitable for detecting abrupt or visually discernible changes, such as land-use conversion or structural damage, rather than slow, continuous deformation processes. As a result, optical data are generally inadequate for capturing the subtle deformation signals associated with construction-induced settlement and consolidation (Massonnet & Feigl, 1998; Hanssen, 2001; Wasowski & Bovenga, 2014). Airborne or terrestrial LiDAR data can provide high-resolution three-dimensional surface information and can detect elevation changes with high accuracy. However, LiDAR-based deformation monitoring is typically constrained by high acquisition costs, limited temporal availability, and logistical challenges related to repeated surveys. In practice, LiDAR campaigns are often conducted as single or sporadic acquisitions rather than as dense, long-term time series, making them unsuitable for continuous monthly monitoring over extended periods, such as one year or longer. This limitation is particularly pronounced in large construction projects and in regions where routine LiDAR surveys are not operationally or financially feasible (Crosetto et al., 2016; Pratesi et al., 2015). In contrast, satellite-based Interferometric Synthetic Aperture Radar (InSAR) provides a unique combination of wide-area coverage, high temporal sampling, and millimetric sensitivity to surface deformation. The systematic acquisition strategy and free data policy of the Sentinel-1 mission enable consistent time-series analysis without the need for repeated field campaigns. Consequently, Sentinel-1 time-series InSAR represents a practical and effective solution for monitoring subtle construction-related deformation, particularly in data-scarce regions where complementary datasets such as LiDAR or dense ground-based measurements are unavailable (Crosetto et al., 2016; Del Soldato et al., 2019).

1.4 Research Questions

This thesis aims to investigate the capability of Sentinel-1 time-series InSAR to monitor construction-induced surface deformation over the Central Business District (CBD) project in Lahore, Pakistan. In particular, the study focuses on evaluating whether radar-based techniques can capture subtle surface changes associated with large-scale construction activities and on assessing the performance of two widely used multi-temporal InSAR approaches, namely PS-InSAR and SBAS, implemented within the PyGMTSAR framework. Based on these objectives, the research is guided by the following research questions:

RQ1: Can Sentinel-1 time-series InSAR detect and characterize construction-induced ground deformation over the CBD Lahore?

RQ2: What are the spatial and temporal patterns of ground deformation observed over the construction site using Sentinel-1 InSAR data?

RQ3: How do PS-InSAR and SBAS differ in terms of deformation patterns, spatial coverage, and time-series behavior over the same study area?

RQ4: To what extent can a radar-only approach provide meaningful information for monitoring construction-related surface changes in a data-scarce urban environment such as Lahore?

2. LITERATURE REVIEW

2.1 Remote Sensing–Based Monitoring of Urban Surface Deformation

Remote sensing has become a key approach for monitoring urban surface deformation because it allows repeated, wide-area observation and can detect subtle displacement patterns that are difficult to capture with ground-based surveys alone. In particular, interferometric synthetic aperture radar (InSAR) is widely used because it can measure ground motion along the satellite line of sight with centimeter-to-millimeter sensitivity, dense spatial sampling, and consistent temporal coverage (Berardino et al., 2002; Ferretti et al., 2001). This capability is especially important in cities, where deformation may be driven by groundwater extraction, soft-soil consolidation, underground construction, and heavy infrastructure loading, often producing localized deformation hotspots that threaten buildings and lifeline networks (Bott et al., 2021; Ramirez et al., 2022). Two families of multi-temporal InSAR methods dominate urban deformation studies: Persistent Scatterer Interferometry (PSI/PS-InSAR) and Small Baseline Subset (SBAS). PSI exploits phase-stable radar targets that are common in built-up areas and supports millimetric motion detection when long SAR stacks are available (Ferretti et al., 2001). SBAS, in contrast, limits decorrelation by forming interferograms from pairs with small spatial and temporal baselines and reconstructs deformation time series from a network of interferograms (Berardino et al., 2002). Because urban scenes contain both stable point targets and more variable surfaces, hybrid approaches that combine PSI and SBAS can increase measurement density and improve overall reliability (Hooper, 2008). This is particularly relevant for construction environments, where coherence may vary between the built core and recently disturbed zones. The operational value of multi-temporal InSAR increased substantially with the Sentinel-1 mission, which provides systematic and freely accessible SAR acquisitions for routine monitoring. Raspini et al. (2018) demonstrated how Sentinel-1 enables a transition from one-off mapping to continuous deformation surveillance by updating time series as new data arrive and screening them for significant trend changes. Their work also emphasized that InSAR results are most useful when interpreted together with contextual information such as geology, land use, and field observations, because measurements are along the line of sight and data coverage depends on coherence (Raspini et al., 2018). At larger scales, nationwide services further illustrate how PSI/SBAS products can support systematic deformation monitoring once data access, processing chains, and quality control are stabilized (Kalia et al., 2017). Several studies highlight why urban deformation monitoring is critical in areas affected by long-term or spatially complex subsidence. Chaussard et al. (2021) showed that subsidence in Mexico City can be severe and persistent over decades, with major impacts on infrastructure and water systems. Bott et al. (2021) similarly emphasized subsidence as a major coastal hazard in Jakarta and Semarang Bay, noting that slow but continuous deformation can become socially normalized while still increasing risk. Although CBD Lahore is a construction-driven case rather than a coastal setting, these studies underline two transferable lessons: urban deformation often has mixed natural and anthropogenic drivers, and its societal relevance becomes clearer when spatial patterns and time-series evolution are documented consistently. Urban construction and underground works are especially well suited to Sentinel-1 PS/SBAS monitoring because they often produce localized, time-varying deformation. Ramirez et al. (2022) demonstrated that PS-InSAR can track deformation associated with tunneling and related activities such as dewatering, linking time-series signals to construction phases. At a different scale, Dong et al. (2021) showed how multi-track Sentinel-1 InSAR can first identify regional stability patterns and then focus on infrastructure corridors, validating results with leveling measurements and achieving millimeter-level agreement. This multi-scale logic is useful for CBD Lahore, where it is important to distinguish deformation confined to the construction footprint from broader subsidence trends. Because urban planning and engineering decisions may rely on InSAR products, accuracy and validation are essential, especially when comparing PSI and SBAS results. Cigna et al. (2021) addressed this by evaluating Sentinel-1 PSI and SBAS velocities against GNSS and leveling, demonstrating that both approaches can be rigorously assessed and that uncertainties can be quantified for responsible use in hazard and infrastructure contexts. Dong et al. (2021) further showed how independent geodetic validation strengthens confidence in infrastructure-scale results. For a one-year study window, such cross-checks and transparent uncertainty discussion are particularly important to avoid over-interpretation. Overall, the literature supports Sentinel-1 multi-temporal

InSAR as a practical and scientifically grounded approach for urban deformation monitoring, including deformation related to major construction activities. Foundational work established PSI and SBAS as robust time-series techniques (Berardino et al., 2002; Ferretti et al., 2001), later studies showed the benefit of combining their strengths in mixed urban environments (Hooper, 2008), and operational services demonstrated their value for regular monitoring and decision support (Kalia et al., 2017; Raspini et al., 2018). Application studies further show that urban deformation can be long-term and severe (Chaussard et al., 2021), socially consequential (Bott et al., 2021), and strongly influenced by construction processes (Ramirez et al., 2022), while validation-focused research emphasizes the need for careful cross-checking with independent measurements (Cigna et al., 2021; Dong et al., 2021). Together, these studies motivate a combined PS-and-SBAS approach for the CBD Lahore construction site, using one-year Sentinel-1 time series to map spatial deformation patterns, track temporal evolution during construction, and interpret results with explicit attention to uncertainty and method complementarity.

2.2 InSAR Techniques for Deformation Monitoring

Interferometric Synthetic Aperture Radar (InSAR) is widely used to measure surface deformation using repeated radar images of the same area. Its main advantage for deformation monitoring is the ability of radar sensors to operate day and night and through cloud cover. Modern InSAR exploits the phase of the radar signal, which contains precise distance information between the satellite and the ground; by comparing the phase from two acquisitions, small changes in satellite-to-ground distance can be detected and interpreted as topography or surface motion. The early DInSAR formulation demonstrated that, after removing topographic effects using a DEM and accounting for noise, phase differences can be interpreted as elevation change or surface deformation over large areas (Gabriel et al., 1989). In practice, deformation monitoring is not simply a matter of subtracting two images. InSAR measurements are affected by several error sources, including temporal decorrelation, atmospheric delays, and geometric factors such as perpendicular baseline variations. These effects limit where and how reliably deformation can be retrieved, particularly in areas undergoing rapid surface change or strong atmospheric variability. A comprehensive synthesis of InSAR capabilities and limitations explains why careful processing is required to separate deformation from noise and artifacts (Massonnet & Feigl, 1998). For this reason, the field has evolved from two-image DInSAR toward multi-temporal InSAR methods that exploit long image stacks. By using temporal redundancy, time-series approaches improve robustness and allow consistent ground motion to be estimated while reducing uncorrelated noise, representing a trade-off between simplicity and stability for long-term monitoring (Osmanoğlu et al., 2016). Within time-series InSAR, two major method families are particularly relevant for urban and construction environments: Persistent Scatterer Interferometry (PSI/PS-InSAR) and Small Baseline Subset (SBAS). PSI focuses on point-like targets that remain coherent over long periods, such as buildings and other stable structures, enabling high-precision deformation estimation on a network of reliable points (Ferretti et al., 2001). The feasibility of PSI depends on data characteristics and environmental conditions, including the number of images, baseline distribution, wavelength, and atmospheric variability, and construction activity itself may locally reduce coherence while nearby stable structures remain usable as reference points (Hanssen, 2005). SBAS, in contrast, reduces decorrelation and phase unwrapping difficulties by forming interferograms only from pairs with small temporal and spatial baselines and inverting the resulting network to retrieve deformation time series (Berardino et al., 2002). This approach is well suited to distributed deformation patterns and often provides broader spatial coverage, particularly where coherence is not limited to bright point targets. Because real scenes commonly mix stable urban structures with changing surfaces, hybrid strategies have been proposed that combine persistent scatterer and small-baseline concepts to improve performance across different land covers (Hooper, 2008). A structured review of PSI further summarizes data requirements, algorithmic principles, and practical issues in time-series deformation analysis (Crosetto et al., 2016). The increasing availability of dense satellite archives, especially from Sentinel-1, has further strengthened time-series InSAR by enabling more stable time series and better separation of deformation from noise. For example, large Sentinel-1 stacks processed with SBAS have been used to map present-day subsidence and relate deformation patterns to geological and infrastructural factors in major urban areas (Cigna & Tapete, 2021). In addition, multi-geometry approaches highlight that InSAR measures motion along the line of sight and that combining different viewing geometries can improve the interpretation of true ground displacement components (Pepe & Calò, 2017). Overall, the literature shows a clear methodological progression from early DInSAR (Gabriel et al., 1989), through systematic assessments of InSAR capabilities (Massonnet & Feigl, 1998), to PSI (Ferretti et al., 2001; Crosetto et al., 2016) and SBAS (Berardino et al., 2002), and finally to hybrid and comparative strategies (Hooper, 2008; Osmanoğlu et al., 2016). These foundations directly support a combined PS and SBAS analysis over an active construction corridor such as CBD Lahore, where PS methods provide precise point-based time series on stable structures, while SBAS complements them with broader spatial coverage and improved coherence management.

2.3 Principles of PS-InSAR

A useful way to introduce PS-InSAR is to start from the limitations of conventional repeat-pass InSAR. In standard InSAR, the phase difference between two SAR acquisitions contains information on topography and surface motion, but in practice it is also affected by orbit errors, atmospheric delays, and changes in ground scattering. When surfaces are vegetated, rough, or change rapidly, the radar echo within a pixel may vary between acquisitions, leading to decorrelation and noisy or unusable interferometric phase. A classic review of SAR interferometry identifies decorrelation, atmospheric disturbances, and data availability as key factors limiting coverage and accuracy, especially outside stable urban targets (Bürgmann et al., 2000). PS-InSAR was developed to work within these constraints by focusing only on pixels that behave as stable, point-like reflectors over long time periods, such as building corners, metallic structures, or exposed rocks. These persistent scatterers remain coherent across many acquisitions, even when most of the scene decorrelates. If a pixel's scattering remains stable, its phase history can be modeled and separated into meaningful components, enabling millimetric-level deformation estimation. The foundational PS framework demonstrated that coherent scatterers can be identified from long temporal stacks and that their phase histories can be jointly exploited to estimate line-of-sight displacement, residual topographic error, and atmospheric phase effects, effectively forming a geodetic-like network of stable observation points (Ferretti et al., 2001). A key practical principle of PS-InSAR is that the observed phase is not pure deformation but a mixture of contributions. Early work emphasized that DEM errors introduce a residual topographic phase dependent on perpendicular baseline, surface motion produces a time-dependent phase term, and the atmosphere adds a spatially correlated but temporally variable phase screen. By exploiting many interferograms with diverse baselines and temporal sampling, these components can be separated more reliably, which explains why PS-InSAR is particularly suited to long-term monitoring (Ferretti et al., 2000). In practice, PS processing is implemented as an estimation workflow rather than a single formula. Typical pipelines involve building an interferometric stack, selecting persistent scatterer candidates using amplitude or phase stability indicators, and then iteratively estimating deformation and residual height while reducing atmospheric and other nuisance components. This workflow perspective explains why quality control and network consistency are central to reliable PS-InSAR results (Bürgmann et al., 2000). Atmospheric phase screen (APS) estimation is especially critical when deformation rates are small, as APS is often the dominant error source. The PS approach exploits the spatial smoothness and temporal variability of atmospheric signals to estimate and remove APS, thereby improving the reliability of the remaining deformation time series (Ferretti et al., 2001). PS-InSAR has also evolved to address nonlinear deformation, which is common in settings such as construction zones or groundwater-related subsidence, where motion may accelerate or change trend over time. Early studies showed that constant-velocity models can be insufficient and emphasized the need for robust strategies to handle time-varying deformation histories (Ferretti et al., 2000). In parallel, small-baseline (SB) approaches were developed to reduce decorrelation by forming interferograms only between acquisitions that are close in time and geometry, improving coherence over distributed scatterers and complementing the PS philosophy (Bürgmann et al., 2000). Because real landscapes rarely consist of purely persistent or purely distributed scatterers, modern time-series methods often combine PS and SB concepts. A well-known multi-temporal approach explicitly integrates both strategies to improve coverage and signal-to-noise across different land covers, which is particularly useful in urban areas mixing stable structures with changing surfaces such as construction zones (Hooper et al., 2004). Related work further showed that phase-stability-driven selection can identify useful coherent points even outside ideal urban settings, emphasizing that the core principle of PS-InSAR is phase stability rather than brightness alone (Hooper et al., 2004; Kampes, 2006). From an application perspective, PS-type methods can provide millimetric precision under favorable conditions but primarily measure motion along the radar line of sight and are best suited to slow, continuous deformation. Interpretation therefore benefits from external information and engineering context, especially in complex environments such as subsidence areas or construction sites (Wasowski). Operational studies over large cities have demonstrated that PS-InSAR and related approaches can deliver dense deformation measurements that support the interpretation of urban subsidence, landslides, and infrastructure-related ground motion (Perissin & Wang, 2011). Finally, PS-InSAR can be viewed as a geodetic estimation problem in which observations, unknown parameters (deformation, residual height, nuisance terms), and quality measures are jointly modeled. This perspective helps explain why PS-InSAR produces reliable time series rather than isolated noisy interferograms, with confidence increasing through redundancy, network structure, and statistical checking (van Leijen, 2014.). In summary, the principles of PS-InSAR can be stated as: (1) select the most stable radar pixels, (2) use many acquisitions to separate deformation from topography and atmosphere, (3) control quality through network-based estimation, and (4) interpret results in line-of-sight geometry with awareness of limitations such as decorrelation and atmospheric artifacts. A comprehensive review confirms this evolution from early PS detection to mature, robust workflows for deformation monitoring (Crosetto et al., 2016).

