Back-to-back approach to SAR interferometry

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Abstract

Interferometric SAR (InSAR) techniques, particularly Persistent Scatterer Interferometry (PSI), have become essential for land deformation monitoring. However, phase unwrapping errors significantly impact the reliability of deformation measurements, especially in areas with high phase noise or rapid deformation. This paper introduces a back-to-back (B2B) approach that enhances PSI results through a direct phase integration of consecutive interferograms, combined with adaptive phase unwrapping error detection and correction. The methodology integrates coherence-based pixel selection, adaptive phase unwrapping with variable thresholds, spatial-temporal consistency checking, and interpolation. Validation across several mining sites confirms the method’s robustness. For example, at the Relave Talabre mine in Chile, the B2B approach increased measurement density by over 20% with respect to standard PSI, and improved temporal consistency between ascending and descending datasets. These results demonstrate that the B2B approach offers enhanced spatial coverage, more reliable phase unwrapping, and operational efficiency for large-scale deformation monitoring in mining environments.

1. Introduction

Interferometric SAR (InSAR) is a well-established remote sensing technique for measuring and monitoring land deformation with millimetre-level precision (Ferretti et al., 2001). Persistent Scatterer Interferometry (PSI) techniques, which exploit large stacks of SAR images to identify persistent radar targets, have been widely developed over the past three decades (see Crosetto et al., 2016 for a review). This paper presents a new approach that it is termed back-to-back (B2B) and that enhances the PSI results obtained with the PSIG processing chain (Devanthéry et al., 2014) through direct integration of consecutive interferogram phases.

Despite advances in PSI methodology, phase unwrapping remains a critical challenge, with errors directly corrupting deformation time series—especially in areas of high phase noise, rapid deformation, or low coherence. Traditional approaches often sacrifice measurement density through conservative thresholds, leading to incomplete spatial coverage. Mining environments amplify these issues, featuring rapid subsidence, variable coherence across diverse surfaces, and thin structures requiring high-resolution, all under demanding safety requirements for both density and reliability.

The B2B method addresses these limitations via direct phase integration of consecutive interferograms, adaptive coherence thresholding per interferogram, perpendicular-baseline filtering to exclude problematic pairs, spatial–temporal consistency checks, and Inverse Distance Weighting (IDW) interpolation. This semi-automatic procedure reduces unwrapping errors by refining pixel selection and eliminating inconsistent areas, improving measurement density, robustness, and operational efficiency. The approach is validated across several mining sites, confirming its value for reliable deformation monitoring.

2. The proposed algorithm

The proposed procedure starts with a stack of co-registered and (optionally) multi-looked SAR images, from which we generate the set of consecutive differential interferograms that connect the first and last images of the stack. The procedure involves the following steps:

1. Coherence-based pixel selection,
2. 2D phase unwrapping,
3. Check of the unwrapped phases,
4. Topographic Correction,
5. Spatial interpolation (optional),
6. Direct phase integration,
7. Atmospheric filtering and geocoding.

The first step is pixel selection, which is usually based on the coherence of the used interferograms. The topographic correction step employs a RANSAC-based (Fischler et al., 1981) baseline detrending to estimate and remove residual topographic errors, ensuring accurate deformation measurements across diverse terrain conditions. On the irregular grid of selected points, the 2D phase unwrapping for sparse data is performed on each of the N-1 interferograms (where N is the number of SAR images).

This latter step can generate phase unwrapping errors. These errors are checked considering the spatial and temporal consistency of the unwrapped phases. If needed, the phase unwrapping can be performed iteratively by using more restrictive thresholds than the one used in step 1. In areas where unwrapping errors persist, the corresponding interferograms can be removed and replaced by other interferograms that guarantee the direct phase integration. Once the unwrapped phases are controlled, the unwrapping phases can be optionally interpolated. This is useful not to lose points due to the above-mentioned adjusting of the thresholds. The interpolated deformation values are then indicated in the final time series, to separate them from the actually measured deformation values.

