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Enhanced Monitoring of Railway Transition Zones: Satellite-Based InSAR for Differential Settlement Detection

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Abstract

Railway transition zones are prone to differential settlements that degrade track geometry and operational safety. Traditional monitoring relies on periodic inspections with insufficient temporal coverage for early detection of problematic settlement trends. This study presents a systematic approach integrating Persistent Scatterer Interferometric Synthetic Aperture Radar (PS-InSAR) and Small Baseline Subset (SBAS) techniques for enhanced differential settlement detection and analysis. A hybrid PS-SBAS processing sequence leverages PS-InSAR's high spatial resolution and SBAS's broader coverage, optimized for railway environments with variable coherence. The methodology incorporates advanced noise reduction, atmospheric correction, and robust time-series post-processing, addressing phase unwrapping errors and outlier displacements. Applied to a 1.6 km Lisbon–Porto railway segment, the approach demonstrates strong correlation with conventional track inspection data, particularly in transition zones including bridge approaches and switches. Results show the hybrid method provides denser, more reliable displacement measurements, capturing long-term settlement patterns and identifying differential settlement hotspots. Findings support satellite-based InSAR as a complementary tool for railway infrastructure monitoring, offering valuable insights for maintenance planning and risk management in resilient transport systems.

Keywords: InSAR, Hybrid PS-SBAS, railway monitoring, bridge transition zone, railway track geometry, turnouts, railway track settlement, long-term monitoring, descriptive modelling, data analytics.

1 Introduction

Railway transition zones, including bridge approaches, underpasses, and switches, are critical infrastructure segments where differential settlements frequently develop due to abrupt changes in support conditions, creating significant challenges for maintenance efficiency. The underlying causes for the accelerated track deterioration in these segments is diverse, varying e.g. from subgrade compaction issues, ballast degradation, and soil variability. This deterioration poses risks to both operational safety and ride comfort, necessitating frequent maintenance interventions and, in severe cases, speed restrictions (Indraratna et al., 2019; Varandas et al., 2020).

Traditional railway geometry monitoring relies primarily on track inspection vehicles equipped with inertial measurement units, providing highly accurate but temporally limited snapshots of track conditions (Luo et al., 2023). These periodic inspections, constrained by operational schedules and resource requirements, often miss critical early-stage settlement development, particularly the progressive differential movements that characterize transition zone degradation. On the other hand, fixed sensor networks offer continuous monitoring but are spatially limited, leaving extensive track segments under-monitored (He et al., 2022; Ngamkhanong et al., 2018).

The increasing exposure of railway networks to climate-driven risks, including extreme weather events and ground instabilities, amplifies the need for comprehensive monitoring solutions that can detect long-term settlement patterns across entire corridors. This challenge requires innovative approaches that complement traditional methods while providing broader temporal and spatial coverage for proactive infrastructure management.

Interferometric Synthetic Aperture Radar (InSAR) technology has emerged as a powerful remote sensing technique for infrastructure deformation monitoring, offering millimeter-to-submillimeter accuracy through phase difference analysis between satellite acquisitions. Two primary multi-temporal InSAR approaches have been developed for surface displacement detection: Persistent Scatterer InSAR (PS-InSAR) and Small Baseline Subset (SBAS) techniques. PS-InSAR excels in high-coherence urban environments by focusing on stable reflectors, enabling precise long-term deformation tracking at critical infrastructure points. However, its dependence on persistent scatterers limits applicability in rural or vegetated areas typical of railway corridors. SBAS-InSAR addresses these limitations by utilizing interferometric pairs with constrained spatial and temporal baselines, enabling reliable measurements over broader, lower-coherence areas but with reduced spatial resolution.