2.4 Principles of SBAS

Small Baseline Subset (SBAS) InSAR is a time-series technique designed to measure surface deformation using stacks of SAR images rather than single interferogram pairs. The main motivation for SBAS is that individual interferograms are often noisy and unreliable, especially in vegetated or rapidly changing urban environments. SBAS improves robustness by selecting and combining only those image pairs with small temporal and spatial baselines, which are more likely to preserve coherence, and by exploiting redundancy across time to reconstruct consistent deformation histories

(Berardino et al., 2002). The core idea of SBAS is the “small baseline” principle: when image pairs are separated by large time intervals or large orbital baselines, coherence tends to degrade and interferometric quality decreases. SBAS therefore builds a network of interferograms from pairs that are close in time and geometry, favoring many high-quality observations over a few risky ones. These interferograms are not used independently but are connected in a network, allowing displacement time series to be reconstructed even when some acquisition dates are not directly linked by a single reliable interferogram (Berardino et al., 2002). This network-based formulation also accounts for the practical case in which strict baseline limits split the data into subsets that must be reconnected to recover a continuous deformation history. Even after careful pair selection, interferometric phase contains contributions from sources other than deformation, most notably atmospheric delays and residual topographic errors caused by imperfections in the DEM. SBAS relies on the fact that deformation typically evolves more consistently through time, whereas atmospheric effects vary more irregularly between acquisitions. By using many interferograms, SBAS reduces atmospheric noise and allows residual topographic effects to be estimated and mitigated through multi-temporal redundancy (Berardino et al., 2002; Lanari et al., 2004). From a methodological perspective, SBAS can therefore be viewed as a multi-step workflow that combines safer interferogram generation with network-based time-series reconstruction to isolate the most consistent deformation signal (Lanari et al., 2004). The accuracy of SBAS products has been evaluated using independent ground measurements such as leveling and GPS. These studies show that SBAS can provide reliable estimates of mean deformation rates and displacement, while also highlighting that errors may vary spatially and often increase with distance from the chosen reference area, making reference point selection and spatial data distribution important in urban applications (Casu et al., 2006). SBAS has also been demonstrated to scale from local sites to regional extents when the interferogram network and processing chain are carefully designed, emphasizing that SBAS is not only an algorithm but a complete workflow involving data selection, quality screening, inversion, and mapping (Casu et al., 2008). With the advent of Sentinel-1, SBAS methods have been adapted to handle large data volumes and frequent revisit times. Parallel SBAS implementations show how deformation time series can be efficiently generated at wide scale and validated against independent GPS observations, confirming the consistency of SBAS products when processing is carefully designed (Manunta et al., 2019). For urban construction environments, deformation may include both steady trends and irregular, episodic movements related to excavation, loading, or groundwater changes. Time-series studies therefore emphasize representing both long-term and short-term components and reducing atmospheric disturbances through temporal and spatial filtering (Mora et al., 2003). This highlights a key principle: SBAS is not limited to producing a single velocity map but is intended to reconstruct deformation histories through time (Mora et al., 2003). Long-term applications further show that SBAS can achieve high spatial detail when datasets from compatible sensors and geometries are combined carefully, provided that sensor differences and consistency constraints are respected to avoid introducing additional noise (Bonano et al., 2012). However, SBAS time-series inversion is sensitive to problematic observations such as phase unwrapping errors, temporary decorrelation, or localized disturbances. Robust, outlier-resistant reconstruction strategies have therefore been proposed to reduce sensitivity to a small number of incorrect interferograms and to improve the stability of the estimated time series (Lauknes et al., 2011). Related work on error propagation in small-baseline MT-InSAR further shows how different error sources can affect both velocity maps and time series, and why quality indicators are essential for identifying reliable pixels and filtering low-quality measurements before interpretation (Pepe, 2021). In real datasets, missing acquisitions or strict baseline limits may fragment the interferogram network into multiple subsets, potentially leading to unstable or unrealistic time series. Constrained SBAS approaches address this issue by introducing additional constraints that help maintain physically reasonable temporal continuity when the network is weakly connected (Liu et al., 2020). In simplified terms, SBAS can be seen as reconstructing a reliable “movie” of ground motion from many imperfect observations by carefully selecting pairs, controlling quality, suppressing atmospheric and DEM-related disturbances, and inverting the network to obtain the most consistent deformation history (Berardino et al., 2002; Lanari et al., 2004). For the CBD Lahore construction site, these principles are particularly relevant because the area includes both stable man-made structures and rapidly changing surfaces. SBAS is well suited to this context because it does not rely on a single interferogram but integrates many observations over time, while also supporting large-scale processing (parallel SBAS), robust inversion against problematic interferograms, and constrained reconstruction in fragmented networks (Lauknes et al., 2011; Liu et al., 2020; Manunta et al., 2019; Pepe, 2021). Together, these studies demonstrate that SBAS is specifically designed for time-series deformation monitoring using SAR image stacks and has been tested, scaled, and refined for real-world applications in urban and infrastructure environments (Bonano et al., 2012; Casu et al., 2006).

2.5 Deformation Monitoring Studies in Lahore

Lahore has become a key case study in Pakistan for land deformation monitoring because rapid urban growth relies heavily on groundwater extraction, while large construction and transport projects add stress to soft alluvial sediments. Recent InSAR studies consistently describe subsidence as an urban risk that develops gradually but can cause serious damage to buildings, roads, and infrastructure, making continuous monitoring essential for informed planning. An early city-scale reference is a one-year Sentinel-1 PSI analysis (August 2018–August 2019) that produced a deformation velocity map of Lahore using a SNAP–StaMPS workflow and interpreted the spatial patterns using multiple contextual datasets, including land cover, soil type, population density, transport networks, surface water channels, and groundwater extraction indicators. This study reported deformation ranging from localized uplift to notable subsidence, with the strongest subsidence concentrated in central Lahore and more stable or uplifted behavior in less populated areas near the Ravi River. Importantly, the authors linked subsidence primarily to groundwater withdrawal, while also highlighting the influence of soil type, land-cover change, and canal or river recharge in moderating deformation in some areas (Ahmad et al., 2022). A subsequent study extended this analysis to 2020–2021 using PS-InSAR with both ascending and descending Sentinel-1 tracks processed in Sarproz. It emphasized the suitability of PS-InSAR for large cities, where buildings and infrastructure provide abundant persistent scatterers for reliable millimeter-level deformation tracking. Within this period, the study reported subsidence reaching approximately −110 mm in areas associated with high groundwater extraction, while some surrounding zones showed uplift of up to about +21 mm. Stronger subsidence was linked to alluvial and clay-rich deposits and heavy building loads, reinforcing the connection between urban conditions and deformation patterns (Hussain et al., 2022). More recently, a long-term, multi-sensor study expanded Lahore deformation monitoring from short snapshots to a decade-scale perspective by integrating Sentinel-1 PS-InSAR (2014–2023) with groundwater storage information. This work generated a dense set of persistent scatterer points and reported subsidence rates on the order of centimeters per year, with the strongest negative rates in densely built-up areas. By combining PS-InSAR results with GRACE groundwater storage anomaly data and depth-to-water measurements from monitoring wells, the study showed consistent groundwater decline at regional scale and higher depth-to-water values in central Lahore. It also reported strong statistical associations between subsidence and groundwater indicators in high-subsidence zones and recommended future validation using GNSS to further strengthen confidence in the results (Gulzar et al., 2025). Together, these studies provide both scientific and practical lessons. First, they consistently favor multi-temporal InSAR methods, especially PS-InSAR, because these approaches are well suited to long time series and dense urban environments and can reduce limitations such as decorrelation compared to two-image methods. Second, they demonstrate that interpretation becomes more robust when deformation patterns are evaluated alongside contextual information such as soil type, water channels, transport corridors, and groundwater use, avoiding oversimplified explanations and improving relevance for decision-making (Ahmad et al., 2022; Gulzar et al., 2025). At the same time, the Lahore literature leaves clear room for focused, site-specific studies. City-wide maps are effective for identifying hotspots and broad drivers, but they cannot fully explain deformation processes at a specific construction site over a limited project period, where local loading, excavation, dewatering, and rapid land-cover change may produce localized signals. In this sense, existing research establishes that subsidence is present, that Sentinel-1 PS-InSAR can monitor it reliably, and that groundwater decline is a major background driver. Your thesis builds on this foundation by focusing on the CBD construction area and by combining PS-InSAR and SBAS over a one-year period to capture both stable-point deformation and distributed deformation patterns relevant to construction monitoring (Ahmad et al., 2022; Gulzar et al., 2025;

Hussain et al., 2022). Overall, Lahore studies show a clear progression from initial city-scale mapping and factor analysis, to recent high-resolution subsidence snapshots, and finally to long-term, multi-sensor integration linking deformation to groundwater dynamics. This progression motivates the present study by highlighting the need for careful, site-specific analysis that translates satellite-based deformation time series into practical understanding for construction and urban management (Ahmad et al., 2022; Gulzar et al., 2025; Hussain et al., 2022).

3. METHODOLOGY

3.1 Area Of Interest

Lahore (31°32′59″N 74°20′37″E) is the capital of Punjab province of Pakistan and the second largest city of the country after Karachi. The metropolitan and built-up extent of Lahore has expanded significantly over the past two decades, as demonstrated by several remote sensing–based studies on urban growth and land use change.

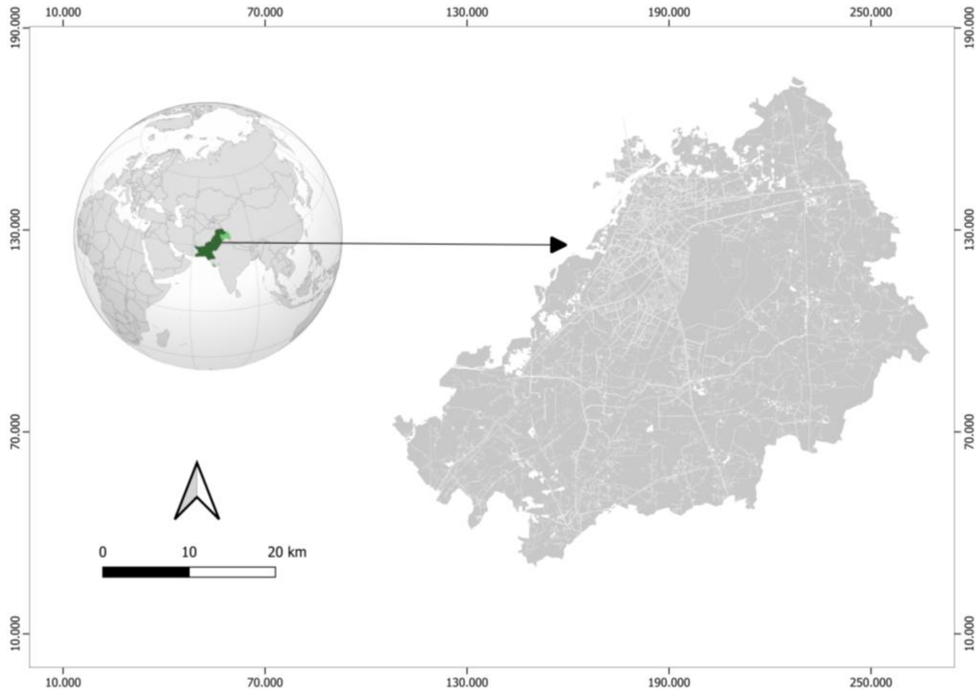

Figure 1: Location Map of Area of Interest

From a radar remote sensing perspective, this continuous increase in built-up infrastructure is advantageous for microwave-based deformation analysis, as dense urban environments provide a higher number of coherent and stable scatterers. A greater proportion of buildings, roads, and concrete surfaces contributes to an increased density of Persistent Scatterer (PS) points in Sentinel-1 acquisitions, which enhances the reliability of PS-InSAR and SBAS processing. The main Area of Interest (AOI) of this research is located in the central part of Lahore city. According to the technical reports of the Central Business District (CBD) Lahore project and visual interpretation of satellite imagery, the study site represents one of the largest ongoing construction zones in the city. The AOI is surrounded by well-known urban landmarks including Model Town, Gaddafi Stadium, Falcon Housing Society, and Packages Mall, and it also contains the historical monument Bab-e-Pakistan. The presence of dense infrastructure, large construction activities, and identifiable reference features provides favorable conditions for deriving meaningful deformation velocities using the combined PS–SBAS approach.

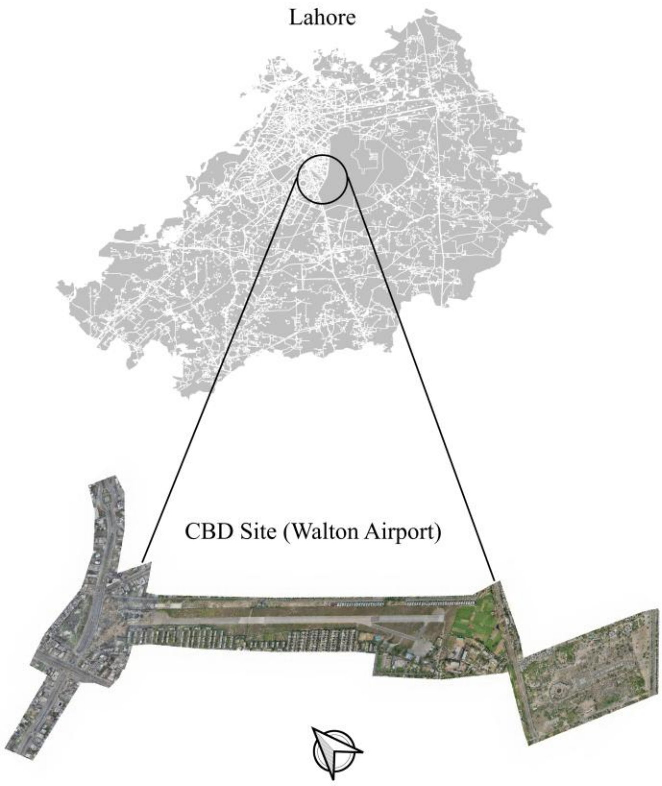

Figure 2 CBD Site Location Map

Site orientation plays a critical role in the outcome of InSAR-based deformation analysis, as it directly influences the selection of the appropriate Sentinel-1 subswath and burst. Correct orientation with respect to the satellite line-of-sight is essential to minimize geometric distortions such as layover and shadow, and to identify zones with reliable backscattering characteristics. This step enables the selection of reference areas with minimal layover effects and supports the identification of stable pixels required for initiating PS–SBAS processing.The selected AOI is located within the core urban fabric of Lahore, which is characterized by dense infrastructure and permanent constructions. Such an environment provides numerous coherent radar targets, including buildings, roads, and concrete surfaces, that act as Persistent Scatterers.

Furthermore, the relatively wide and open configuration of the site ensures clear visibility in Sentinel-1 geometry, while the ongoing construction activities offer ideal conditions for detecting recent surface changes and deformation trends.

3.2 Selection of Sentinel-1 Swath and Orbit Geometry

A crucial pre-analysis step prior to interferometric processing is the selection of an appropriate Sentinel-1 swath, as orbit geometry and satellite viewing angle have a direct impact on deformation results. In many cases, a single swath does not fully cover the Area of Interest (AOI), or the AOI is located near the edge of the swath, where geometric distortions and lower coherence may affect the reliability of PS–SBAS analysis. Therefore, careful evaluation of swath coverage is essential to ensure optimal acquisition geometry.

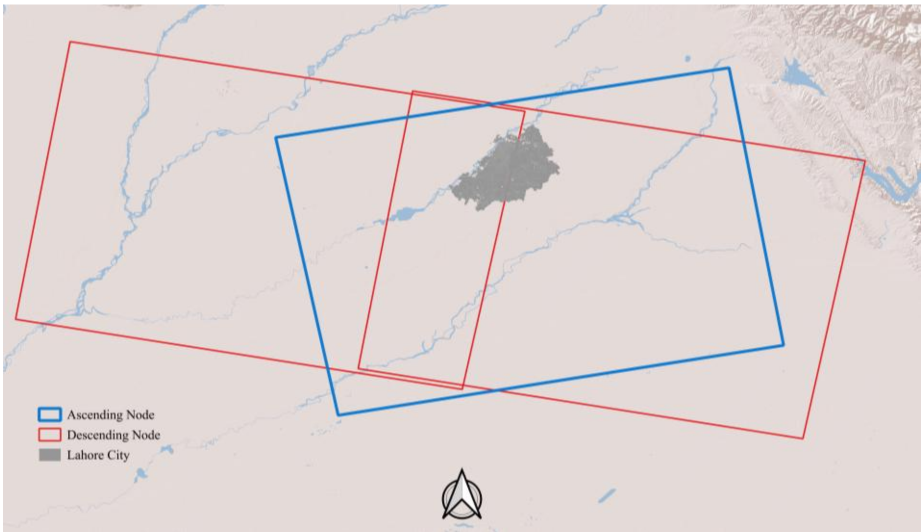

Figure 3 Optimal Swath Selection

The study area was examined in both ascending and descending viewing modes in order to determine the most suitable observation geometry. An optimal configuration is achieved when the AOI lies within the middle subswath of the Sentinel-1 IW acquisition, as this ensures consistent burst identification and minimizes potential discontinuities during time-series processing. When the AOI is positioned at the margins of a swath, variations in burst IDs and incidence angles can complicate the interferometric workflow and increase the risk of processing failure. As illustrated in Figure 3, the ascending swath (shown in blue) provides the most favorable geometry, with the AOI located near the central part of the subswath and well within a single burst segment. This configuration allows the selection of only the necessary bursts, reducing redundant data handling and significantly decreasing processing time. The assessment of swath suitability was performed using real-time visualization through the ASF Vertex platform, which enabled interactive inspection of orbit footprints and burst coverage prior to downloading Sentinel-1 scenes.