The following step is direct phase integration using the simple network of interferograms, as it is illustrated in Figure 1. The next step is the filtering of the atmospheric component, based on the spatial and temporal characteristics of deformation and phase components. This is then followed by geocoding to achieve the final deformation products.

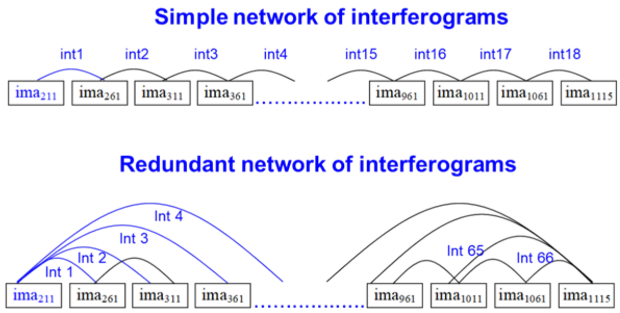

Figure 1. Types of networks of interferograms.

3. Study Areas and Dataset

The B2B methodology was validated across several mining sites in different continents, representing diverse geological settings, terrain conditions, and operational challenges. In this paper, three sites including Relave Talabre (Chile), El Brocal (Peru) and Chambishi (Zambia) are used to demonstrate the methodology's performance across varying environmental conditions, from flat tailings facilities to complex topographic relief, and under different deformation regimes. All sites utilized Sentinel-1 SAR imagery processed with multi-look factors of 1×4 (azimuth × range).

The Relave Talabre tailings dam is in the Atacama Desert, one of the driest regions in the world. The site consists of a tailing storage facility with flat to gently sloping terrain and surface conditions typical of active mining operations. The dataset includes dual-geometry Sentinel-1 acquisitions, with 33 ascending images reduced to 27 during processing and 35 descending images reduced to 33 (ranging from March 2023 to April 2024) after excluding a small number of interferograms.

The El Brocal mine lies at high elevation in the Andes, around 4,300 m above sea level. It is an open-pit polymetallic mine extracting zinc, lead, and silver, with multiple tailings dams, waste rock dumps, and active mining zones under moderate topographic relief and variable atmospheric conditions. The analysis used an ascending Sentinel-1A track with 20 images, covering March 2025 to October 2025. IDW interpolation settings were used with coherence thresholds adapted per interferogram, ranging from 0.75 to 0.79, depending on quality.

The Chambishi tailing storage facility experienced a major cascading failure on 18 February 2025, when piping through the divisional wall between two upper compartments triggered a wall collapse, allowing supernatant water from the active compartment to overtop into an inactive one. This site was processed using 34 Sentinel-1 images from January 2024 to February 2025.

4. Results

The B2B approach was validated across three mining sites with diverse geological settings and deformation regimes, utilizing Sentinel-1 SAR imagery processed with multi-look factors of 1×4. Table 1 summarizes the key parameters and comparative results for each case study, demonstrating consistent performance improvements across all sites.

The Relave Talabre site provided dual-geometry validation for the B2B approach, with both ascending and descending Sentinel-1 tracks demonstrating substantial measurement density improvements over standard PSIG processing. Ascending geometry processing generated 258,113 points compared to 219,465 from PSIG (18% increase), while descending geometry achieved 319,852 points versus 259,628 (23% increase), as shown in Figures 2 and 3. These gains provided enhanced spatial coverage particularly along tailings dam peripheries, embankment slopes, and transitional zones between stable and deforming areas, where adaptive thresholding and IDW interpolation recovered measurements that conservative PSIG filtering excluded.

	Coherence Threshold	PSIG Points	B2B Points	Density Increase
Relave Talabre (Asc)	0.8	219,465	258,113	+18%
Relave Talabre (Asc)	0.8	259,628	319,852	+23%
El Brocal	0.75 – 0.79 (adaptive)	36,788	45,072	+22.5%
Chambishi	0.79 – 0.82 (adaptive)	662	1,939	+193%

Table 1. Summary of case parameters and comparative results between standard PSIG and B2B approaches.