Recent railway applications have demonstrated InSAR's potential for nationwide monitoring and risk assessment. Studies have successfully applied PS-InSAR for transition zone analysis (Tao et al., 2025; Wang et al., 2018), integrated InSAR with ground-penetrating radar for comprehensive subsurface characterization (Bianchini Ciampoli et al., 2020), and validated satellite measurements against track inspection data (Kizilirmak & Cakir, 2024). However, existing research primarily focuses on macro-scale corridor monitoring and overall subsidence detection, with limited attention to differential settlement estimation at the shorter wavelengths (15-40m) characteristic of railway transition defects.

This limitation stems from current InSAR processing techniques' inability to achieve sufficient resolution and accuracy for detailed track irregularity analysis at critical wavelengths. For railway managers, the primary concern extends beyond regional subsidence rates to rapid differential settlement development that directly impacts operational safety and ride quality.

This research advances InSAR application for high-resolution railway infrastructure monitoring by presenting a hybrid PS-SBAS processing approach that maintains spatial resolution while ensuring precision necessary for transition zone analysis. The methodology, originally introduced in (Varandas et al., 2025), systematically combines PS-InSAR's high spatial detail with SBAS's broader coverage, optimized for railway environments with variable coherence. The approach includes advanced time-series correction methods addressing phase unwrapping errors and outlier displacements, enabling reliable differential settlement detection and quantification. In this paper, the proposed approach is applied to a 1.6 km segment of the Lisbon–Porto railway.

2 Methods

This section briefly presents the hybrid PS-SBAS processing approach that was introduced in (Varandas et al., 2025). This approach systematically combines the high spatial resolution of Persistent Scatterer InSAR (PS-InSAR) (Ferretti et al., 2001), with the broader coverage capabilities of Small Baseline Subset (SBAS) techniques (Berardino et al., 2002), specifically optimized for railway infrastructure monitoring.

Figure 1 presents the complete research flowchart for this investigation, illustrating the systematic four-stage processing methodology that forms the core of this hybrid approach. The workflow begins with SAR data preprocessing and concludes with validated railway longitudinal profile generation, also incorporating advanced time-series correction methods to address common InSAR processing artifacts.

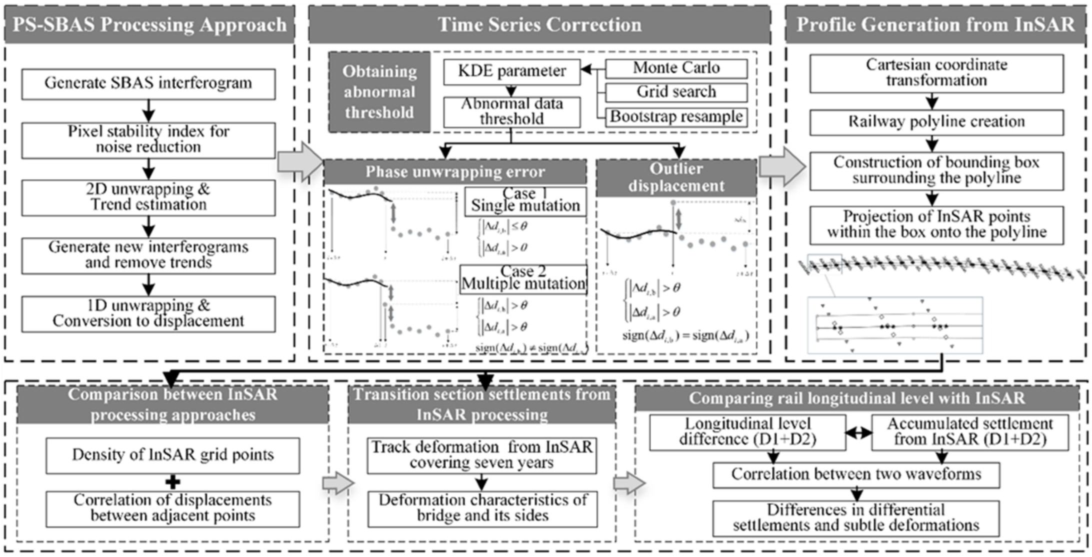

Figure 1. Methodology flowchart (from (Varandas et al., 2025))

2.1 Hybrid PS-SBAS processing sequence

The proposed PS-SBAS methodology proceeds through four interconnected stages designed to minimize noise, refine atmospheric corrections, and ensure high-resolution results at critical infrastructure points.