3.3 Time-Series InSAR Processing Framework Using PyGMTSAR

The PyGMTSAR framework has been recently introduced as a Python-based implementation that follows the same fundamental interferometric processing principles as GMTSAR. While both frameworks rely on identical InSAR concepts and workflows, they differ significantly in terms of computational environment and usability. GMTSAR operates primarily on Linux-based systems and requires advanced knowledge of software installation, dependency management, and environment configuration. In contrast, PyGMTSAR is designed to support cloud-based and containerized processing environments, minimizing the need for complex setup procedures. This design allows users to focus primarily on data preparation, parameter selection, and deformation analysis, rather than on software configuration and system-level troubleshooting. By simplifying data access, orbit handling, and processing execution, PyGMTSAR provides a more accessible and efficient platform for time-series InSAR analysis, while preserving the robustness of the original GMTSAR interferometric workflow. Moreover, the Python-based interface makes the processing chain more transparent and easier to reproduce, which is particularly important for academic studies and long-term monitoring projects. The modular structure of PyGMTSAR allows individual processing steps to be inspected, adjusted, and repeated when necessary, improving both flexibility and reliability of the analysis. In addition, the integration with widely used scientific Python libraries facilitates data visualization, quality control, and post-processing, enabling a smoother transition from raw SAR data to interpretable deformation products.

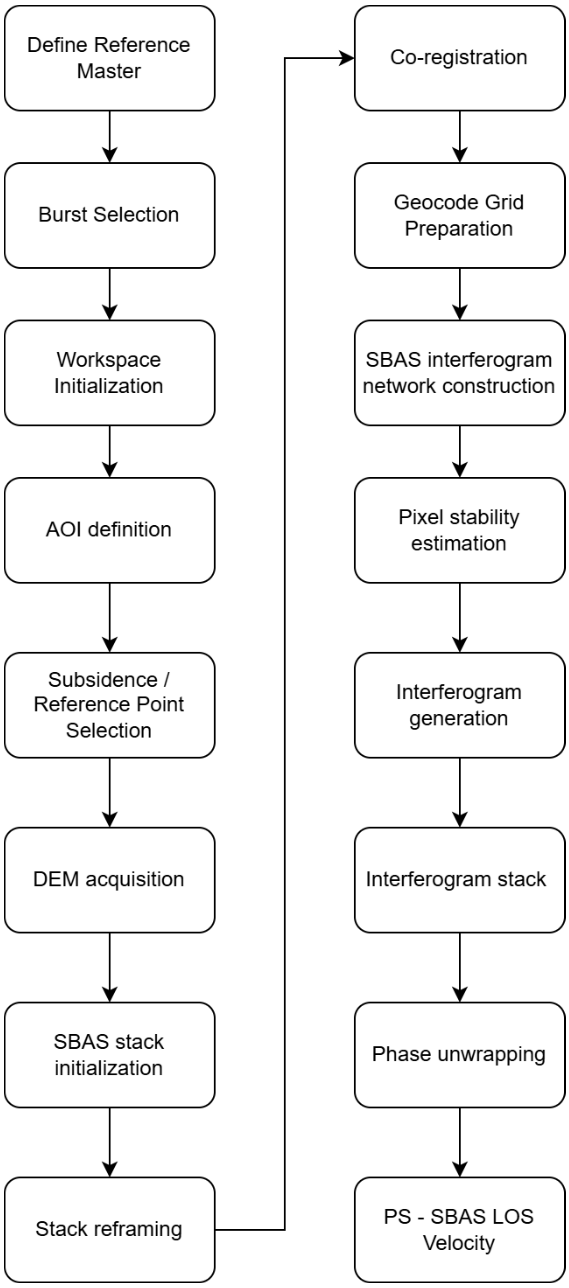

Figure 4 PyGMTSAR Based PS-SBAS Workflow

3.3.1 Computational Environment and Software Setup

Since the analysis was executed within a cloud-based environment, the PyGMTSAR framework and its required dependencies were verified against the runtime configuration prior to initiating data processing. This preliminary validation ensured compatibility between the processing environment and the computational requirements of the workflow.

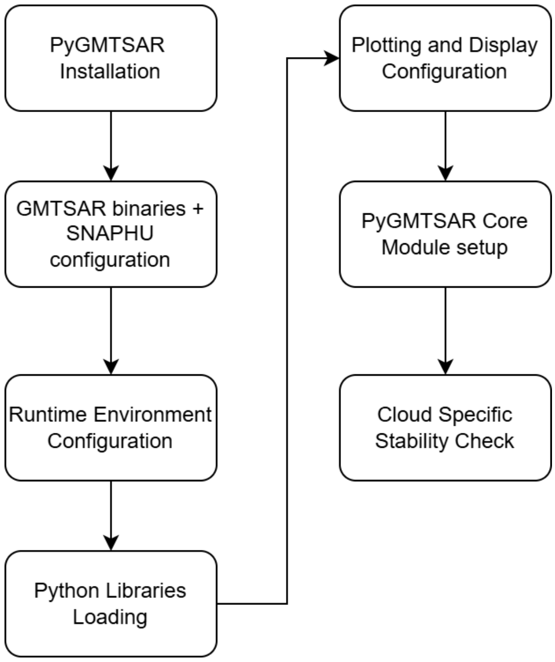

Figure 5 Computational Environment Initialization

The configuration was checked sequentially to confirm that all required components were correctly installed and accessible before proceeding with the interferometric analysis.The use of a cloud-based platform enabled on-the-fly environment verification and updates when necessary, thereby reducing the likelihood of configuration-related interruptions during processing. As a result, the analysis workflow was executed only after confirming that the computational environment was stable and properly configured.

3.3.2 DEFINING SENTINEL – 1 SLC SCENES AND PROCESSING PARAMETERS

The definition of the Sentinel-1 image dataset represents a critical step in the interferometric analysis. As summarized in the table 1, the subswath was selected through a preliminary visual inspection of the Sentinel-1 swath coverage to ensure full overlap with the Area of Interest.

Table 1 Sentinel 1 Data Specification

Parameter	Description
Satellite	Sentinel-1A
Product type	SLC
Acquisition mode	Interferometric Wide (IW)
Polarization	VV
Orbit direction	Ascending
Subswath	IW2
Acquisition period	06-Nov-2023 to 24-Nov-2024
Number of scenes	34

This targeted subswath selection allows the backend processing to focus exclusively on the required data, thereby improving computational efficiency by avoiding unnecessary processing of unused swaths. In addition, the orbit direction was explicitly defined as a processing parameter, as mixing acquisitions from different viewing geometries can lead to inconsistencies and processing errors in time-series InSAR analysis. All images used in this study were acquired in ascending orbit to maintain a consistent acquisition geometry throughout the observation period. The temporal extent of the dataset was determined based on prior knowledge of the construction activities at the study site. A total of 34 Sentinel-1 images acquired over approximately one year were selected to capture the evolution of surface deformation during the construction phase. Dual-polarized data were available; however, VV polarization was used for the interferometric analysis due to its higher sensitivity to surface structure and vertical deformation characteristics in urban environments.

3.3.3 AOI AND BURST SELECTION

The coordinates of the reference and subsidence points are (31.503378,74.335999) and (31.504391,74.336223), respectively. This spatial extent was selected to fully encompass the construction site, which is divided into multiple development phases.

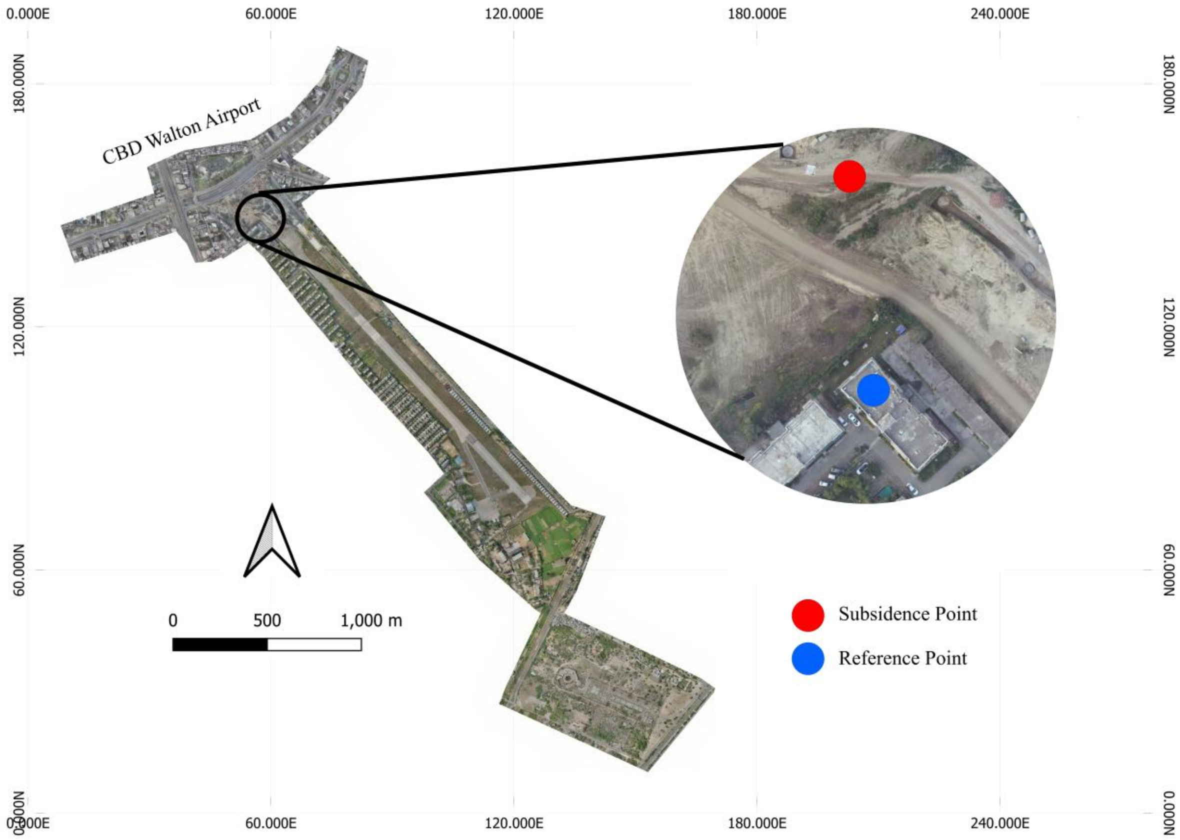

Figure 6 Reference and Subsidence Points

As construction activities initiated from Phase 1 highlighted in Figure 6, particular emphasis was placed on this zone for deformation analysis. Based on the project master plan, the construction of an underground parking plaza commenced around November 2023. Consequently, the point of subsidence was selected within this phase to capture the expected deformation signal associated with excavation and structural loading. In parallel, a reference point was chosen in close proximity to point of subsidence but located in an area expected to remain relatively stable throughout the observation period. Burst selection was performed in conjunction with the AOI definition to ensure that all selected Sentinel-1 bursts consistently covered the subsidence point, reference point, and the surrounding construction phases. In total, 33 bursts were selected, all focusing on the same spatial footprint and fully contained within the defined bounding box. This integrated selection of AOI, reference geometry, and bursts ensured spatial consistency and reliability for subsequent time-series interferometric analysis.

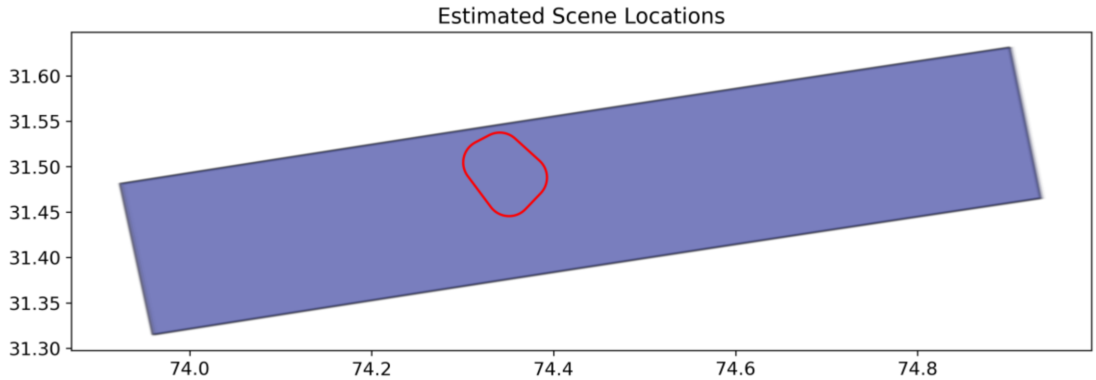

Figure 7 Selected Burst and Bounding Box of AOI

3.3.4 DEM LOADING

Following the burst selection and AOI delineation, a Digital Elevation Model (DEM) referenced to the WGS84 ellipsoid was loaded using the same spatial extent as the defined AOI in Figure 8. This is done for consistent topographic correction and geometric alignment for all subsequent interferometric processing steps.

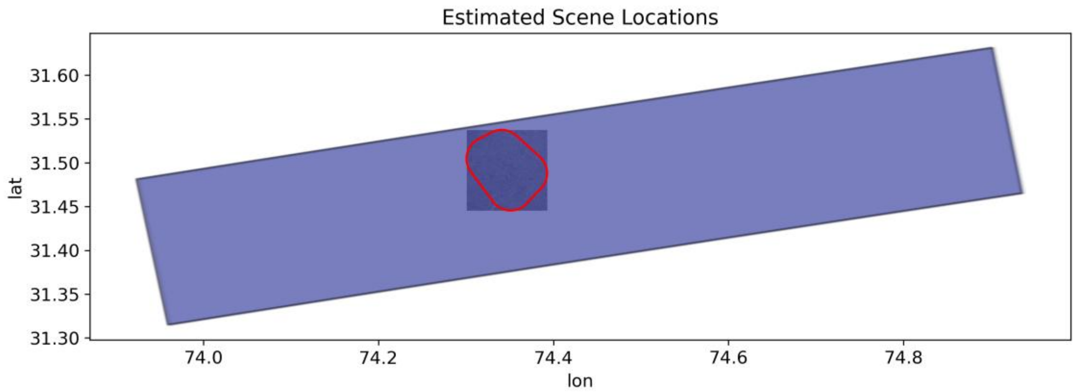

Figure 8 Dem Loading on AOI

3.3.5 STACK COREGISTRATION

Next step is the co-registration of all the images to a common reference geometry to ensure same pixel grid and burst to burst consistency, which is an essential step because InSAR requires subpixel alignment and any kind of misalignment inside this stack would create phase errors. Just like each step is important this step makes sure that each image in the stack aligns perfectly pixel by pixel with the reference image. The acquired images are saved in radar geometry and this sbas computation projects the SLC images into a geocoded grid. This step links radar pixels into real world coordinates without degrading their original pixel resolution.