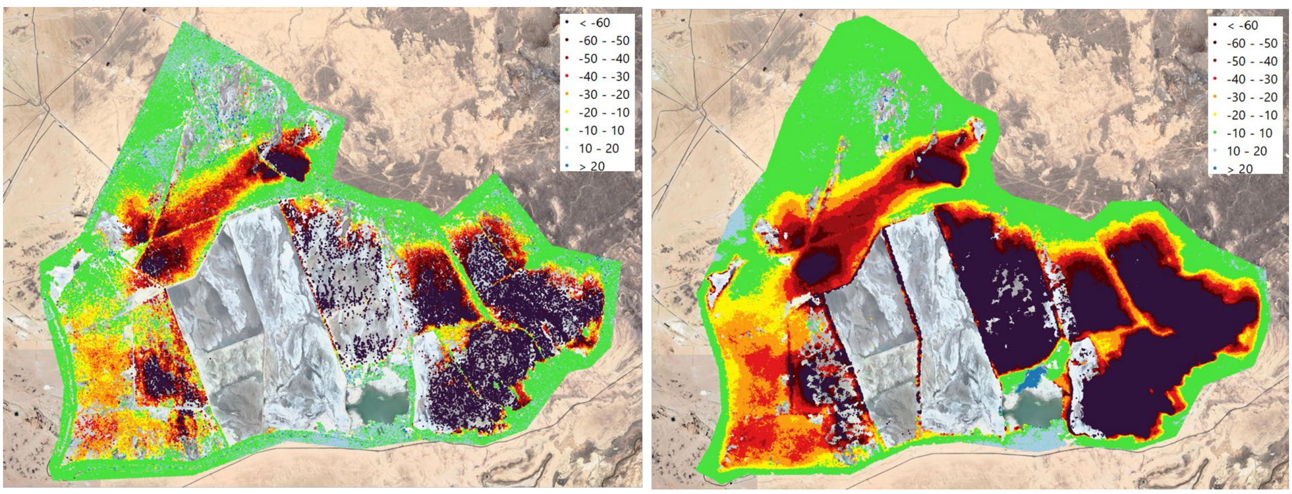

Figure 2: Accumulated deformation map from PSIG (left) and the corresponding map generated with B2B (right) in ascending case over Relave Talabre. The first map contains 219465 measurement points, while the other one contains 258113 measurement points.

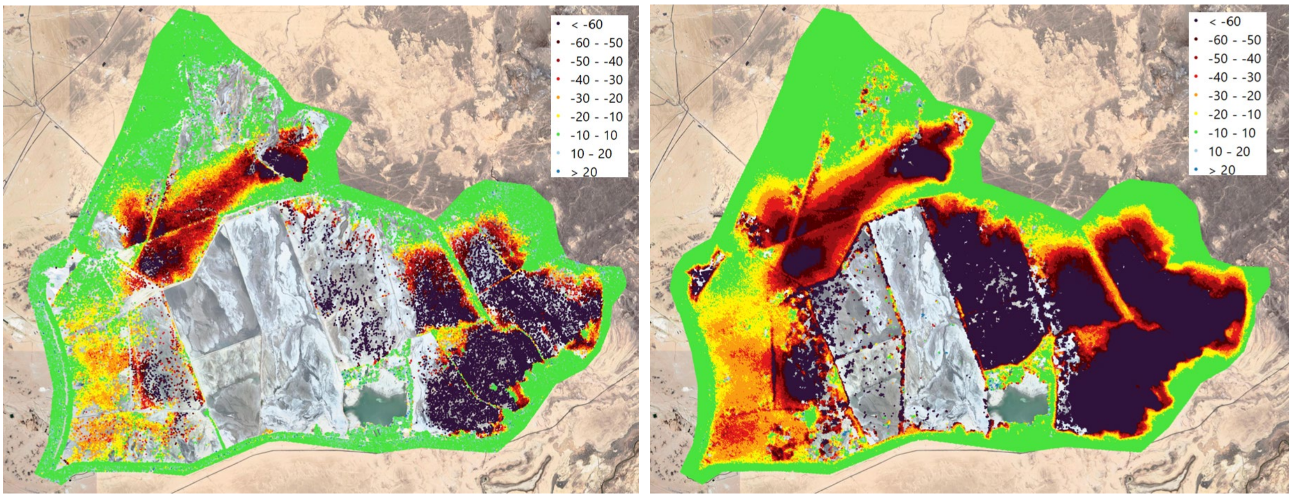

Figure 3. Accumulated deformation map from PSIG (left) and the corresponding map generated with B2B (right) in descending case over Relave Talabre. The first map contains 259,628 measurement points, while the other one contains 319,852 measurement points.

