



Synthetic Aperture Radar Techniques for Assessing Surface Subsidence: A Comparative Analysis of Methodologies

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Abstract

Synthetic Aperture Radar (SAR) has revolutionized the geospatial assessment of surface subsidence, offering precise, temporally dense, and spatially continuous measurements regardless of weather or illumination conditions. This paper presents a comprehensive analysis of SAR-based techniques employed in the detection and quantification of surface subsidence, including Differential Interferometric SAR (D-InSAR), Persistent Scatterer Interferometry (PSI), Small Baseline Subset (SBAS), and Coherent Pixel Technique (CPT). The theoretical frameworks, operational requirements, spatial-temporal resolutions, and inherent limitations of each method are examined. A comparative evaluation is provided to illustrate the strengths and trade-offs of these techniques across varying geological contexts, urban environments, and subsidence-inducing mechanisms such as mining, groundwater extraction, and tectonic activity. The review underscores the growing relevance of SAR interferometry in deformation monitoring and risk mitigation and identifies emerging trends in data fusion, machine learning integration, and satellite mission advancements.

Keywords: Surface Subsidence, Synthetic Aperture Radar, InSAR, Persistent Scatterer Interferometry, Deformation Monitoring

1. Introduction

Surface subsidence refers to the gradual or sudden downward movement of the Earth's surface, typically resulting from the extraction of subsurface resources, groundwater depletion, mining activities, tectonic adjustments, or the natural consolidation of soils. This phenomenon can have severe socio-economic and environmental consequences, including structural damage to infrastructure, increased flood risk, disruption of transportation networks, and reduced agricultural productivity (Galloway & Burbey, 2011; Chaussard *et al.*, 2014) ^[6, 2]. Accurate and continuous monitoring of surface subsidence is therefore critical for geohazard risk assessment, infrastructure resilience planning, and sustainable land-use management.

Traditional ground-based methods for measuring land deformation, such as leveling, extensometers, and GNSS, offer high precision but are spatially limited and logistically demanding. These methods are not scalable for regional or national-level applications and often fail to capture localized deformations in heterogeneous terrains (Tarquini *et al.*, 2014; Liu *et al.*, 2018) ^[12, 9]. In contrast, satellite remote sensing, particularly Synthetic Aperture Radar (SAR) interferometry, has transformed the monitoring of ground subsidence by providing high-resolution, temporally consistent, and spatially extensive deformation measurements.

SAR systems are active remote sensing instruments that emit microwave pulses toward the Earth's surface and record the backscattered signals. Their capability to operate under all weather conditions, during day or night, and across varying terrains makes them uniquely suited for ground deformation monitoring (Massonnet & Feigl, 1998; Zebker & Villasenor, 1992) ^[10, 14]. Interferometric SAR (InSAR) techniques, which analyze the phase difference between two or more SAR acquisitions, enable the detection of ground displacement at centimeter to millimeter levels along the satellite's line-of-sight (LOS) direction (Hanssen, 2001) ^[7]. The most basic form of this technology, Differential InSAR (D-InSAR), involves generating an interferogram between two SAR images acquired at different times to detect surface displacement (Gabriel *et al.*, 1989) ^[5].

However, this technique is sensitive to spatial and temporal decorrelation, atmospheric delays, and orbital inaccuracies. To address these limitations, more advanced multi-temporal techniques have been developed. Persistent Scatterer Interferometry (PSI) identifies stable radar targets, such as buildings and rocks, whose backscatter remains coherent over time, thereby allowing for the estimation of long-term deformation trends with high precision (Ferretti *et al.*, 2001)^[4]. Alternatively, the Small Baseline Subset (SBAS) technique focuses on distributed scatterers and short baseline interferograms to preserve coherence in natural terrains (Berardino *et al.*, 2002)^[1].