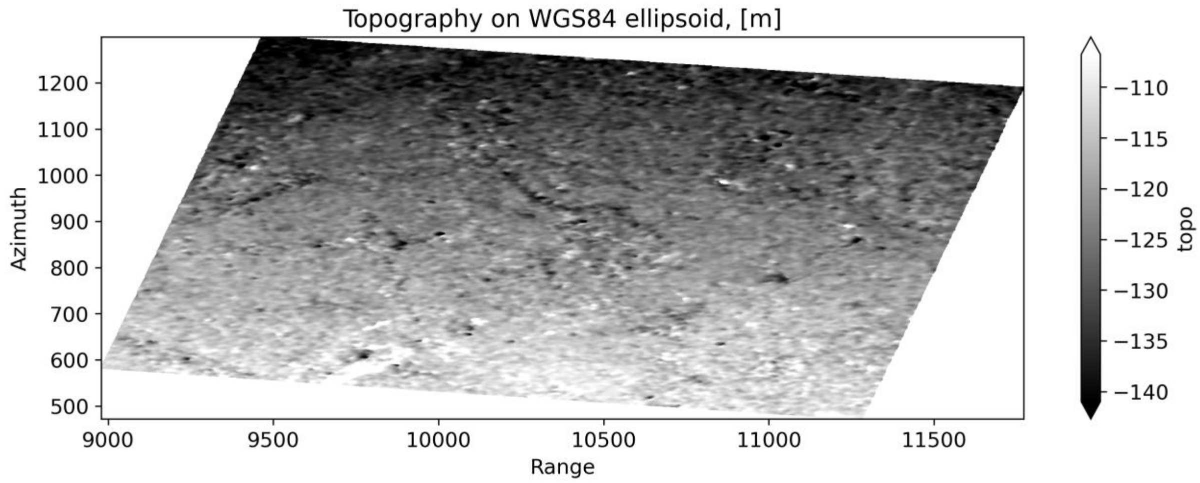

Figure 9 Topography on WGS84 Datum

3.3.6 SBAS BASELINE PAIRS

The next step involves the generation of the Small Baseline Subset (SBAS) interferometric network, in which each row of the baseline table corresponds to a single interferogram formed between two Sentinel-1 acquisitions (Table 2). This table is used to evaluate the spatial and temporal baseline characteristics of the interferometric pairs and to assess their suitability for time-series interferometric analysis. The SBAS baseline table provides insight into satellite acquisition geometry by summarizing the temporal separation and perpendicular baseline differences between image pairs. These parameters are critical for minimizing spatial and temporal decorrelation and ensuring reliable interferometric phase estimation. The reference (master) acquisition selected for this analysis is assigned a perpendicular baseline of zero, indicating that all other baselines are measured relative to this image. This choice stabilizes the interferometric network and facilitates consistent phase referencing. The remaining acquisitions exhibit perpendicular baseline differences with magnitudes ranging from approximately −426 m to +426 m across the 63 interferometric pairs.

Table 2 Perpendicular Baseline Pairs of Sentinel 1 SLC

No.	Reference Date	Repeat Date	Ref. Baseline (m)	Rep. Baseline (m)	Pair Baseline (m)	Temporal Baseline (days)
0	2023-11-06	2023-11-18	-120.68	-241.94	-121.26	12
1	2023-11-06	2023-11-30	-120.68	-43.97	76.71	24
2	2023-11-18	2023-11-30	-241.94	-43.97	197.97	12
3	2023-11-18	2023-12-12	-241.94	-122.38	119.56	24
4	2023-11-30	2023-12-12	-43.97	-122.38	-78.41	12
5	2023-11-30	2023-12-24	-43.97	-6.63	37.34	24
6	2023-12-12	2023-12-24	-122.38	-6.63	115.75	12
7	2023-12-12	2024-01-05	-122.38	-134.50	-12.12	24
8	2023-12-24	2024-01-05	-6.63	-134.50	-127.87	12
9	2023-12-24	2024-01-17	-6.63	-45.40	-38.77	24
10	2024-01-05	2024-01-17	-134.50	-45.40	89.10	12
11	2024-01-05	2024-01-29	-134.50	-199.86	-65.36	24
12	2024-01-17	2024-01-29	-45.40	-199.86	-154.46	12
13	2024-01-17	2024-02-10	-45.40	-78.52	-33.12	24
14	2024-01-29	2024-02-10	-199.86	-78.52	121.34	12
15	2024-01-29	2024-02-22	-199.86	-148.26	51.60	24
16	2024-02-10	2024-02-22	-78.52	-148.26	-69.74	12
17	2024-02-10	2024-03-05	-78.52	-202.46	-123.94	24
18	2024-02-22	2024-03-05	-148.26	-202.46	-54.20	12
19	2024-02-22	2024-03-17	-148.26	-185.81	-37.55	24
20	2024-03-05	2024-03-17	-202.46	-185.81	16.65	12
21	2024-03-05	2024-03-29	-202.46	-182.17	20.29	24
22	2024-03-17	2024-03-29	-185.81	-182.17	3.64	12
23	2024-03-17	2024-04-10	-185.81	240.93	426.74	24
24	2024-03-29	2024-04-10	-182.17	240.93	423.10	12
25	2024-03-29	2024-04-22	-182.17	-64.55	117.62	24
26	2024-04-10	2024-04-22	240.93	-64.55	-305.48	12
27	2024-04-10	2024-05-04	240.93	-125.16	-366.09	24
28	2024-04-22	2024-05-04	-64.55	-125.16	-60.61	12
29	**2024-04-22**	**2024-05-16**	**-64.55**	**0.00**	**64.55**	**24**
30	**2024-05-04**	**2024-05-16**	**-125.16**	**0.00**	**125.16**	**12**
31	2024-05-04	2024-05-28	-125.16	-53.99	71.17	24
32	2024-05-16	2024-05-28	0.00	-53.99	-53.99	12
33	2024-05-16	2024-06-09	0.00	70.72	70.72	24
34	2024-05-28	2024-06-09	-53.99	70.72	124.71	12
35	2024-05-28	2024-06-21	-53.99	57.21	111.20	24
36	2024-06-09	2024-06-21	70.72	57.21	-13.51	12
37	2024-06-09	2024-07-03	70.72	159.44	88.72	24
38	2024-06-21	2024-07-03	57.21	159.44	102.23	12
39	2024-06-21	2024-07-15	57.21	-1.20	-58.41	24
40	2024-07-03	2024-07-15	159.44	-1.20	-160.64	12
41	2024-07-03	2024-07-27	159.44	107.55	-51.89	24
42	2024-07-15	2024-07-27	-1.20	107.55	108.75	12
43	2024-07-15	2024-08-08	-1.20	-10.06	-8.86	24
44	2024-07-27	2024-08-08	107.55	-10.06	-117.61	12
45	2024-07-27	2024-08-20	107.55	-51.73	-159.28	24
46	2024-08-08	2024-08-20	-10.06	-51.73	-41.67	12
47	2024-08-08	2024-09-01	-10.06	-45.29	-35.23	24
48	2024-08-20	2024-09-01	-51.73	-45.29	6.44	12
49	2024-08-20	2024-09-13	-51.73	-219.07	-167.34	24
50	2024-09-01	2024-09-13	-45.29	-219.07	-173.78	12
51	2024-09-01	2024-09-25	-45.29	-171.94	-126.65	24
52	2024-09-13	2024-09-25	-219.07	-171.94	47.13	12
53	2024-09-13	2024-10-07	-219.07	-364.08	-145.01	24
54	2024-09-25	2024-10-07	-171.94	-364.08	-192.14	12
55	2024-09-25	2024-10-19	-171.94	-173.13	-1.19	24
56	2024-10-07	2024-10-19	-364.08	-173.13	190.95	12
57	2024-10-07	2024-10-31	-364.08	-121.01	243.07	24
58	2024-10-19	2024-10-31	-173.13	-121.01	52.12	12
59	2024-10-19	2024-11-12	-173.13	-33.94	139.19	24
60	2024-10-31	2024-11-12	-121.01	-33.94	87.07	12
61	2024-10-31	2024-11-24	-121.01	-71.59	49.42	24
62	2024-11-12	2024-11-24	-33.94	-71.59	-37.65	12

The repeart acquisition dated 16 May 2024 was selected as the master image (Figure 10); therefore, its perpendicular baseline is defined as zero and appears in multiple interferometric pairs, regardless of whether it is listed as the reference or repeat acquisition.

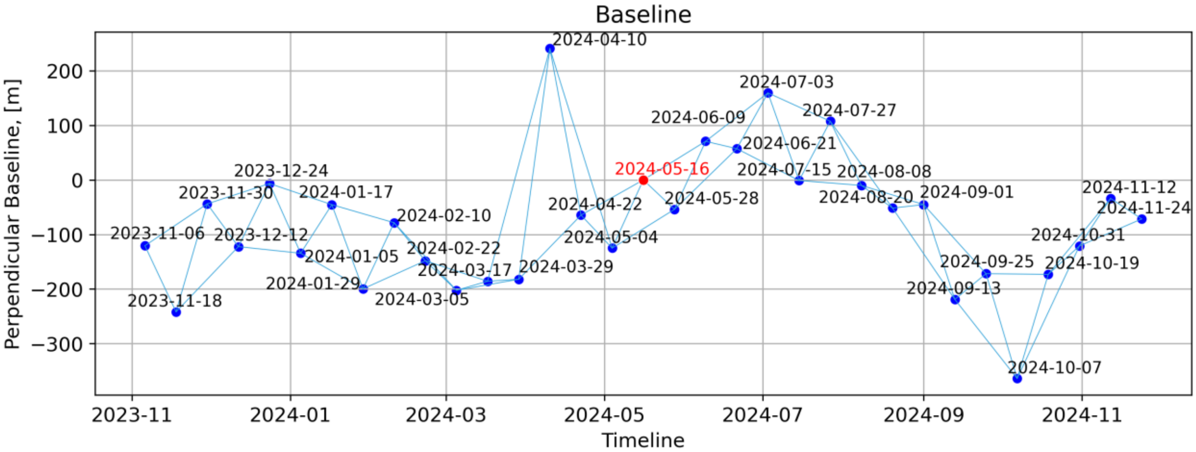

Figure 10 Perpendicular and Temporal Baselines relative to reference image (red)

3.3.7 PERSISTENT SCATTERER FUNCTION (PSF) ESTIMATION

After constructing the SBAS interferometric network, pixel stability was evaluated to identify persistent scatterers suitable for time-series inversion.

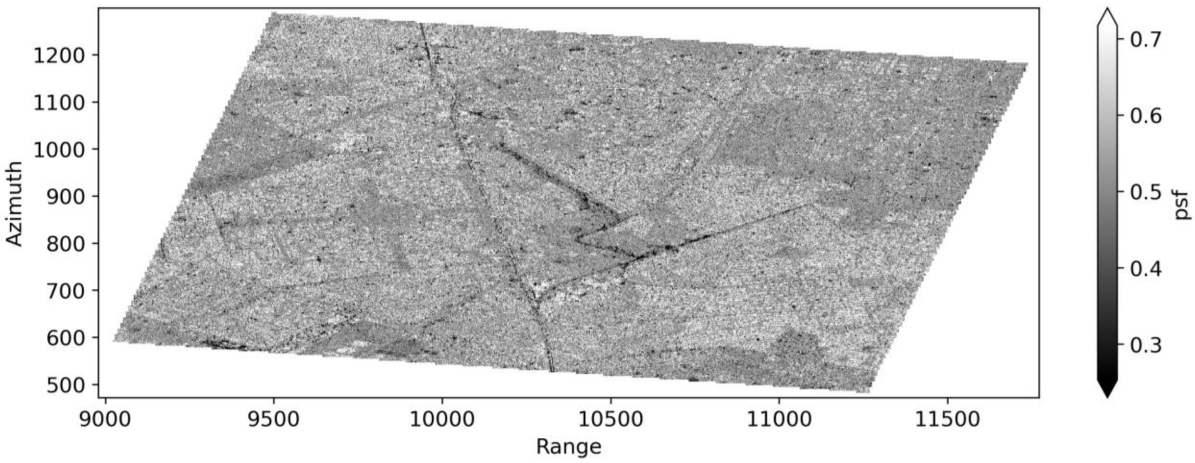

Figure 11: PS Function

In Persistent Scatterer Interferometry (PSI), reliable deformation estimates are obtained by selecting resolution elements whose radar return is dominated by temporally stable scatterers and whose interferometric phase remains coherent across the image stack (Ferretti et al., 2001). Following this principle, PyGMTSAR computes a pixel-wise stability measure (PSF) to highlight consistently coherent targets and to down-weight decorrelating areas during subsequent interferogram formation and inversion (Figure 11), consistent with widely used PS selection strategies based on low phase variance/stable phase behavior(Hooper, 2008).

3.3.8 SBAS Interferogram Generation and Phase Evaluation

Following the persistent scatterer function (PSF) estimation, interferograms were generated for the selected SBAS baseline pairs in Figure 12. At this stage, the interferometric phase remains wrapped and therefore does not represent deformation or subsidence directly. Instead, these interferograms are used to visually assess pixel behavior, phase continuity, and noise characteristics within the dataset. The wrapped phase interferograms shown in Figure 12 are presented in radar geometry (range–azimuth coordinates) and serve as a quality control step prior to phase unwrapping. This inspection allows identification of decorrelated areas, excessive noise, or phase discontinuities that could adversely affect subsequent processing. Although interferogram coherence is evaluated at this stage, no deformation measurements are derived until phase unwrapping and time-series inversion are performed.

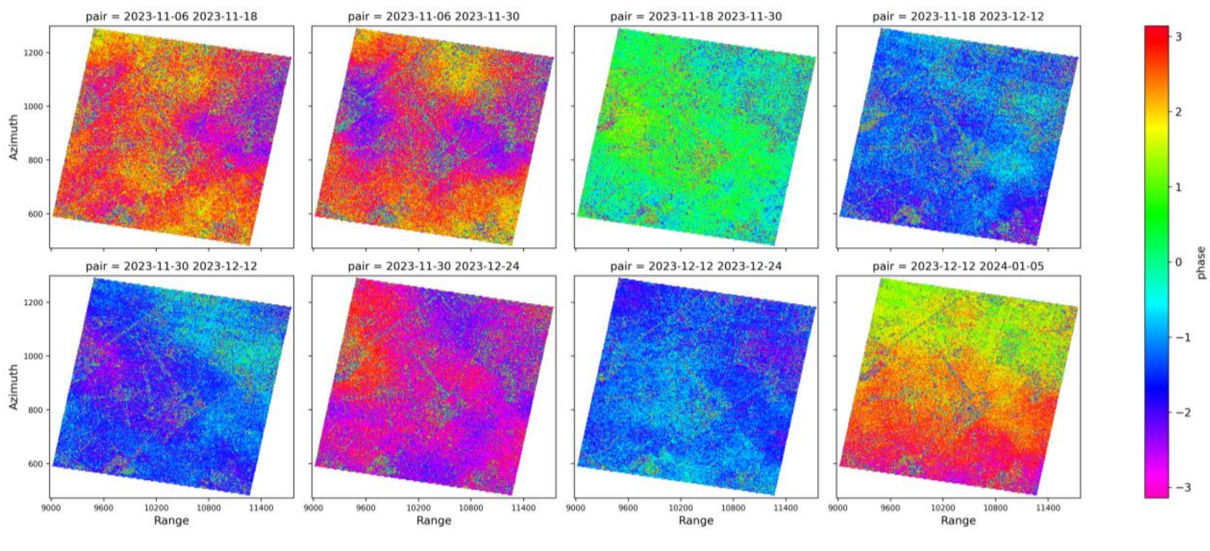

Figure 12 SBAS Pairs (wrapped)

3.3.9 SBAS Correlation

Another quality control step prior to the generation of the main deformation results involves the visualization of interferometric correlation pairs. In addition to the wrapped phase interferograms, interferometric correlation (coherence) maps were generated for the same SBAS pairs to quantify pixel-wise phase reliability. Correlation values range from 0 to 1, where higher values indicate stronger similarity between acquisitions and therefore more reliable phase information, while lower values reflect decorrelation caused by temporal changes, surface dynamics, or geometric effects. Figure 13 presents representative SBAS correlation maps in radar geometry (range–azimuth coordinates). These maps serve as a quality control layer to identify low-coherence regions that may adversely affect phase unwrapping and subsequent time-series inversion. Moreover, the correlation estimates are used during phase unwrapping to guide the process by giving more importance to reliable pixels and reducing the influence of pixels affected by noise or decorrelation. This helps ensure that the unwrapped phase is more stable and less affected by errors.