In El Brocal mine, the B2B method yielded 45,072 measurement points compared to 36,788 from PSIG (22.5% increase), as shown in Figure 4. The adaptive coherence thresholds (0.75–0.79) was adjusted to each of the interferograms. The enhanced coverage proved particularly valuable for monitoring multiple structures including the open pit, tailing dams, and waste rock dumps within a single processing framework.

The Chambishi tailings storage facility, which experienced catastrophic failure on 18 February 2025, provided the most dramatic validation of the B2B approach's value for safety-critical monitoring. Standard PSIG processing produced only 662 measurement points—insufficient coverage for reliable stability assessment—while the B2B method achieved 1,939 points (193% increase), as illustrated in Figure 5. This nearly threefold improvement in spatial coverage enabled detection of critical precursory deformation patterns. Time series analysis of points within the failure zone (Figure 6a, yellow circle in Figure 5 bottom) revealed clear deformation acceleration in the final dates before the failure event, representing a classic precursory signal consistent with progressive failure mechanisms. The interpolation index (Figure 6b) demonstrates transparent data provenance, with values of 0 indicating original measurements, 1 indicating IDW-interpolated values, and -1 indicating excluded data. Critically, the acceleration signal was based primarily on original measurements, confirming reliability of this key finding.

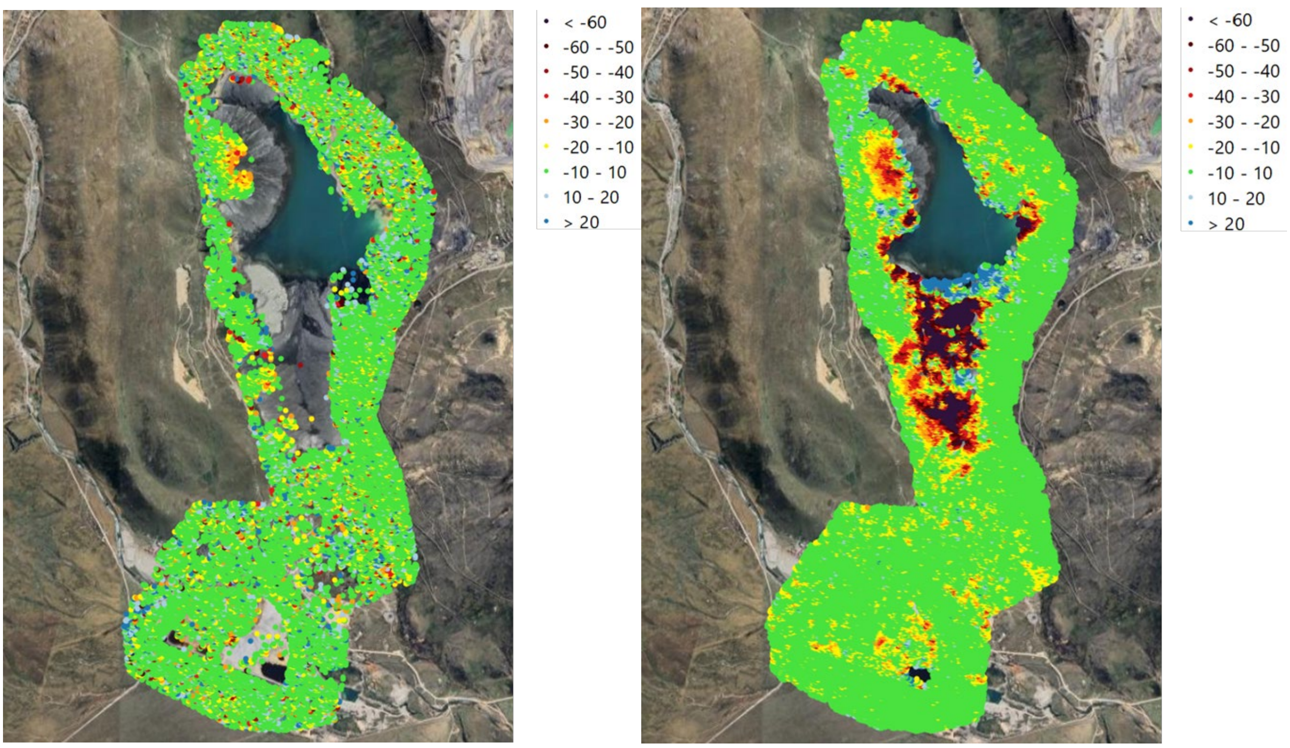

Figure 4. Accumulated deformation map coming PSIG (left) and the corresponding map generated with the algorithm described in this paper (right) over the Brocal case. The first map (left) contains 36,788 measurement points, while the other one (right) contains 45,072 measurement points.