Stage 1: Data Preprocessing and Pixel Stability Index

Following SAR image downloading, reframing, and alignment, a Pixel Stability Index (PSI) is derived from the stack based on stability of pixel amplitude (reflectivity). The PSI identifies stable pixels using the inverse coefficient of variation:

$$\mathrm{PSI} = \frac{\mu_A}{2\sigma_A} \quad (1)$$

where μ_A and σ_A are respectively the mean and the standard deviation of the amplitude values. This index serves as a spatial mask to prioritize stable targets throughout subsequent processing stages, with only pixels exhibiting very low correlation values (<0.15) excluded from analysis.

Stage 2: Gaussian weighted filtering of Interferograms

A dense SBAS interferometric pair mesh is created with small temporal baselines (<90 days), followed by application of a two-dimensional spatial Gaussian filter weighted by the PSI:

$$\mathrm{G(x,y)} = \frac{\mathrm{PSI(x,y)}}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \quad (2)$$

The filter equation incorporates PSI values as weights, prioritizing stable pixels while maintaining numerical stability for subsequent unwrapping operations. The 100-meter filter width balances three critical requirements: (i) atmospheric noise suppression, (ii) numerical stability in low-coherence regions, and (iii) terrain adaptability without over-smoothing high-coherence areas. To minimize noise contribution, the top three interferogram pairs for each date are selected based on their average correlation values.

Stage 3: 2D Unwrapping and atmospheric correction

Next, selected interferograms are decimated to a 15-meter grid, and 2D unwrapping is applied to estimate non-displacement phase contributions, including atmospheric, topographical, orbital, and noise components.

Multivariate regression, weighted by correlation coefficients, separates displacement signals from noise contributions, enabling extraction of actual ground deformation from the complex interferometric phase.

Stage 4: High-resolution 1D unwrapping

A new set of undecimated interferograms are generated with estimated noise subtracted from previous processing stages. A tighter 30-meter Gaussian filter preserves higher frequency signal components relevant to track-specific deformations while reducing unwanted neighbouring pixel influences. One-dimensional temporal unwrapping finally converts phase measurements to line-of-sight displacements on pixels with sufficient coherence, maintaining the high-resolution grid essential for detailed railway monitoring.

2.2 Time-series correction methods

Despite above described InSAR processing procedure, abnormal and sudden displacement jumps still occasionally appear in time-series data due to phase unwrapping errors and outlier measurements. The methodology thus incorporates advanced correction techniques using Kernel Density Estimation (KDE) for threshold identification and polynomial fitting for data restoration.

Abnormal Data Identification

Two primary abnormal behaviours are addressed: sudden vertical jumps affecting subsequent measurements and isolated outlier displacements inconsistent with surrounding temporal patterns. A statistical approach based on KDE models the displacement change distributions to establish optimal thresholds for abnormal data detection. Monte Carlo analysis with embedded grid search and Bootstrap resampling determines optimal bandwidth and confidence level parameters, achieving F1-scores exceeding 0.95 for error identification.

Phase Unwrapping Error Correction

Two correction cases are implemented: single mutation points where isolated abrupt jumps occur, and multiple consecutive mutation points spanning several measurements. Fifth-order polynomial fitting provides optimal correlation ($R^2 > 0.8$) for reconstructing realistic displacement trends. Corrected displacements maintain physical consistency with expected railway infrastructure behaviour while preserving genuine deformation signals.