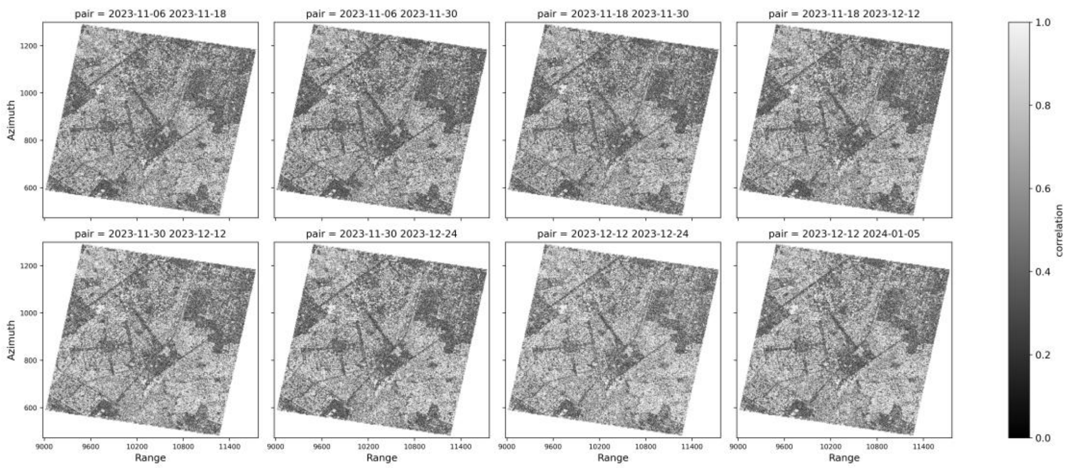

Figure 13 SBAS correlation (coherence) maps

3.4 Two-Dimensional Phase Unwrapping of SBAS Interferograms

3.4.1 SBAS Phase

After interferogram generation and quality assessment, two-dimensional phase unwrapping was performed to convert the wrapped interferometric phase into a continuous phase field. Phase unwrapping is a critical step in time-series InSAR processing, as the wrapped phase is inherently ambiguous and does not directly represent surface displacement. In this study, phase unwrapping was carried out using the SNAPHU algorithm integrated within the PyGMTSAR framework. The unwrapping process utilizes interferometric correlation information to guide the solution, allowing reliable pixels to be unwrapped first while minimizing error propagation in noisy or decorrelated areas. Figure 14 shows representative unwrapped SBAS interferograms in radar geometry (range–azimuth coordinates). At this stage, the phase is continuous across the scene; however, it still represents relative phase differences rather than physical displacement. The unwrapped phase forms the basis for subsequent time-series inversion and line-of-sight deformation estimation.

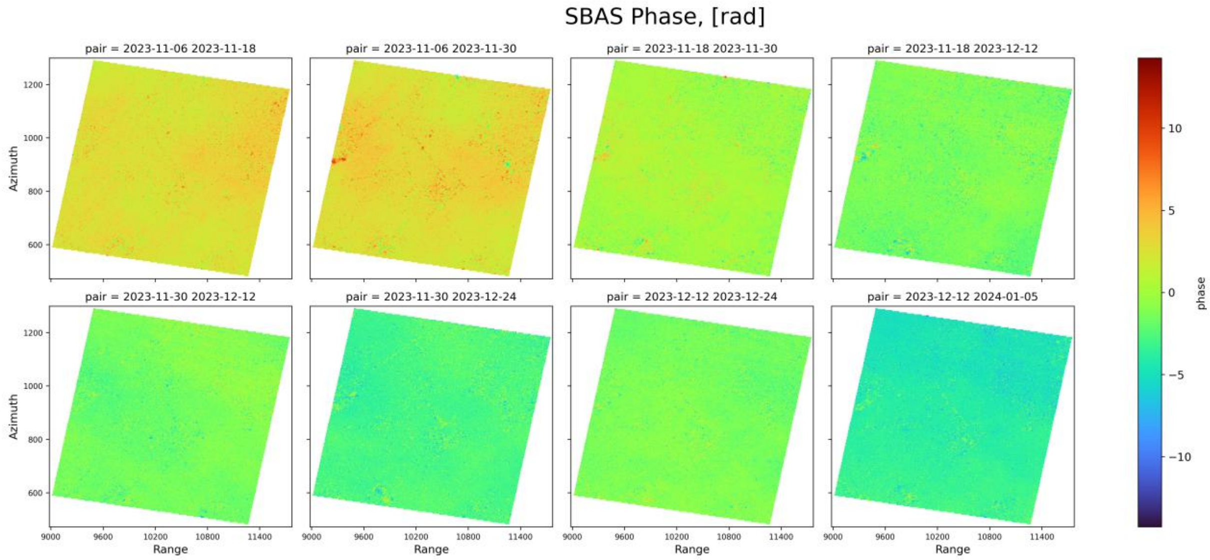

Figure 14 Representative unwrapped SBAS interferograms after two-dimensional phase unwrapping, shown in radar geometry.

Interferometric phase values are initially wrapped within the range of −π to +π, which prevents direct interpretation in terms of surface displacement. When the phase is unwrapped, these ambiguities are resolved and the phase values become spatially continuous and consistent across the scene. Phase unwrapping is therefore a necessary step to enable meaningful interpretation of interferometric phase variations. Without unwrapping, the phase information cannot be reliably related to deformation or subsidence, and the results remain physically ambiguous. After unwrapping, the phase patterns become interpretable, and the spatial variations shown in Figure 14 represent a continuous phase field that can be further converted into line-of-sight displacement in subsequent processing steps.

3.4.2 SBAS Trend

Following phase unwrapping, the Small Baseline Subset (SBAS) method calculates the phase trend for each interferometric pair. The SBAS trend phase shows the overall and smooth change in phase between two satellite images, while reducing random noise and small irregular variations. In simple terms, it highlights the main phase pattern that is common across the area and removes unnecessary fluctuations. Figure 15 presents examples of SBAS trend phase maps in radar geometry (range–azimuth coordinates). Compared to the wrapped and unwrapped interferograms, these maps appear much smoother, which indicates that noise has been reduced and the phase information is more consistent. At this stage, the values are still expressed in radians and do not yet represent ground displacement. Estimating the SBAS trend phase is an important preparation step before calculating deformation. It helps organize the phase information in a clean and stable way, making it easier to correctly combine all interferograms in the next step. Therefore, the trend phase serves as a key input for generating reliable deformation time-series results.

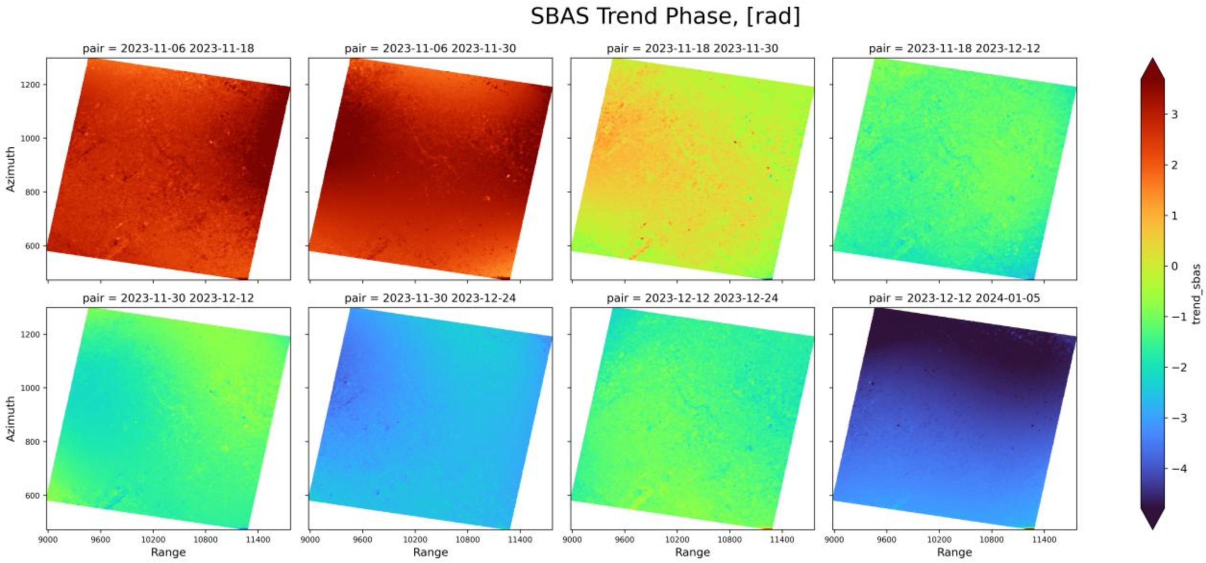

Figure 15 SBAS Phase Trend is the smoothed and consistent phase behaviour extracted from unwrapped interferograms, used to prepare reliable deformation time-series estimation.

3.4.3 SBAS PHASE RESIDUALS (UNWRAPPED PHASE − TREND)

After calculating the SBAS trend phase, the next step is to compute the residual phase. This is done by removing the smooth trend from the unwrapped interferograms. The residual phase shows only the remaining phase changes that are not part of the overall trend. Figure 16 presents examples of SBAS residual phase maps in radar geometry.

Compared to the trend phase, these maps show smaller and more localized variations across the study area. These variations are important because they contain the detailed information needed to estimate surface deformation. This step helps to separate systematic effects, such as large-scale phase trends, from the actual ground movement. By doing this, the deformation signal becomes clearer and more reliable before the final displacement time-series is calculated.

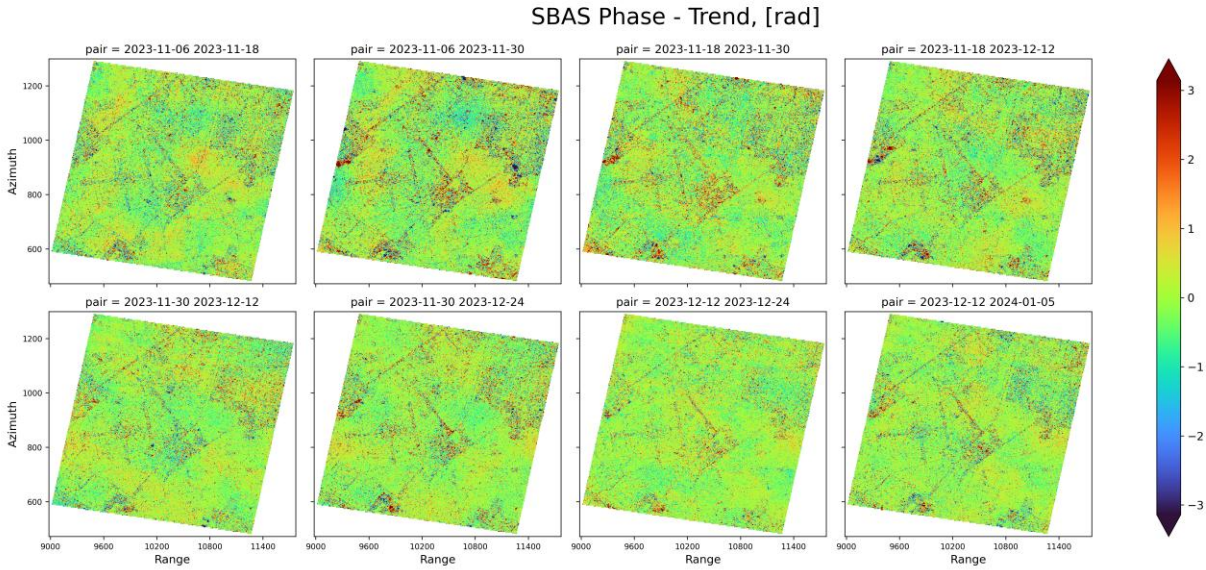

Figure 16 Residual phase after removing the smooth phase trend from the unwrapped interferograms.

3.5 PS Analysis

3.5.1 PS PHASE

After the SBAS processing steps, a Persistent Scatterer (PS) analysis was carried out, and PS interferometric pairs were generated. Persistent scatterers are pixels that remain stable over time and usually correspond to man-made structures such as buildings, roads, and paved surfaces, which consistently reflect the radar signal across multiple acquisitions. In this analysis, phase values are expressed in radians and are used to identify these stable pixels. The stable pixels detected in the PS analysis represent the persistent scatterers. The reference point shown in Figure 6 corresponds to one such stable pixel, along with other nearby stable points distributed around the CBD construction site. The PS phase maps display the phase values of these reliable pixels for each interferometric pair (Figure 17). Compared to SBAS interferograms, PS phase images contain fewer pixels; however, these pixels exhibit more stable and less noisy phase behavior. This makes it easier to identify reliable phase information prior to deformation estimation. The main purpose of the PS analysis is to focus on high-quality, stable pixels while minimizing the influence of noise and temporal decorrelation. Therefore, PS phase products complement the SBAS approach and contribute to a more robust deformation analysis, particularly in urban and construction-dominated areas.

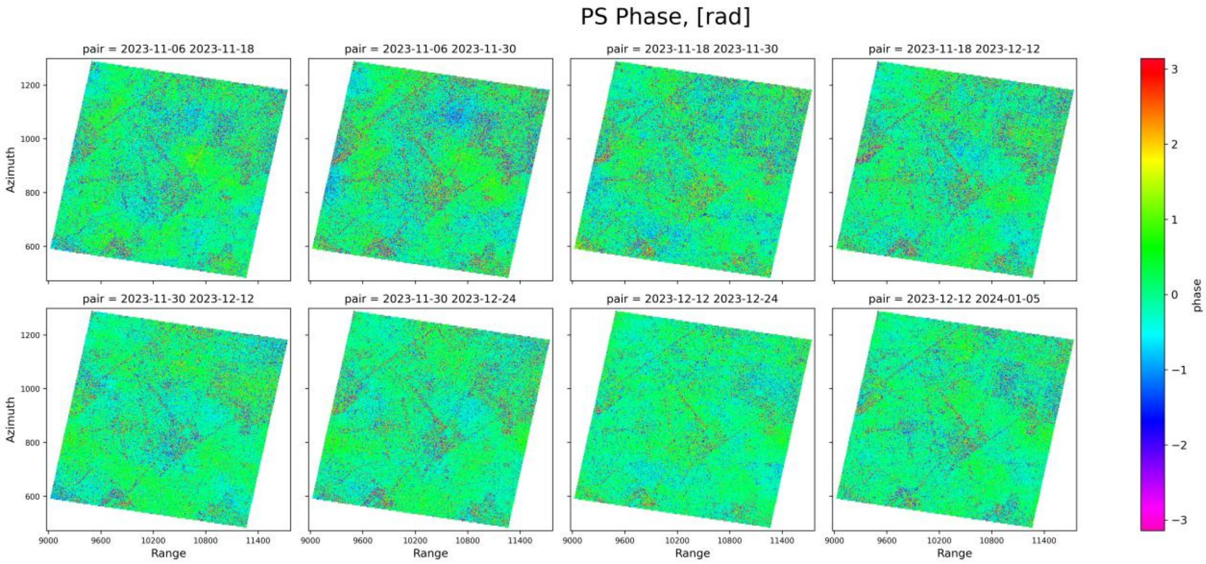

Figure 17 PS Phase Pairs

3.5.2 PS CORRELATION

After generating the PS interferometric pairs, PS correlation (coherence) maps were computed to evaluate the stability and quality of the selected persistent scatterers. Correlation values indicate how similar the radar signal remains between two acquisitions for each pixel. The correlation values range from 0 to 1. Pixels with values close to 1 (shown as brighter or white areas in the maps) represent highly stable reflectors, meaning these locations consistently reflect the radar signal over time. Such pixels typically correspond to man-made structures like buildings, roads, and other rigid surfaces, and are therefore suitable for deformation analysis. In contrast, darker pixels indicate lower correlation, which may result from temporal changes, surface movement, vegetation, or noise, leading to temporal or spatial decorrelation. Figure 18 presents representative PS correlation maps in radar geometry (range–azimuth coordinates). These maps serve as a quality control step to visually assess the stability of the PS interferometric pairs. Only pixels with sufficiently high correlation are considered reliable and retained for further deformation estimation, while low-correlation pixels are excluded to reduce noise and improve the robustness of the analysis. Overall, PS correlation analysis ensures that the deformation results are derived from stable and trustworthy pixels, complementing the SBAS processing and enhancing the reliability of the final displacement measurements, particularly in urban and construction-dominated environments.