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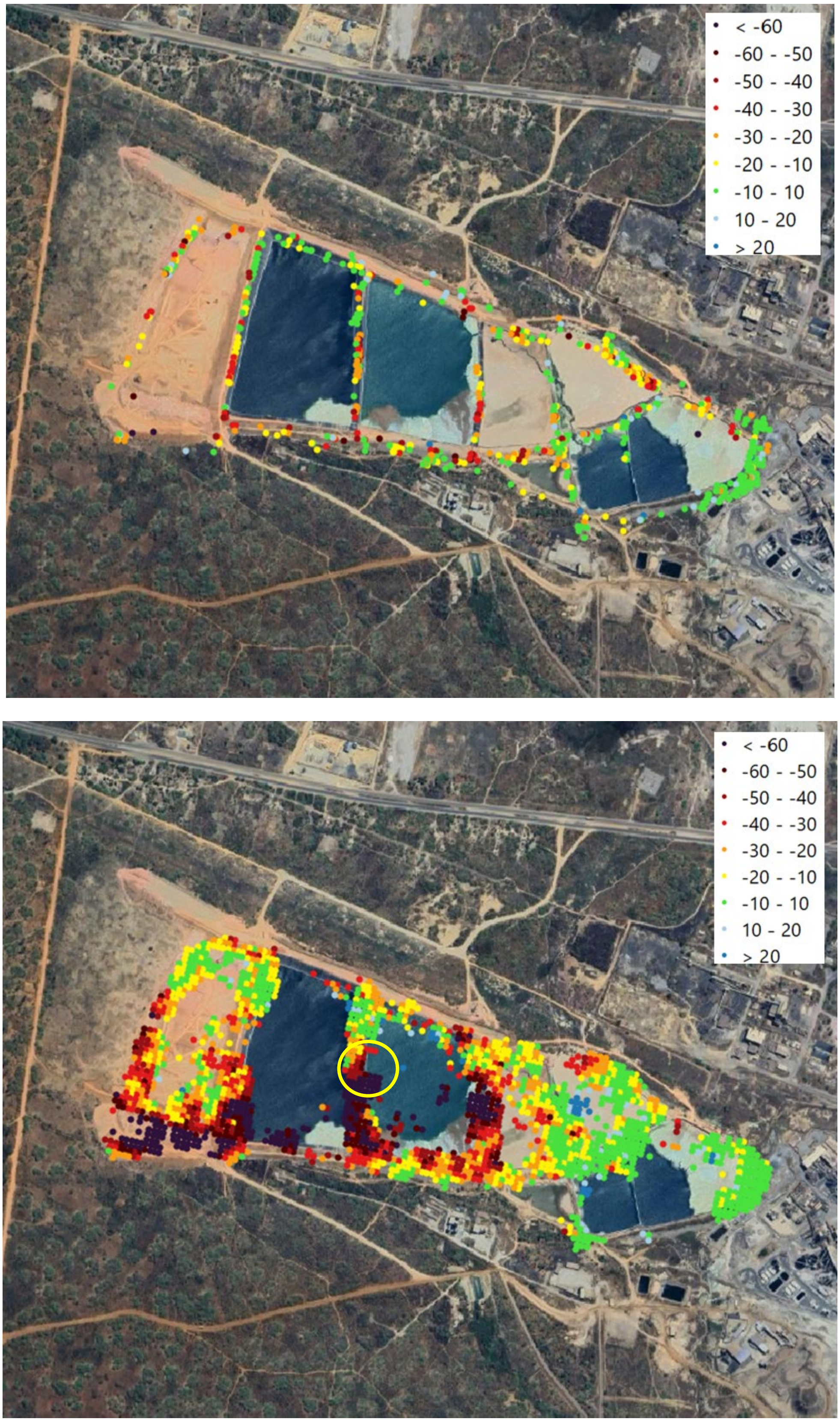