In recent years, newer approaches such as the Coherent Pixel Technique (CPT) have emerged, which combine elements of both PSI and SBAS, enabling deformation monitoring across mixed land cover types (Lanari *et al.*, 2004)^[8]. These techniques have been successfully applied in diverse settings, from urban subsidence caused by groundwater withdrawal (Tomás *et al.*, 2012)^[13] to mining-induced ground movement (Ng *et al.*, 2012)^[11], and to fault deformation associated with seismic activity (Crosetto *et al.*, 2005)^[3].

Given the variety of SAR-based interferometric methods and their growing operational relevance, this paper undertakes a detailed review and comparative analysis of four major SAR-based techniques—D-InSAR, PSI, SBAS, and CPT—for assessing surface subsidence. The aim is to evaluate their methodological frameworks, performance characteristics, data requirements, and practical applications to inform their selection and implementation in different subsidence scenarios

applications to inform their selection and implementation in different subsidence scenarios.

2. Theoretical Framework of SAR-Based Subsidence Monitoring

The theoretical foundation of Synthetic Aperture Radar (SAR)-based surface subsidence monitoring lies in the principle of radar interferometry, commonly referred to as Interferometric Synthetic Aperture Radar (InSAR). InSAR exploits the phase difference between two or more SAR images acquired over the same geographic area at different times to detect and measure ground surface displacement. The accuracy and reliability of InSAR-derived deformation depend on a comprehensive understanding of the electromagnetic interaction between radar signals and the Earth's surface, as well as the ability to isolate the deformation component from various phase noise sources.

At the core of SAR interferometry is the concept that any change in the round-trip distance between the satellite sensor and a coherent target on the ground manifests as a phase shift in the returned radar signal. When two complex SAR images—acquired at times t_1 and t_2 are co-registered and processed to form an interferogram, the phase difference $\Delta\phi$ encodes multiple geophysical and environmental components:

$$\Delta\phi = \phi_{\text{defo}} + \phi_{\text{topo}} + \phi_{\text{orb}} + \phi_{\text{atm}} + \phi_{\text{noise}} \quad (1)$$

Where:

ϕ_{defo} is the deformation-induced phase,

ϕ_{topo} is the topographic phase (due to surface elevation differences),

ϕ_{orb} is the phase error arising from satellite orbit

inaccuracies,

ϕ_{atm} represents atmospheric phase delay,

ϕ_{noise} includes thermal noise, temporal and spatial decorrelation.

To isolate ϕ_{defo} , the desired deformation signal, advanced processing techniques are employed to model and eliminate the other components. Topographic contributions can be removed using a high-quality Digital Elevation Model (DEM), such as the SRTM or TanDEM-X DEM. Orbital errors are mitigated through precise orbit determination data and polynomial fitting. Atmospheric effects are typically addressed using spatial and temporal filtering, especially in multi-temporal interferometry (Ferretti *et al.*, 2001; Berardino *et al.*, 2002)^[4, 1].

The geometric relationship between phase change and ground deformation is governed by the radar wavelength λ and the line-of-sight (LOS) vector. The deformation Δd along the LOS direction is expressed as:

$$\Delta d = \frac{\lambda \cdot \Delta\phi}{4\pi} \quad (2)$$

Where:

Δ is the LOS displacement between two acquisitions,

λ is the radar wavelength (e.g., ~5.6 cm for C-band Sentinel-1, ~3.1 cm for X-band TerraSAR-X),

$\Delta\phi$ is the measured phase difference.

This formulation implies that a full 2π phase cycle corresponds to a half-wavelength change in distance. Consequently, even a slight displacement (on the order of millimeters) can be detected with high precision, provided that phase coherence between acquisitions is maintained.

However, phase measurements are inherently ambiguous because they are modulo 2π , and multiple integer cycles (fringes) can represent the same apparent displacement. This leads to the necessity of phase unwrapping, a computational step that reconstructs the absolute phase change across the scene. Accurate phase unwrapping is critical in InSAR processing and often determines the fidelity of the derived deformation maps (Hanssen, 2001)^[7].