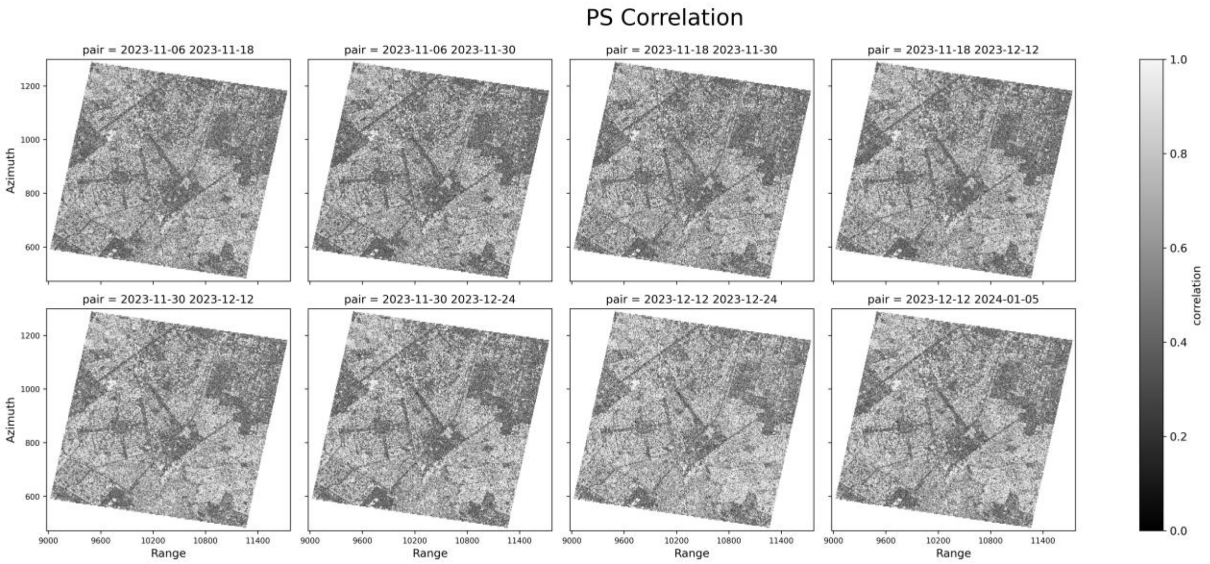

Figure 18 PS Correlation Pairs

In summary, this chapter described the complete processing workflow adopted in this study, starting from Sentinel-1 data selection and site orientation, through SBAS and PS interferometric processing, and concluding with quality control steps based on phase stability and correlation analysis. Each step was carefully designed to ensure reliable phase information, minimize noise, and isolate stable pixels suitable for deformation monitoring over the CBD construction site. The methodology establishes a foundation for extracting line-of-sight deformation time series and cumulative displacement maps. Based on this processing framework, the following chapter presents and discusses the derived results, focusing on the spatial and temporal evolution of ground deformation and its relationship with construction activity in the study area.

4. RESULTS AND DISCUSSION

4.1 SBAS Results

Figure 19 presents the SBAS cumulative Line-of-Sight (LOS) displacement maps for selected dates during the monitoring period. These maps illustrate how ground deformation develops gradually over time in relation to the construction activities within the Central Business District (CBD) area. At the beginning of the observation period, the study area shows near-zero displacement, indicating that the ground surface was largely stable before the major construction activities began. This initial stability is clearly visible in the earliest displacement map, where most pixels appear uniform and close to zero. As the SBAS method compares the reference acquisition with multiple subsequent images (slave images), changes in the ground surface gradually become detectable. With the progression of time, spatially coherent deformation patterns start to appear, particularly within the CBD construction site.

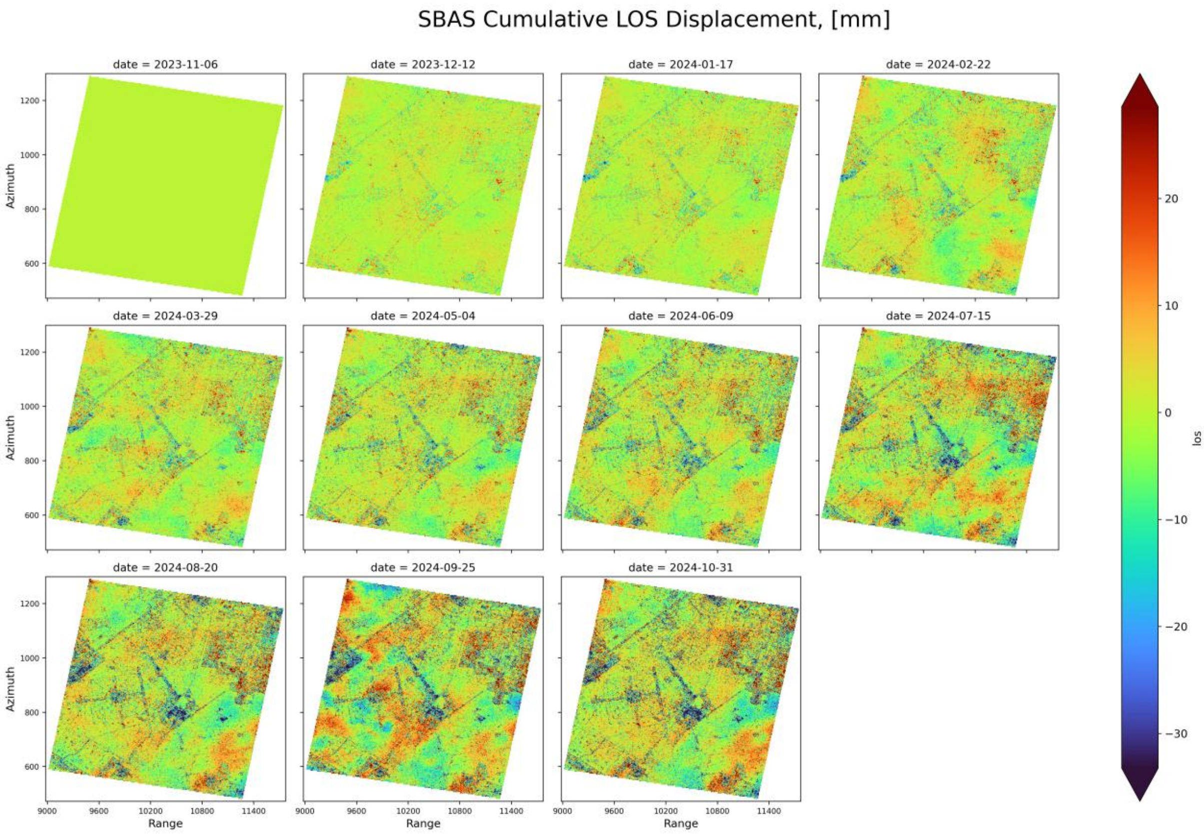

Figure 19 SBAS Cumulative LOS Displacement

These patterns are not random; instead, they show consistent spatial continuity, which is a key indicator of real ground movement rather than noise. The blue-colored regions in Figure 18 highlight areas experiencing negative LOS displacement, which corresponds to subsidence along the satellite's viewing direction. From March 2024 onwards, the deformation signal becomes more pronounced. The displacement values increase in magnitude, reaching approximately –20 mm to –30 mm, indicating a peak period of construction activity. This timing matches well with the known construction schedule, during which multiple phases of excavation and foundation work were active simultaneously. Importantly, the deformation grows gradually and continuously, rather than appearing suddenly, which further confirms that the observed signal represents actual ground deformation. The Area of Interest (AOI) corresponding to the CBD site shows a steady increase in deformation over time, forming smooth and continuous patterns across successive dates. This temporal continuity demonstrates how deformation accumulates as construction progresses. In contrast, the surrounding urban fabric remains largely unchanged throughout the monitoring period. The stability of nearby urban areas serves as a reference and validation, confirming that the detected deformation is localized to the construction site and not caused by processing artifacts or atmospheric noise.

According to the CBD master plan (Figure 19), construction activities were carried out in multiple phases, with major work beginning in Phase I around 9 November 2023, including the installation of retaining piles and excavation. The deformation patterns observed in Figure 19 align well with this timeline. Areas such as Bab-e-Pakistan, located toward the lower part of the study area, also show consistent deformation behavior linked to excavation activities, which persists across multiple acquisitions. The absence of abrupt or unrealistic displacement jumps further supports the reliability of the SBAS results. The smooth temporal evolution of deformation indicates that the SBAS technique is effectively capturing real construction-induced ground movement, rather than noise or decorrelation effects. Overall, Figure 19 clearly demonstrates how deformation initiates, evolves, and accumulates over time in response to large-scale construction activities. Each map represents the total ground movement accumulated from the reference date up to that specific time, measured along the satellite's line of sight. The strong agreement between the SBAS cumulative results and the known construction timeline confirms that SBAS is a robust and reliable approach for regional-scale deformation monitoring, particularly in urban and infrastructure development contexts.

Figure 20 Master Plan of CBD Lahore

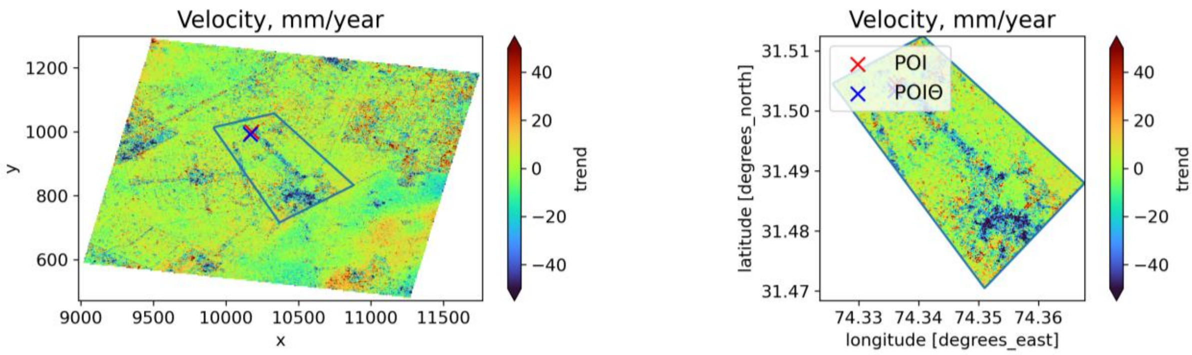

Figure 21 SBAS Line of Sight (LOS) Velocity

The SBAS cumulative Line-of-Sight (LOS) displacement maps (Figure 19) and the SBAS LOS velocity map (Figure 21) together provide a complete picture of ground deformation in the study area over time. While the cumulative displacement maps show how much the ground has moved in total since the reference date, the velocity map summarizes how fast the ground is moving on average per year. The cumulative displacement maps reveal a progressive increase in deformation within the CBD construction site as time advances. Early dates show almost no displacement, indicating stable ground conditions before major construction activities began. As construction progresses, especially from early 2024 onward, the deformation becomes more pronounced and spatially coherent. This gradual increase confirms that the observed displacement is time-dependent and continuous, rather than sudden or random. The SBAS LOS velocity map complements these findings by converting the accumulated deformation into a rate of motion (mm/year). Areas that show large cumulative displacement also exhibit higher velocity values, confirming consistency between the two results. This agreement strengthens confidence in the reliability of the SBAS processing. The LOS velocity map shows three main behaviors in Figure 21:

- Blue pixels dominate the CBD construction area, indicating ground movement away from the satellite, which is commonly interpreted as subsidence ;
- Green pixels represent areas with near-zero velocity and correspond mainly to the surrounding urban fabric, such as roads and buildings, which remain stable throughout the observation period ;
- Red to orange pixels appear sparsely and indicate localized motion towards the satellite, possibly related to surface compaction, structural loading, or minor uplift effects.

The velocity values range approximately from −50 mm/year to +50 mm/year, which indicates significant deformation activity within the construction zone. In contrast, the surrounding areas remain largely stable, further confirming that the detected deformation is localized and driven by construction activities, rather than atmospheric noise or processing errors. One of the key strengths of these results is their spatial and temporal consistency. The deformation patterns observed in the cumulative displacement maps evolve smoothly over time, and the velocity map reflects these same areas as zones of high deformation rates. This consistency confirms that the SBAS method is capturing real ground movement, not random fluctuations. Furthermore, the deformation patterns align well with the known construction timeline of the CBD project, including excavation and pile installation phases. Areas such as Bab-e-Pakistan continue to show persistent deformation signatures across multiple acquisitions, indicating long-term ground disturbance rather than temporary noise. Together, the cumulative displacement and velocity results demonstrate that SBAS InSAR is an effective tool for monitoring large-scale construction-induced ground deformation. The technique successfully distinguishes between stable urban regions and actively deforming zones, providing valuable insight into both the magnitude and rate of ground movement. These results highlight the usefulness of SBAS for regional deformation monitoring, especially in rapidly developing urban environments where continuous ground stability assessment is critical. The clear correspondence between satellite-derived deformation patterns and real-world construction activity further validates the robustness of the applied methodology.

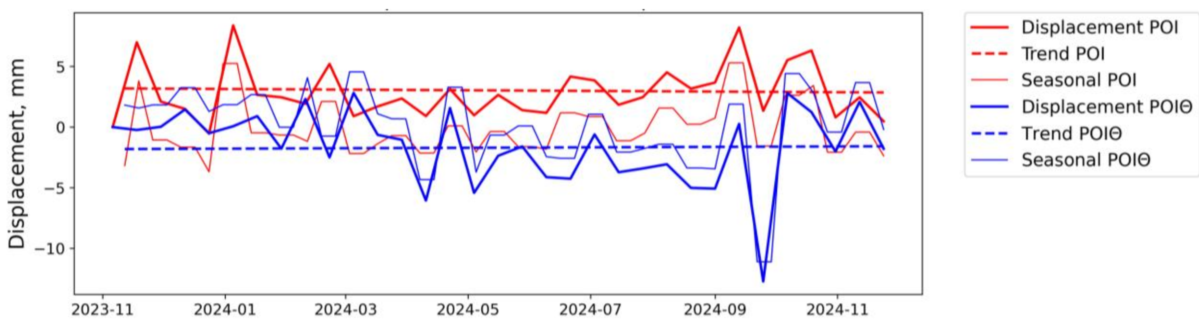

Figure 22 SBAS LOS Displacement Seasonal Trend Decomposition using Loess

To further understand the temporal behavior of ground deformation, Seasonal–Trend decomposition using Loess (STL) was applied to the SBAS line-of-sight (LOS) displacement time series. The radar signal received by the SAR sensor contains a mixture of different information components wrapped within the phase signal. These components include long-term ground movement, short-term fluctuations caused by noise or atmospheric effects, and sometimes repeating patterns referred to as seasonal or periodic variations. STL decomposition separates this mixed signal into three clear components (Figure 22):

- the observed displacement, which represents the total SBAS-measured movement ;
- the trend component, which captures the long-term ground motion such as subsidence or uplift ;
- the seasonal component, which represents short-term, repeating fluctuations around the trend.

This separation is important because it helps filter and categorize the radar signal, allowing meaningful deformation signals to be distinguished from noise. Figure 21 presents the STL decomposition results for both the Point of Interest (POI), located within the CBD construction site, and the reference point (POIΘ). In the figure, the solid thick line represents the total SBAS displacement, the dashed line shows the long-term trend, and the thin line represents the seasonal component. At the POI, the trend component (red dashed line) shows a clear and continuous increase over time. This indicates persistent long-term ground movement, which is consistent with ongoing construction activities such as excavation and pile installation at the site. The positive trend represents cumulative deformation that develops gradually, confirming that the observed displacement is systematic and not random. The seasonal component (thin red line) shows small oscillations around zero, indicating temporary variations that do not accumulate over time. These short-term fluctuations are likely caused by atmospheric effects, minor surface changes, or measurement noise. Together, these results demonstrate that most of the displacement at the POI is driven by long-term construction activity rather than seasonal effects. In contrast, the STL results for the reference point (POIΘ) show that the trend component remains close to zero throughout the observation period. This indicates stable ground conditions at the reference location. Although short-term fluctuations are present in the observed displacement signal, they do not show any persistent increase or decrease. This confirms that POIΘ is a reliable stable reference point and supports the overall validity of the SBAS deformation results. Overall, the STL decomposition clearly demonstrates that deformation within the CBD construction site is dominated by a long-term trend, while seasonal variations play a secondary role. By separating real deformation signals from short-term noise, this analysis strengthens the interpretation of SBAS results and provides strong evidence that the detected subsidence is directly related to construction activity rather than artifacts or atmospheric disturbances.

4.2 PS Results

Figure 23 presents the cumulative Line-of-Sight (LOS) displacement maps obtained from the Persistent Scatterer (PS) analysis for selected dates during the monitoring period. Unlike the SBAS approach, which analyzes deformation using a large number of pixels over a wide area, PS analysis focuses only on a smaller set of very stable pixels. These pixels usually correspond to man-made structures such as buildings, roads, and paved surfaces, which consistently reflect the radar signal over time. Because of this, PS results are less affected by noise and provide more reliable deformation information in urban and construction-dominated environments.