Outlier Displacement Correction

Outlier corrections target isolated measurement anomalies where single points exhibit unrealistic displacement values inconsistent with neighboring temporal patterns. The methodology distinguishes outliers from unwrapping errors through directional analysis of displacement changes, applying appropriate polynomial fitting to restore data continuity.

2.3 Railway profile generation

The transformation from InSAR grid measurements to railway longitudinal profiles requires systematic geometric processing. Geographic coordinates are converted to Cartesian coordinates using appropriate UTM projections, with railway centerline polylines constructed along track axes. A bounding box methodology selects relevant InSAR points within defined track corridors (typically 10 meters width), projecting measurements onto centerline polylines for longitudinal profile construction.

A moving average filtering with optimized window lengths (15-25 meters) reduces projection-induced irregularities while preserving settlement patterns relevant to railway defect wavelengths. Window length optimization considers characteristic wavelengths of railway longitudinal defects, particularly D1 (3-25m) and D2 (25-70m) bands defined in European standards. Sensitivity analysis using normalized Euclidean distance minimization between filtered profiles and track inspection data confirms optimal smoothing parameters.

This comprehensive methodology enables reliable detection and quantification of differential settlements in railway transition zones while maintaining the spatial resolution necessary for infrastructure-specific deformation analysis. The approach addresses both technical challenges of InSAR processing and practical requirements of railway monitoring applications.

3 Case-Study and Data

The methodology was applied to a 1.6 km segment of the Lisbon–Porto railway in Portugal, a double ballasted track carrying intense mixed passenger and freight traffic with operational speeds reaching 220 km/h. This segment was strategically selected due to known longitudinal defects developing particularly in transition zones, specifically bridge approaches and railway switches, making it an ideal testbed for validating the proposed hybrid PS-SBAS approach.

The analysed railway segment traverses a region characterized by alluvial formations, presenting variable coherence conditions typical of mixed urban-rural environments. This geological setting offers both high-coherence infrastructure points and challenging low-coherence agricultural areas adjacent to the tracks, providing a comprehensive test environment for the hybrid processing approach.

3.1 SAR Dataset Specifications

SAR data were acquired from ascending orbits of the Sentinel-1A satellite operating in C-band wavelength, comprising 239 images spanning eight years of analysis from January 2016 to December 2023. The Sentinel-1A satellite maintains an average revisit time of 12 days, providing consistent temporal sampling throughout the observation period. All data were obtained from NASA's ASF Vertex repository (https://www.earthdata.nasa.gov/data/tools/vertex) and processed using Spotlite's online platform, which provides multitemporal SAR interferometry capabilities for infrastructure monitoring applications.

3.2 Comparative processing results

Three distinct InSAR processing approaches were implemented to evaluate the proposed methodology: traditional SBAS, conventional PS-InSAR, and the hybrid PS-SBAS technique. Figure 2 presents the spatial distribution comparison of InSAR measurement points along the 1.6 km railway segment, clearly demonstrating the superior point density and coverage achieved by the hybrid approach.

The SBAS processing generated points with approximately 23-meter spacing in each orthogonal direction, while PS-InSAR achieved 15×4-meter resolution. The proposed PS-SBAS method delivered optimal performance with 14×3.5-meter point spacing, providing the highest spatial resolution while maintaining reliable measurements across variable coherence zones.

Given the study objective of detecting differential settlements with wavelengths shorter than 40 meters, the SBAS approach proved inadequate due to excessive point spacing along the railway centerline. Subsequent analysis therefore focused on comparing PS-InSAR with the hybrid PS-SBAS methodology.

3.3 Performance validation

Cross-correlation analysis between nearby point pairs validated the superior performance of PS-SBAS processing. Statistical analysis of normalized zero-lag cross-correlation values for point pairs within seven meters distance demonstrated quantitative superiority of the hybrid approach. Table 1 presents the comparative results:

Processing	Mean (x)	Standard deviation (μ)
PS-InSAR	0.9888	0.0298
PS-SBAS	0.9934	0.0161

Table 1. Statistical analysis of zero-lag cross-correlation calculated for PS-InSAR and PS-SBAS data sets.