A crucial aspect of SAR-based subsidence monitoring is coherence, a measure of the similarity between SAR image pairs. High coherence implies minimal changes in surface conditions (e.g., land cover, moisture content) and yields reliable phase measurements. Coherence is typically quantified as:

$$\gamma = \frac{|\langle s_1 s_2^* \rangle|}{\sqrt{(|s_1|^2)(|s_2|^2)}} \quad (3)$$

Where:

s_1 and s_2 are the complex radar signals at times t_1 and t_2 ,

$\langle \cdot \rangle$ denotes spatial averaging,

$\gamma \in [0, 1]$ with values near 1 indicating high coherence.

The coherence threshold determines the reliability of phase measurements; hence, many SAR-based techniques selectively analyze only those pixels that maintain coherence over time. This principle is foundational in techniques such as Persistent Scatterer Interferometry (PSI) and the Coherent Pixel Technique (CPT), which leverage high-coherence pixels to derive precise deformation time series.

Multi-temporal InSAR (MT-InSAR) approaches enhance traditional two-pass InSAR by incorporating a large stack of SAR images over time. This enables temporal filtering,

atmospheric phase screening, and cumulative deformation estimation. Two dominant MT-InSAR methodologies include:

1. Persistent Scatterer Interferometry (PSI) – which focuses on point targets with high temporal coherence, such as man-made structures.
2. Small Baseline Subset (SBAS) – which emphasizes phase consistency over distributed targets using interferogram pairs with small temporal and spatial baselines to mitigate decorrelation.

The conceptual advancement from single-pair D-InSAR to time-series MT-InSAR represents a major theoretical and operational leap. These techniques permit deformation velocity mapping, acceleration trend detection, and anomaly prediction in geologically active or anthropogenically influenced areas (Hooper *et al.*, 2004; Lanari *et al.*, 2004)^[8]. Finally, Line-of-Sight Deformation to Vertical/Uplift Conversion is often required when interpreting subsidence phenomena. Since SAR sensors measure displacement in the LOS direction, true vertical or horizontal components must be inferred using geometric modeling, sometimes incorporating ascending and descending orbit data:

$$dd_v = \frac{d_{asc} \sin(\theta_{desc}) - d_{desc} \sin(\theta_{asc})}{\sin(\theta_{asc} + \theta_{desc})} \quad (4)$$

Where:

D_v is the vertical displacement,
 d_{asc} and d_{desc} are LOS displacements from ascending and descending passes,
 θ is the incidence angle.

In summary, SAR-based subsidence monitoring rests on well-established electromagnetic, geometric, and statistical principles that enable sub-centimeter displacement measurements across large spatial extents. The development of multi-temporal processing algorithms and high-resolution satellite missions continues to enhance the theoretical robustness and application versatility of these techniques.

3. SAR Techniques for Surface Subsidence Monitoring

The application of Synthetic Aperture Radar (SAR) interferometry in monitoring surface subsidence has evolved through several methodological innovations designed to improve measurement precision, spatial coverage, temporal resolution, and reliability across different surface conditions. This section presents an expanded exposition of the four primary SAR-based techniques used in subsidence monitoring: Differential InSAR (D-InSAR), Persistent Scatterer Interferometry (PSI), Small Baseline Subset (SBAS), and the Coherent Pixel Technique (CPT). Each method builds upon the foundational principles of radar interferometry but is optimized for specific environmental settings, data conditions, and deformation scenarios.

3.1. Differential InSAR (D-InSAR)

Differential Interferometric SAR (D-InSAR) is the most fundamental approach to deformation monitoring. It uses two single-look complex (SLC) SAR images acquired at different times over the same geographic area. By computing the phase difference between these two acquisitions, an interferogram is generated that reflects the total deformation that has occurred during the acquisition interval..

The process includes co-registration of the image pair, removal of topographic phase using a reference Digital Elevation Model (DEM), and phase filtering and unwrapping to retrieve the deformation signal. The interferometric phase, after removing orbital and topographic effects, predominantly reflects line-of-sight (LOS) surface displacement.