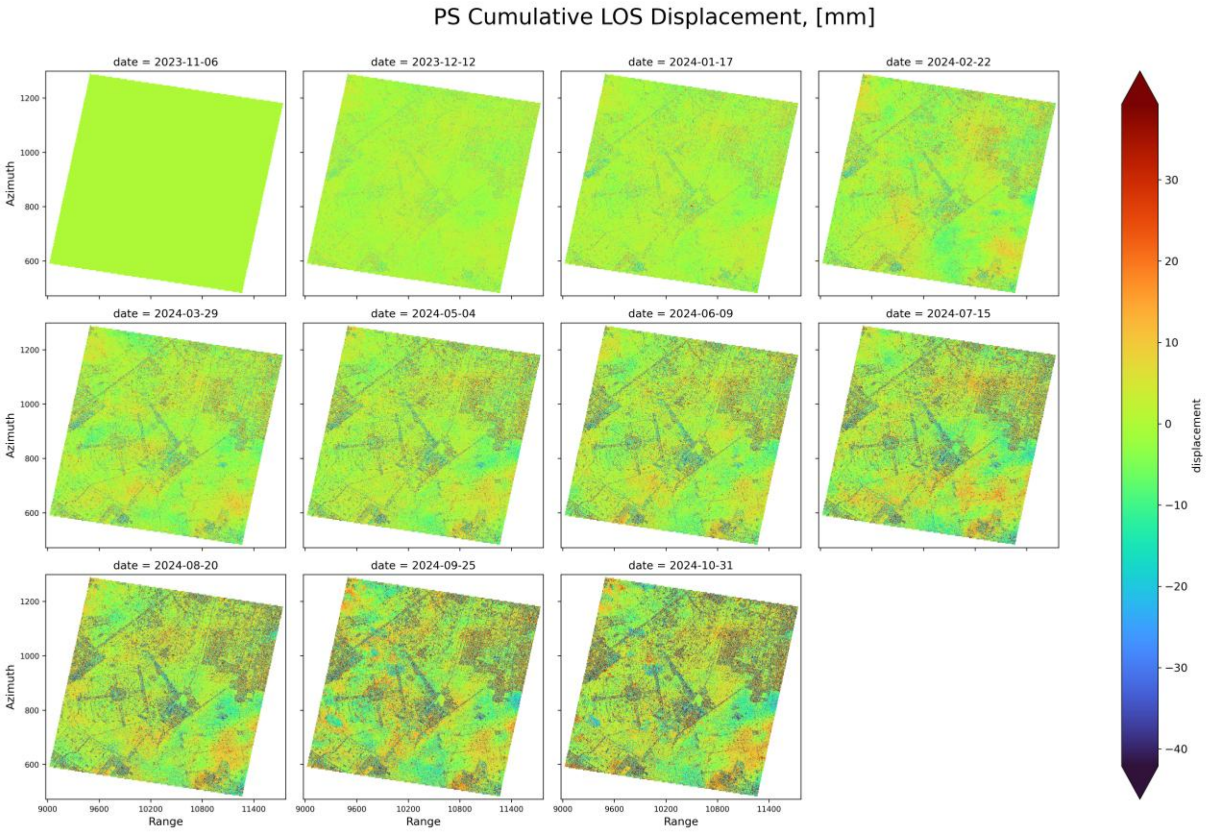

Figure 23 PS Cumulative LOS Displacement

At the beginning of the observation period, the PS cumulative displacement map shows values close to zero across most of the study area. This indicates that the selected persistent scatterers were stable at the reference date and confirms that a reliable baseline was established for the analysis. The uniform appearance of the earliest map demonstrates that no significant ground movement had occurred before the main construction activities started. As time progresses, small but clear displacement patterns begin to appear within the CBD construction site. These changes are visible only at the persistent scatterer locations, which appear as discrete points rather than a continuous surface. Despite the lower spatial density, the deformation signal becomes increasingly coherent and systematic over time. This indicates that the detected movement is not random but represents real ground deformation captured at stable reflectors. From early 2024 onwards, cumulative displacement values increase noticeably within the construction area. Blue-colored pixels indicate ground movement away from the satellite, corresponding to subsidence along the satellite's viewing direction. The magnitude of displacement continues to grow gradually, reaching values of approximately –30 mm to –40 mm in later dates. This steady increase in displacement matches well with the known timeline of construction activities, including excavation and foundation work. Importantly, the deformation observed in the PS results develops smoothly over time, without sudden jumps or unrealistic changes. This gradual and continuous behavior further confirms that the measured displacement is caused by actual construction activity rather than atmospheric disturbances or processing artifacts. In contrast, the surrounding urban areas remain largely stable throughout the monitoring period, showing minimal displacement at persistent scatterer locations. The stability of these areas provides an internal reference and strengthens the reliability of the PS analysis. Overall, the PS cumulative LOS displacement maps clearly illustrate how deformation accumulates over time at stable ground targets within the CBD construction site (Figure 6). Although PS results contain fewer pixels than SBAS results, they offer higher confidence in the detected deformation due to their focus on stable reflectors. The strong agreement between PS deformation patterns, SBAS results, and the known construction schedule confirms that PS analysis is a robust and effective method for monitoring construction-induced ground deformation, especially in dense urban environments.

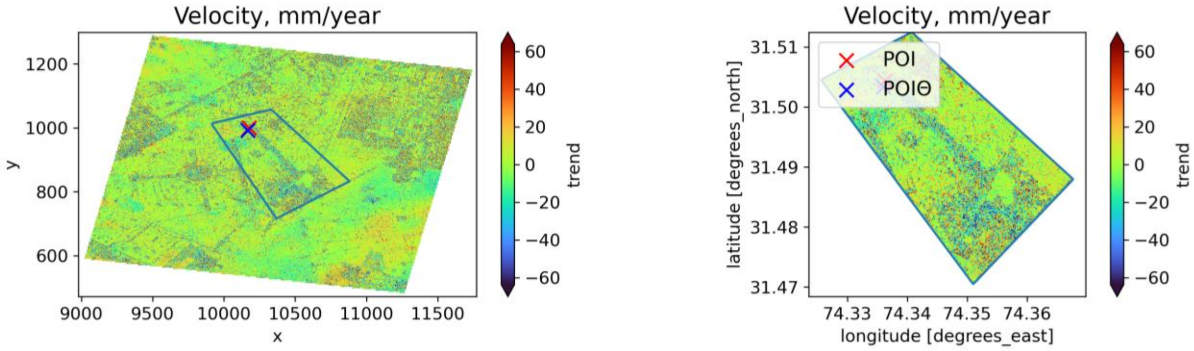

Figure 24 PS Line of Sight (LOS) Velocity

Figure 24 shows the Persistent Scatterer (PS) Line-of-Sight (LOS) velocity map for the study area. This map explains how fast the ground is moving at very stable locations, measured in millimeters per year (mm/year). Similar to the SBAS results, this map shows ground movement along the direction in which the satellite looks at the Earth, which is called the Line of Sight (LOS). At first glance, the map shows a large number of stable pixels, especially over buildings and paved areas. These stable pixels appear mostly in green, indicating very little or no movement. This confirms that the study area is well suited for PS analysis, because PS works best when there are many solid and stable objects such as buildings, roads, and concrete surfaces. The presence of these stable targets strengthens the reliability of the PS results. The reference point and the subsidence point used in this analysis are the same as those used in the SBAS results. The reference point is located on a stable building, while the subsidence point is located near the underground parking plaza in Phase I of the CBD construction area. These points help compare stable ground with moving ground. One clear difference between PS and SBAS results is the range of velocity values. In the PS velocity map, the deformation values range approximately from –60 mm/year to +60 mm/year, which is about 20 mm/year higher than what was observed in the SBAS velocity results. This difference is expected and meaningful. The reason for this difference is how the two methods work. SBAS averages movement over many pixels, including less stable ground such as soil and construction areas. This averaging smooths the results and reduces extreme values. On the other hand, PS analysis does not average pixels. Instead, it focuses only on very stable targets, such as buildings that reflect the radar signal clearly in every satellite image. In this study, the building used as the reference point remains visible and stable in all satellite acquisitions. Even if the ground underneath that building is slowly moving, the PS method can still detect this movement accurately because the building provides a strong and consistent radar signal. This allows PS to capture stronger and more precise deformation values, especially in areas affected by construction activities. The higher deformation values seen in the PS results therefore indicate that localized ground movement is being captured more clearly, particularly around the underground parking area. This shows that PS is very effective at detecting small but important movements beneath stable structures. Overall, the PS velocity results complement the SBAS findings. While SBAS provides a smooth regional picture of deformation, PS highlights detailed and localized ground movement at stable locations. The consistency between PS and SBAS patterns confirms that the observed deformation is real and related to construction activity rather than noise. Further analysis using STL decomposition helps explain whether this movement is mainly long-term construction-driven deformation or short-term variation, which is discussed in the next section.

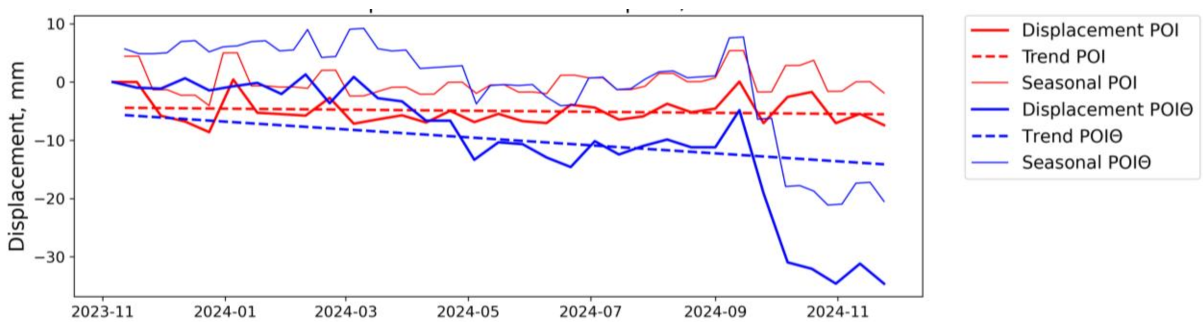

Figure 25 PS STL Decomposition

The STL results from both SBAS and PS methods show very similar overall behavior, which means both techniques are observing the same ground movement trend in the study area. In these graphs, the blue line represents the subsidence point, while the red line represents the reference point. At first, the reference point appears mostly stable. However, near the end of the monitoring period, the blue line starts to show noticeable variation. Since it is located just behind the CBD construction boundary wall, it is still affected by the same construction activities, such as excavation and underground work. In PS analysis, a reference point is chosen because it reflects the radar signal clearly and consistently over time. This means it is stable in terms of radar signal, not necessarily stable in terms of ground movement. A point can be easy for the satellite to see every time, but the ground underneath it can still move. This is exactly what is happening here. Because the reference point is close to the subsidence zone, the PS method is able to capture small ground movements at that location as well. Another important difference can be seen when comparing SBAS and PS STL results. In the SBAS STL graph, noticeable variation appears around September, while in the PS STL graph, stronger variation appears closer to the last image acquisition. This difference happens because SBAS smooths the signal by averaging many pixels over a wider area. As a result, strong local changes are reduced or softened. On the other hand, PS focuses on individual stable targets, such as buildings or walls, and therefore captures local ground movement more clearly and with larger values. The blue line variation also clearly shows that the subsidence point is stable in radar visibility but not completely stable on the ground. Even though its trend and seasonal components remain mostly normal, small changes are still visible due to its location near the construction site. Similarly, the subsidence point in the PS STL graph shows slightly stronger changes than in the SBAS STL results. This again confirms that PS is more sensitive to localized deformation. Despite these differences in magnitude, both PS and SBAS show the same overall deformation pattern, meaning both methods agree on when and where the ground is moving.

Overall, the STL analysis confirms that:

- The ground deformation is mainly caused by long-term construction activity;
- The reference point is affected because of its proximity to the subsidence area;
- PS results show larger variations because they track individual stable reflectors;
- SBAS results are smoother because they average deformation over many pixels.

This strong agreement between PS and SBAS strengthens confidence in the results and confirms that the observed deformation is real and construction-related, not noise or processing error.

4.3 Reference and Subsidence Point Analysis

The first graph shows the results for POI, which is the reference point. This point was chosen in an area that looks stable, such as near a building or solid structure, and it is used mainly for comparison. The results show that the ground at POI is almost not moving at all. The calculated movement is about –0.9 mm per year, which is extremely small. This amount is so tiny that it is considered negligible, meaning it does not represent real ground sinking. This is supported by the P-value, which is 0.52. In simple terms, a high P-value means that the small changes seen in the graph are most likely caused by noise, such as small measurement errors or natural signal variations, and not by real ground movement.

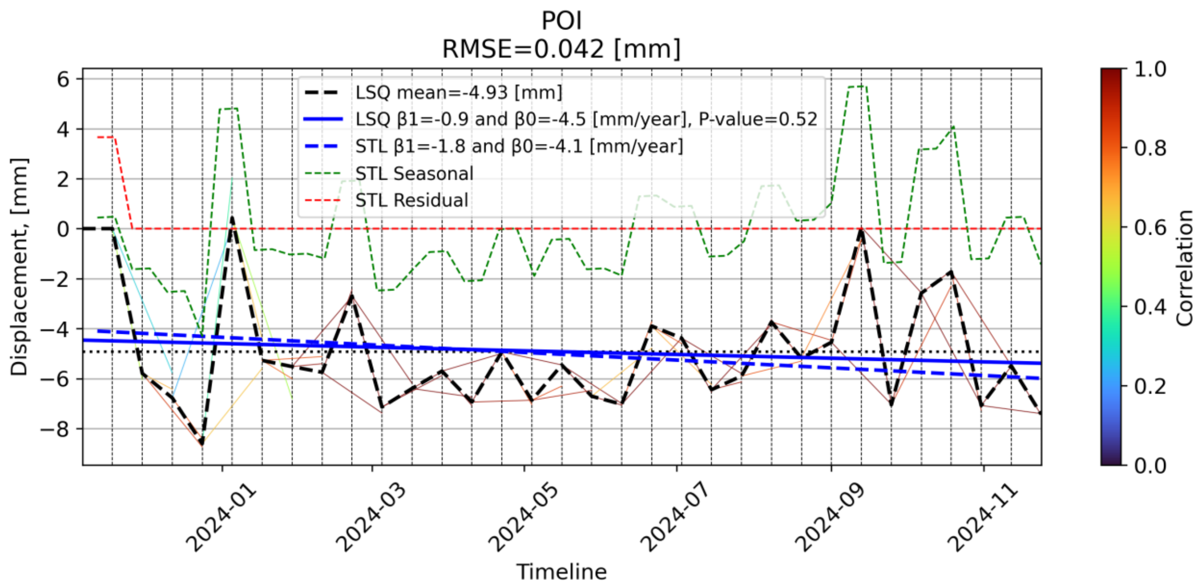

Figure 26 Displacement time series with least-squares (LSQ) trend fitting of Reference Point

In the Figure 26:

- The black dashed line (actual measurements) stays very close to zero.
- The blue trend line is almost flat.
- The green seasonal line shows small ups and downs, which are normal and can be caused by weather, moisture, or atmosphere.
- The red residual line stays close to zero, showing that there is no unexplained behavior.

The RMSE value of 0.042 mm is very small. This means the satellite measurements are very precise and reliable. Overall, this graph confirms that POI is stable and can safely be used as a reference point.