PS-SBAS achieved superior performance with higher mean correlation (0.9934 vs 0.9888) and substantially lower standard deviation (0.0161 vs 0.0298), indicating greater consistency and reliability in temporal correlation between adjacent measurements. This quantitative comparison demonstrates that the hybrid PS-SBAS approach provides both denser point distributions and stronger temporal correlation, establishing its superiority for railway transition zone monitoring where spatial continuity and measurement reliability are critical for differential settlement detection.

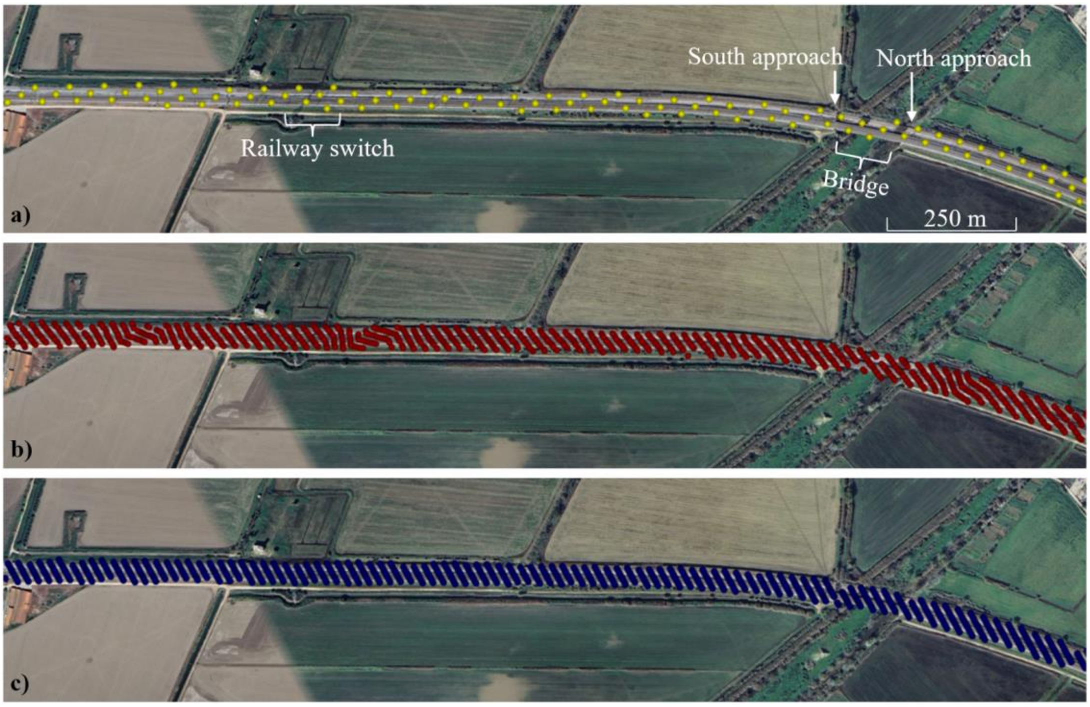

Figure 2. InSAR grid of points along a railway track segment with 1.6 km length obtained with: (a) SBAS, (b) PS- InSAR, and (c) combined PS-SBAS approach (from (Varandas et al., 2025))

4 Results and Validation

The hybrid PS-SBAS methodology was applied to generate longitudinal railway profiles for the 1.6 km Lisbon–Porto railway segment, focusing on critical transition zones including bridge approaches and railway switches. This section presents the key findings and validates the approach against conventional track inspection data.

4.1 Longitudinal Profile Generation Results

The transformation from InSAR grid measurements to railway longitudinal profiles demonstrated the effectiveness of the correction methodologies developed. Initial profiles exhibited significant erratic oscillations incompatible with realistic railway track behaviour, primarily caused by phase unwrapping errors and outlier displacements. The application of the KDE-based correction method, optimized through Monte Carlo analysis with F1-scores exceeding 0.95, successfully eliminated these artifacts (Varandas et al., 2025).