While D-InSAR offers a relatively simple and computationally light approach, it is prone to several limitations:

- Temporal decorrelation occurs when surface characteristics change between acquisitions, reducing coherence.
- Atmospheric artifacts, such as tropospheric delays, can introduce phase noise.
- Orbital inaccuracies may cause residual geometric phase errors.

Because of these limitations, D-InSAR is most effective in arid or urban regions with stable surface properties and short revisit intervals. It is particularly suited for capturing abrupt or episodic deformation events, such as co-seismic ground movements or sudden mining collapses (Massonnet & Feigl, 1998; Gabriel *et al.*, 1989)^[10, 5].

3.2. Persistent Scatterer Interferometry (PSI)

Persistent Scatterer Interferometry (PSI) is a multi-temporal technique developed to overcome the decorrelation and atmospheric challenges of conventional D-InSAR. Instead of relying on single image pairs, PSI utilizes long time series of SAR acquisitions to identify persistent scatterers (PS)—pixels that exhibit high phase stability over time due to strong and consistent radar reflections.

These persistent scatterers are typically associated with man-made structures, such as buildings, bridges, and road surfaces, or with natural features like exposed rock. The deformation signal is extracted by analyzing the temporal evolution of the interferometric phase at each PS location, while simultaneously modeling and removing atmospheric artifacts and orbital errors using statistical filtering.

The main advantages of PSI include:

- Millimeter-level accuracy in deformation measurement.
- Long-term temporal coherence, enabling trend analysis and early warning systems.
- Atmospheric phase correction using spatial-temporal filtering algorithms.

However, PSI is limited by:

- Sparse spatial coverage in vegetated or rural areas due to a lack of suitable reflectors.
- High computational cost associated with time-series analysis and point-target selection.

PSI has been widely used in urban subsidence studies, especially for monitoring infrastructure settlement, tunnel-induced ground deformation, and aquifer depletion in megacities (Ferretti *et al.*, 2001; Crosetto *et al.*, 2005)^[4, 3].

3.3. Small Baseline Subset (SBAS)

The Small Baseline Subset (SBAS) technique addresses the spatial limitations of PSI by focusing on distributed scatterers (DS)—areas where coherence is not associated with a single strong reflector, but rather with a spatially homogeneous

region exhibiting moderate radar backscatter.

SBAS decomposes a large stack of SAR images into multiple interferogram pairs with short temporal and spatial baselines. This selection minimizes decorrelation and increases the likelihood of coherent phase retrieval even in natural and vegetated terrains. A time-series analysis is then performed to estimate deformation trends, similar to PSI.

Key features of SBAS include:

- Improved spatial coverage, especially in non-urban, agricultural, or forested areas.
- Capability to detect slow, long-term deformation processes, such as land subsidence from groundwater extraction or tectonic creep.
- Reduced sensitivity to decorrelation through optimal interferogram network design.

Limitations of SBAS:

- Moderate spatial resolution compared to PSI, as it operates on pixel groups rather than individual targets.
- High data volume and processing time, especially when analyzing hundreds of interferograms.
- Limited effectiveness in detecting rapid or non-linear displacements due to its reliance on smooth temporal modeling.

SBAS has been successfully employed in monitoring subsidence in deltaic regions, agricultural plains, and landslide-prone slopes (Berardino *et al.*, 2002; Lanari *et al.*, 2004)^[1, 8].

3.4 Coherent Pixel Technique (CPT)

The Coherent Pixel Technique (CPT) is a hybrid method

designed to integrate the strengths of PSI and SBAS. CPT identifies groups of pixels—rather than isolated scatterers or distributed targets—that maintain high coherence both spatially and temporally across a SAR time series. By aggregating phase measurements from coherent pixel clusters, CPT enhances both spatial continuity and phase stability.