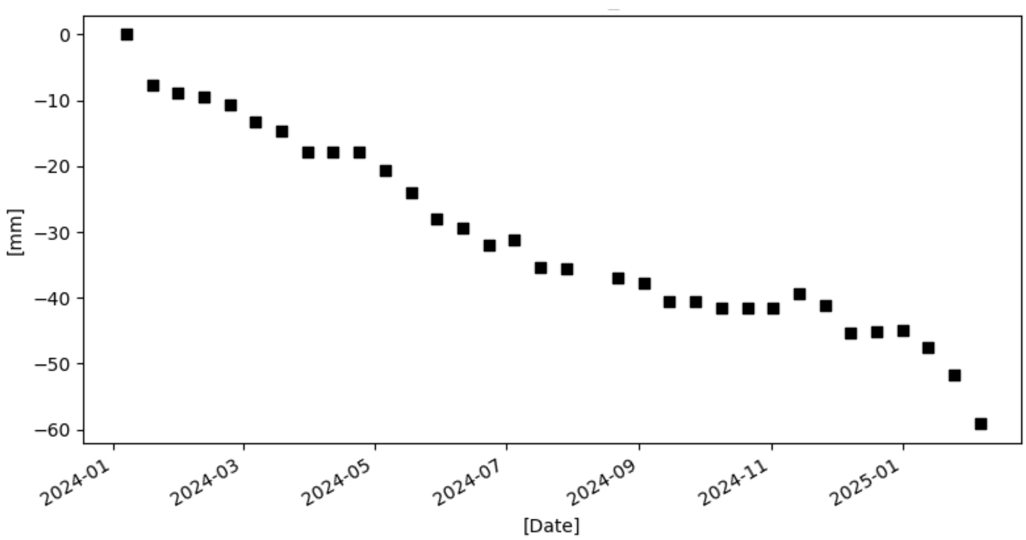
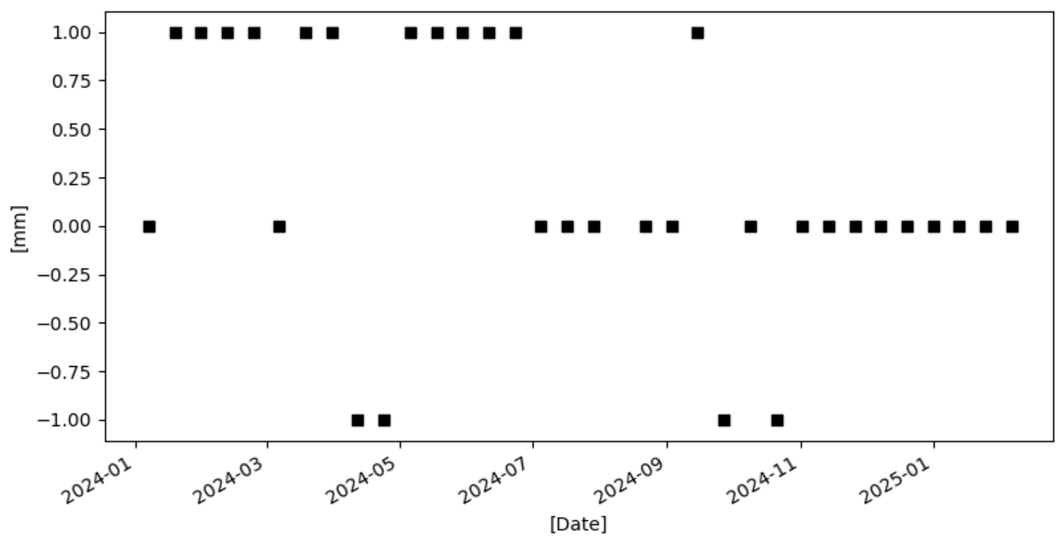