Moving average filtering with a 21-meter window length further refined the profiles, balancing noise reduction with preservation of relevant deformation patterns.

This window length aligns with characteristic wavelengths of railway longitudinal defects (15-70m) defined in European standards, and sensitivity analysis confirmed optimal performance through minimized normalized Euclidean distance between filtered profiles and track inspection data.

The corrected profiles revealed coherent settlement patterns across the analyzed segment, with general downward motion observed throughout the monitoring period. Most significantly, the methodology successfully captured differential settlements developing at critical infrastructure points, particularly in transition zones where abrupt support condition changes occur, as will be seen next.

4.2 Bridge transition analysis

Figure 3 presents a comparison between the rail longitudinal level measured from track inspections and the track profile derived from InSAR processing. The location of the bridge south approach and of the railway switch is indicated in the figure. The comparison encompasses a 52-month period (March 2016 to July 2020) selected to exclude tamping operations that could mask natural settlement evolution.

The track inspection data (blue line) shows the average left-right rail longitudinal level in the D1+D2 wavelength range (3-70m). The differential settlement evolution (red line) identifies segments undergoing active deformation, with the south approach exhibiting the most pronounced changes.

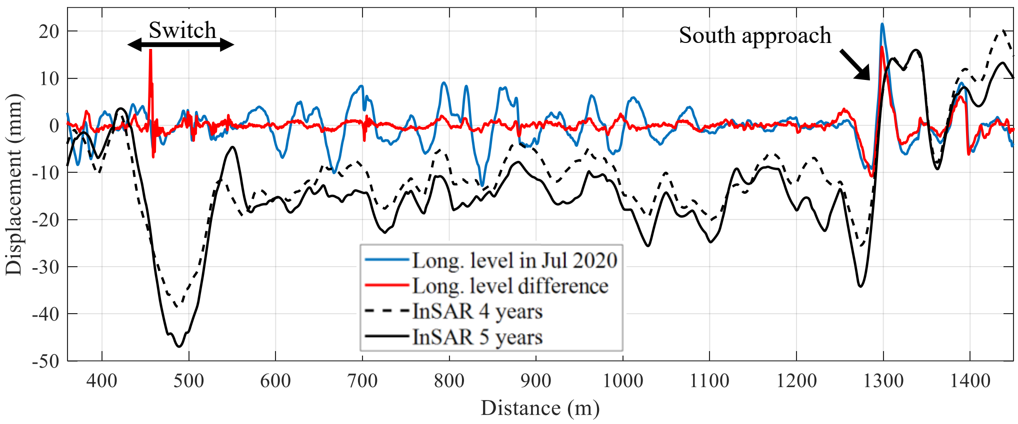

Figure 3. Rail longitudinal level from regular track inspection (D1 + D2) and track profile generated from InSAR processing (from (Varandas et al., 2025))

InSAR-derived profiles (black lines) demonstrate strong correlation with inspection data in regions experiencing active differential settlement. The 52-month cumulative settlement (dashed line) shows approximately 40mm differential settlement in the south bridge approach, increasing to 49mm after an additional year (solid line). This sustained and spatially coherent deformation trend, observed in surrounding ground points beyond the rail level alone, provides evidence that the defect stems from subgrade settlement rather than isolated ballast issues.

Critically, the methodology detected a railway switch settlement with approximately 130m wavelength and >40mm amplitude – a defect invisible to conventional D1+D2 inspection systems due to its wavelength exceeding the 70m cutoff. This demonstrates InSAR's capability to identify potential infrastructure problems in wavelength ranges not covered by traditional monitoring.