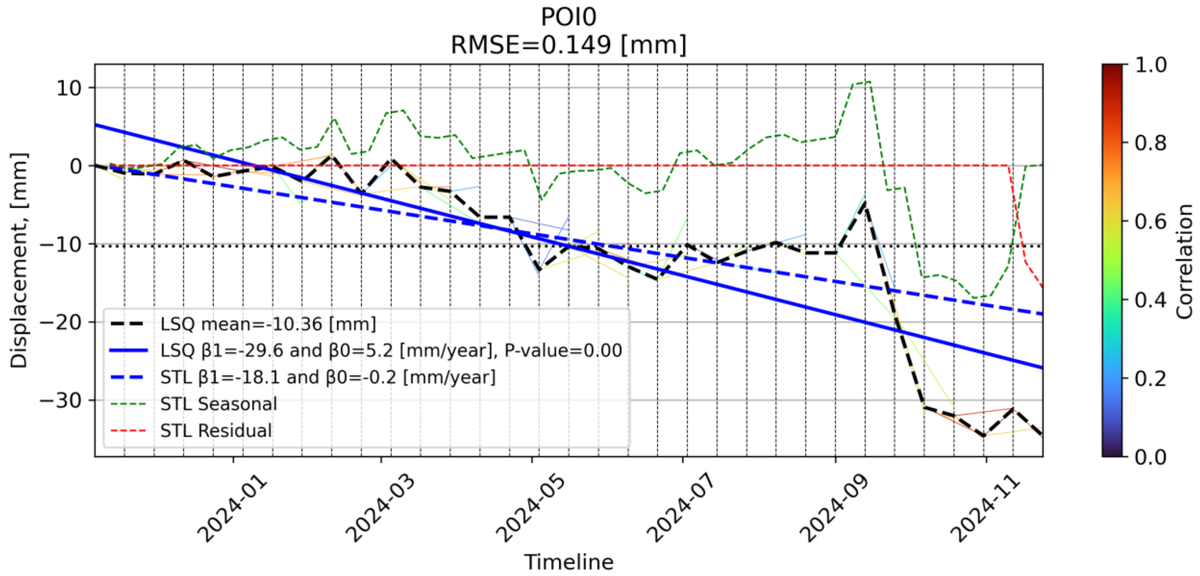

Figure 27 Displacement time series with least-squares (LSQ) trend fitting of Subsidence Point

Figure 27 tells a very different story. This graph represents POI0, which is located inside or very close to the construction area. Here, the ground is clearly sinking, which scientists call subsidence. The blue trend line slopes strongly downward, showing a sinking rate of about –29.6 mm per year. This is a large amount of movement and cannot be ignored. The P-value here is 0.00, which means this sinking is definitely real and not caused by noise or random error. The green seasonal line looks like waves going up and down. This shows short-term changes, such as:

- soil expanding when it gets wet,
- soil shrinking when it dries,
- small atmospheric effects.

However, even with these short-term ups and downs, the ground keeps sinking overall. This is shown by the STL trend, which still indicates a strong downward movement of about –18.1 mm per year. This means the problem is long-term, not temporary.

One of the most important observations occurs between September and November 2024. During this period, the ground displacement shows a sudden and significant drop, decreasing from approximately –5 mm to nearly –35 mm. This sharp change indicates a rapid increase in ground movement within a short time span. Such a pattern strongly suggests the occurrence of intense construction activities during this period, such as deep excavation or underground structural work. The timing of this abrupt subsidence aligns well with the known construction schedule, thereby strengthening the conclusion that the observed deformation is directly related to human-induced activities rather than natural or random effects. The red dashed line in the graphs, referred to as the residual component, represents any remaining movement that is not explained by the trend or seasonal components. In both graphs, this residual remains very close to zero throughout the monitoring period. This behavior is an important quality indicator, as it shows that the analysis has successfully captured almost all of the ground movement present in the data. The minimal residual values imply that there is very little unexplained noise, which in turn confirms the reliability and robustness of the results. When both figures are compared, a clear contrast between the reference point (POI) and the subsidence point (POI0) becomes evident. The POI shows almost no displacement and remains stable throughout the entire observation period, confirming its suitability as a reference point. In contrast, POI0 exhibits strong and continuous subsidence, with a clear downward trend over time. This distinct difference demonstrates that the deformation detected by both SBAS and PS InSAR is real and not an artifact of processing or atmospheric effects. Furthermore, it confirms that the ground deformation is localized within the construction area, while the surrounding regions remain stable. Overall, these results validate the reliability of SBAS and PS InSAR techniques for monitoring construction-related ground deformation.

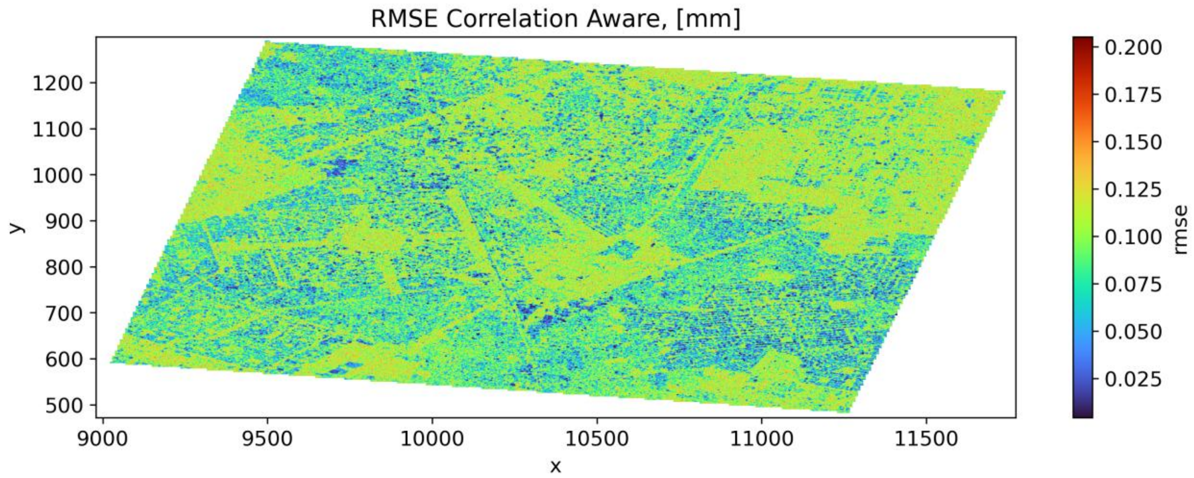

Figure 28 Root Mean Square Error (RMSE) Map

The analysis of ground deformation through SBAS and PS InSAR provides a detailed look at how the Earth's surface is shifting at two specific locations, referred to as POI and POI0. To understand these results, we must first look at the reference point, POI, which represents a stable area used for comparison. The data for POI shows a very small movement rate of only -0.9 mm per year, which is essentially negligible. This is confirmed by a P-value of 0.52; in statistics, a high P-value like this tells us that the tiny bit of movement we see is likely just random noise or a tiny measurement error rather than the ground actually sinking. The black dashed line, representing the raw measurements, stays very close to the zero mark throughout the entire year of 2024. The incredibly low RMSE of 0.042 mm highlights that our satellite measurements are extremely precise, acting like a very steady ruler that confirms this specific spot is not in danger. POI0, we see a much more dramatic story of ground subsidence, which is the scientific term for the ground sinking. The solid blue line shows a steep downward slope, calculating a sinking rate of -29.6 mm per year. P-value here is 0.00, which is the strongest possible evidence that this sinking is real and not a mistake. When we look at the green dashed line, labeled STL Seasonal, we see a wavy pattern that looks like a heartbeat. This represents the ground breathing it might rise slightly when it rains and the soil swells, and sink when it gets dry. However, even with this natural seasonal breathing, the overall trend shown by the thick dashed blue line remains at -18.1 mm per year. This proves that beneath the temporary seasonal changes, there is a permanent, underlying problem causing the land to drop. The most concerning part of the POI0 graph line occurs between September and November 2024. During this short window, the black dashed line shows the ground dropping sharply from -5 mm to nearly -35 mm. This sudden dip suggests that something specific happened during those months to accelerate the sinking. Finally, the red dashed line at the top, called the STL Residual, represents any leftover movement that the model couldn't explain. Since this red line stays very flat and close to zero, it proves that our analysis successfully captured almost every detail of how the ground is moving. To ensure these specific findings are reliable across the entire study area, a Correlation Aware RMSE map was generated. This map acts as a quality report for every pixel analyzed by the satellite. The colors on this map represent the margin of error, with cool colors like blue and green indicating very high precision. Most of the region shows an error value between 0.05 mm and 0.10 mm, which is remarkably low. This widespread accuracy confirms that the sinking observed at POI0 is not an isolated error or a technical glitch, but a reflection of true ground movement. The blue areas, representing the most stable data points, are typically found on solid ground or man-made structures that provide clear reflections back to the satellite. By combining the specific point-by-point graphs with this broad quality map, we can conclude with high confidence that the subsidence identified in this study is a significant and real geophysical event that warrants further investigation into local environmental or human-driven causes.

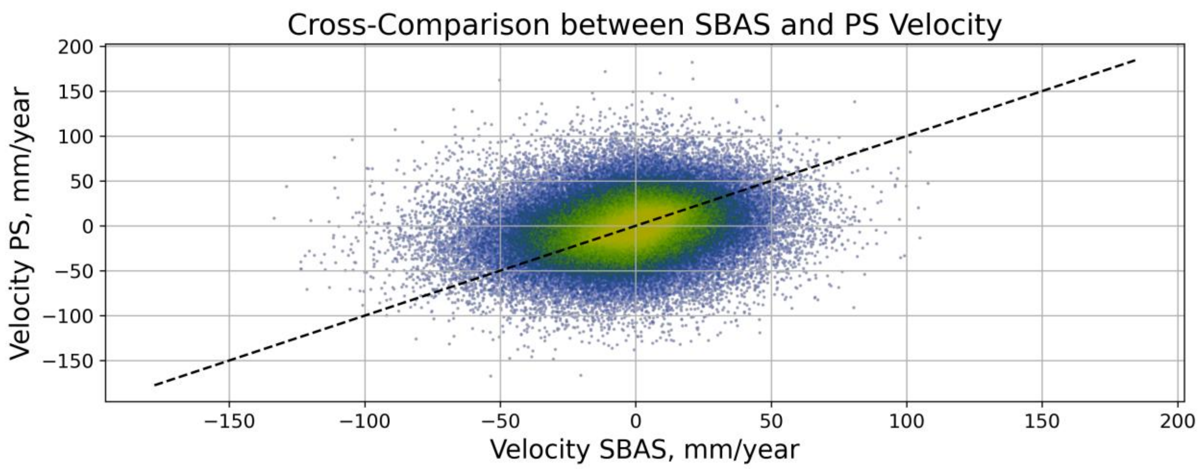

Figure 29 RMSE PS-SBAS Correlation Map

The analysis of ground deformation through SBAS and PS InSAR provides a detailed look at how the Earth's surface is shifting at two specific locations, referred to as POI and POI0. To understand these results, we must first look at the reference point, POI, which represents a stable area used for comparison. The data for POI shows a very small movement rate of only -0.9 mm per year, which is essentially negligible. This is confirmed by a P-value of 0.52; in statistics, a high P-value like this tells us that the tiny bit of movement we see is likely just random noise or a tiny measurement error rather than the ground actually sinking. The black dashed line, representing the raw measurements, stays very close to the zero mark throughout the entire year of 2024. The incredibly low RMSE of 0.042 mm highlights that our satellite measurements are extremely precise, acting like a very steady ruler that confirms this specific spot is not in danger. POI0, we see a much more dramatic story of ground subsidence, which is the scientific term for the ground sinking. The solid blue line shows a steep downward slope, calculating a sinking rate of -29.6 mm per year. P-value here is 0.00, which is the strongest possible evidence that this sinking is real and not a mistake. When we look at the green dashed line, labeled STL Seasonal, we see a wavy pattern that looks like a heartbeat. This represents the ground breathing it might rise slightly when it rains and the soil swells, and sink when it gets dry. However, even with this natural seasonal breathing, the overall trend shown by the thick dashed blue line remains at -18.1 mm per year. This proves that beneath the temporary seasonal changes, there is a permanent, underlying problem causing the land to drop. The most concerning part of the POI0 graph line occurs between September and November 2024. During this short window, the black dashed line shows the ground dropping sharply from -5 mm to nearly -35 mm. This sudden dip suggests that something specific happened during those months to accelerate the sinking. Finally, the red dashed line at the top, called the STL Residual, represents any leftover movement that the model couldn't explain. Since this red line stays very flat and close to zero, it proves that our analysis successfully captured almost every detail of how the ground is moving. To ensure these specific findings are reliable across the entire study area, a Correlation Aware RMSE map was generated. This map acts as a quality report for every pixel analyzed by the satellite. The colors on this map represent the margin of error, with cool colors like blue and green indicating very high precision. Most of the region shows an error value between 0.05 mm and 0.10 mm, which is remarkably low. This widespread accuracy confirms that the sinking observed at POI0 is not an isolated error or a technical glitch, but a reflection of true ground movement. The blue areas, representing the most stable data points, are typically found on solid ground or man-made structures that provide clear reflections back to the satellite. Finally, we conducted a cross-comparison between the two main methods used in this study: SBAS and PS. The scatter plot shows how these two techniques compare when measuring the velocity of the ground. In the center of the Figure 29, there is a bright yellow and green cluster where most of the data points are gathered, specifically around the zero mark. This tells us that for the majority of the area, both methods agree that the ground is stable. The black dashed diagonal line represents a perfect match between the two methods. Because the cloud of dots follows this diagonal line closely, it proves that the two different scientific formulas we used are giving us very similar answers. This agreement between the SBAS and PS methods gives us double the confidence that our measurements are correct. By combining the specific point-by-point graphs, the quality map, and this method comparison, we can conclude with high certainty that the subsidence identified in this study is a significant and real geophysical event. In summary, the results obtained from SBAS and PS InSAR analyses consistently reveal construction-induced ground deformation within the study area. The agreement between both methods and the real-world construction timeline confirms the reliability of the observations. These findings provide the foundation for the conclusions discussed in the next chapter.

5. CONCLUSION

This study demonstrates that Synthetic Aperture Radar (SAR) technology is a powerful and reliable tool for detecting very small ground surface changes at the millimeter level. Using freely available Sentinel-1 data, it was possible to monitor subtle ground deformation over time, even in a complex and active urban construction environment. The short revisit time of Sentinel-1 (approximately 6 days) provides high temporal resolution, which allows continuous observation of construction-related ground movement as it evolves. The Central Business District (CBD) construction site in Lahore, Pakistan, proved to be an ideal case study due to its large scale, multi-phase development, and ongoing excavation activities. Both Small Baseline Subset (SBAS) and Persistent Scatterer (PS) InSAR techniques successfully captured deformation patterns associated with construction work. SBAS provided a clear regional overview of how deformation initiated, evolved, and accumulated over time, while PS analysis focused on stable radar targets such as buildings and paved surfaces, revealing stronger and more localized deformation signals. The PS velocity results showed higher deformation values compared to SBAS. This difference highlights the higher sensitivity of PS InSAR, as it tracks individual stable reflectors rather than averaging deformation over larger pixel areas. The use of time-series analysis and Seasonal–Trend decomposition using Loess (STL) further strengthened the results by separating long-term deformation trends from short-term seasonal effects and noise. These analyses confirmed that the observed ground movement was mainly driven by sustained construction activity rather than temporary environmental variations. An important strength of this study was the availability of ground knowledge. Being physically familiar with the construction site, construction phases, and exact locations of the subsidence and reference points greatly improved the interpretation and reliability of the results. The strong agreement between satellite-based measurements and real construction timelines confirms the robustness of SBAS and PS InSAR for urban deformation monitoring. Overall, this research shows that SBAS and PS InSAR are highly effective and complementary techniques for monitoring construction-induced ground deformation. SBAS offers a reliable large-scale perspective, while PS provides precise measurements over critical infrastructure. Together, they form a powerful, non-invasive monitoring framework that can support urban planning, infrastructure safety assessment, and risk management in rapidly developing cities.

6. LIMITATIONS AND FUTURE WORK

Despite the strong results, this study has some limitations that should be acknowledged. One important limitation is the lack of accurate elevation information above mean sea level for the CBD construction site. Without precise height data, it is difficult to fully separate vertical and horizontal components of ground movement. Additionally, no multi-temporal LiDAR data were available for the study area. If such data had existed, it would have allowed a more detailed validation of the subsidence patterns and a clearer understanding of how surface elevation changed over time. Another limitation is the use of only one satellite viewing geometry. The analysis was based on a single orbit direction, which means the deformation results are expressed along the satellite's Line of Sight (LOS). True vertical and horizontal ground movement components could not be fully extracted. Using both ascending and descending Sentinel-1 orbits would allow separation of east–west and north–south motion, leading to a more complete three-dimensional deformation analysis. Future research can build upon this work in several ways. The upcoming NISAR satellite mission will provide new radar data with different wavelengths and improved sensitivity. Combining Sentinel-1 and NISAR data could offer deeper insights into how large-scale urban construction projects appear across multiple radar sensors. This multi-sensor approach would improve deformation detection and increase confidence in the results. Future studies could also integrate InSAR with ground-based measurements such as GNSS, leveling surveys, or LiDAR to enhance accuracy and validation. Extending the monitoring period beyond the current timeline would allow long-term assessment of post-construction ground stability. Finally, applying this combined SBAS–PS framework to other rapidly developing urban areas could help decision-makers detect early signs of excessive subsidence and promote safer, more sustainable infrastructure development.

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