Figure 5. Accumulated deformation map coming from the PSIG processing (top) and the corresponding map generated with the algorithm described in this paper (bottom) over Chambishi (Zambia) case. The first map (left) contains 662 measurement points, while the other one (right) contains 1939 measurement points.



(a) Time series over a single point in the yellow circle in Figure 5 (bottom).



(b) Interpolation index indicating 0: original, 1: interpolated, -1: excluded.

Figure 6. Deformation time series along with the interpolation index over Chambishi.

Comparative analysis across sites reveals that the magnitude of B2B improvement correlates with site challenge level: from 18–23% in the favorable conditions of Relave Talabre, to 22.5% in the complex terrain of El Brocal, to 193% in the challenging environment of Chambishi. This performance values demonstrate to be consistent across varying conditions, with greatest benefits obtained where standard PSI approaches struggle most.

5. Conclusions

This paper has introduced a new InSAR processing approach, which is termed back-to-back (B2B). The approach has been validated using three test sites. The new approach significantly enhances PSI performance through direct phase integration of consecutive interferograms, combined with adaptive phase unwrapping error detection and correction. Validation across three diverse mining sites demonstrates the methodology's robustness and its practical value for operational deformation monitoring in challenging environments.

The B2B approach delivers three primary advantages over standard PSI processing. First, enhanced measurement density ranging from 18% in favourable conditions to 193% in challenging environments provides more complete spatial coverage critical for comprehensive structural monitoring. Second, improved phase unwrapping reliability through integrated adaptive coherence thresholding, perpendicular baseline filtering, and spatial-temporal consistency checking ensures that only reliable measurements contribute to final deformation products. Third, operational efficiency gains from semi-automatic error detection and standardized quality control reduce manual intervention and enable consistent processing across multiple sites and time periods.

The practical implications for mining monitoring are substantial. At Chambishi, the dramatic density improvement (193%) enabled detection of precursory deformation acceleration (~20 mm) before the February 2025 failure. At El Brocal, enhanced coverage across complex terrain encompassing multiple structures demonstrates value for comprehensive mine-wide monitoring. The Relave Talabre dual-geometry results confirm that the B2B approach maintains temporal consistency while improving density.

Methodologically, the B2B approach consists of an adaptive processing framework that adjusts coherence thresholds to individual interferogram quality rather than applying fixed global thresholds, integrated quality control addressing multiple potential error sources within a unified processing chain, and transparent data provenance through clear distinction between original measurements and interpolated values. These contributions address longstanding challenges in operational SAR interferometry.

While validation results are highly encouraging, future work should explore machine learning approaches for automatic threshold optimization, computational efficiency improvements for very large areas or near-real-time applications, integration with advanced PSI variants and automated early warning systems, and extension to other challenging InSAR applications including urban infrastructure, landslide monitoring, volcanic deformation, and subsidence monitoring. The fundamental principles of adaptive thresholding, direct phase integration, and systematic quality control are broadly applicable beyond mining environments.

The B2B approach improves the performance of SAR interferometry over rapidly changing environments by directly resolving persistent phase unwrapping and density limitations. With global mining operations facing intensifying regulatory requirements for comprehensive monitoring of tailings dams, waste facilities, and critical infrastructure, B2B methods that deliver simultaneous improvements in spatial coverage and measurement reliability will become essential for regulatory compliance and effective risk management.

Acknowledgements

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