4.2 Discussion and practical implications

The comparison between INSAR derived track profile and longitudinal profiles from regular inspections made in section 4.2 revealed both strengths and limitations of the InSAR approach. While strong correlation exists between InSAR measurements and track inspection data in transition zones with high differential settlement rates, it was also seen that prominent rail longitudinal defects observed in track inspection data between 600-1100m lack corresponding signatures in InSAR profiles. This discrepancy occurs because these defects remain essentially stable over time, as confirmed by the differential settlement analysis (red line). Since InSAR processing estimates cumulative settlement development, it naturally performs best where differential settlement rates are high rather than where static defects exist.

The results presented show that the hybrid PS-SBAS approach can offer several key advantages for railway infrastructure monitoring. Long-term settlement pattern detection enables identification of gradual deformation trends that periodic inspections might miss between measurement campaigns. The methodology provides broader wavelength coverage, successfully detecting defects >70m that fall outside conventional inspection ranges.

Spatial continuity across entire corridors allows comprehensive monitoring without the spatial limitations of fixed sensor networks. The 12-day revisit time of Sentinel-1A provides consistent temporal sampling for trend analysis, though current Sentinel-1C addition will reduce this to 6 days, enhancing temporal resolution for rapid change detection.

Several limitations constrain current InSAR application in railway monitoring. Resolution constraints limit detection to millimeter-scale movements, though this proves sufficient for infrastructure-relevant deformations. Atmospheric effects and orbital inaccuracies can introduce noise, though the hybrid processing approach effectively mitigates many such artifacts.

The methodology assumes abrupt displacement anomalies represent processing errors rather than actual ground disturbances. While correction algorithms successfully address most unwrapping problems, distinguishing between artificial and real signals without supplementary maintenance records remains challenging.

Results strongly support InSAR's role as a valuable complement to traditional railway monitoring rather than a replacement. The technology excels at capturing long-term differential settlement evolution and identifying defects in extended wavelength ranges. However, traditional inspection methods remain essential for detailed geometry assessment and short-wavelength defect detection.

The combination of InSAR's broad coverage with conventional inspection's precision offers enhanced maintenance planning capabilities. InSAR can identify problematic sections requiring focused attention, optimizing deployment of detailed inspection resources and enabling proactive intervention strategies.

This comprehensive validation demonstrates that satellite-based InSAR monitoring provides valuable insights for railway infrastructure management, particularly for transition zone monitoring where differential settlements pose significant operational risks.

5 Conclusions

This study successfully demonstrates the effectiveness of a hybrid PS-SBAS InSAR approach for monitoring differential settlements in railway transition zones. The proposed methodology systematically integrates PS-InSAR's high spatial resolution with SBAS's broader coverage, achieving optimal performance with 14×3.5-meter point spacing and superior temporal correlation between adjacent measurements compared to conventional approaches.

The hybrid processing sequence, incorporating advanced time-series correction methods using KDE-based threshold identification and polynomial fitting, effectively addresses phase unwrapping errors and outlier displacements. Applied to the 1.6 km Lisbon–Porto railway segment, the methodology captured critical infrastructure behavior including 40-49mm differential settlement in the south bridge approach over 52+ months and detected a railway switch settlement with 130m wavelength exceeding 40mm amplitude.

Comparison with conventional track inspection data confirms strong correlation in transition zones experiencing active differential settlement, establishing InSAR's value as a complementary monitoring tool. The approach successfully identifies long-term settlement patterns and infrastructure defects beyond traditional D2 wavelength ranges (>70m), enhancing maintenance planning capabilities.

While current limitations include millimeter-scale resolution constraints and atmospheric effects, this research advances satellite-based railway monitoring toward comprehensive infrastructure management. The methodology provides railway operators with enhanced early detection capabilities for differential settlements, supporting proactive maintenance strategies and contributing to more resilient transport systems. Future developments incorporating machine learning optimization and higher-resolution sensors will further strengthen InSAR's role in railway infrastructure monitoring.

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