CPT utilizes a coherence-based thresholding mechanism and statistical correlation tests to detect reliable pixels. These are then subjected to interferogram stacking, atmospheric filtering, and deformation modeling similar to PSI and SBAS frameworks.

CPT offers:

- Higher spatial density of measurements than PSI in partially vegetated or peri-urban areas.
- Adaptability to diverse land cover types, including mixed urban–rural landscapes.
- Capability to monitor non-linear deformation patterns, depending on the temporal sampling frequency.

Nevertheless, CPT still depends on:

- Sufficient SAR acquisitions to form stable pixel networks.
- Moderate coherence across the SAR stack, which may degrade in regions with dynamic vegetation or surface moisture fluctuations.

Applications of CPT include monitoring subsidence in transitional zones where PSI is limited and SBAS is imprecise, such as expanding urban fringes or mining-affected rural communities (Manunta *et al.*, 2019).

Table 1: Summary of Key Methodological Distinctions

| Technique | Target Type | Land Cover Suitability | Spatial Resolution | Temporal Accuracy | Best Use Cases |
|-----------|-------------------------|--------------------------|--------------------|-------------------|---------------------------------------|
| D-InSAR | Any coherent pixel pair | Arid, urban, bare ground | Variable, limited | Low | Rapid deformation, short-term studies |
| PSI | Point scatterers | Urban, infrastructure | High (point-level) | High | Long-term monitoring in cities |
| SBAS | Distributed scatterers | Rural, agricultural | Moderate | High | Subsidence in natural terrains |
| CPT | Coherent pixel groups | Transitional or mixed | Moderate to high | High | Complex or heterogeneous surfaces |

Each technique thus represents a complementary toolset within the broader SAR interferometry framework. The selection of an appropriate method should be based on the study area's land cover, available SAR data volume and frequency, expected deformation rate, and the required spatial and temporal precision.

4. Challenges, Limitations, and Opportunities

Despite the remarkable advancements in SAR-based techniques for surface subsidence monitoring, several persistent challenges and limitations continue to constrain their effectiveness across diverse landscapes, sensor systems, and application domains. These challenges span technical, environmental, data-centric, and operational dimensions. At the same time, ongoing research and technological innovation are presenting new opportunities to overcome these barriers and expand the practical utility of SAR interferometry for geohazard monitoring and land deformation analysis.

4.1. Technical and Environmental Challenges

One of the primary challenges in SAR interferometry is temporal and spatial decorrelation, which arises when the

radar signal experiences significant variations between acquisitions due to changes in land surface properties. Temporal decorrelation is particularly severe in vegetated, agricultural, or snow-covered areas, where surface moisture, biomass, or land use activities fluctuate rapidly. Spatial decorrelation occurs when the perpendicular baseline between SAR acquisitions is too large, exceeding the critical baseline limit for a given sensor's wavelength and acquisition geometry (Zebker & Villasenor, 1992)^[14].

Another significant issue is the atmospheric phase delay, especially in low-lying or humid regions. Atmospheric heterogeneity—caused by variations in temperature, humidity, and pressure—induces differential delays in the radar signal that may mimic or obscure true ground deformation. Although time-series techniques such as PSI and SBAS incorporate spatial and temporal filtering strategies to suppress these artifacts, residual atmospheric errors may persist, particularly in regions with strong tropospheric gradients (Hanssen, 2001; Li *et al.*, 2006)^[7].

Topographic errors present additional limitations. Residual DEM inaccuracies used for removing the topographic phase component in D-InSAR can introduce significant errors in the final deformation maps. This is especially true in

mountainous terrain or rapidly urbanizing areas where DEMs may not represent the current surface accurately. Furthermore, high-relief regions introduce layover and shadow effects, which distort the radar return signal and limit the visibility of certain terrain facets (Massonnet & Feigl, 1998)^[10].

Geometric limitations associated with line-of-sight (LOS) measurements are inherent in SAR systems. SAR sensors detect deformation only in the satellite's LOS direction, which is an oblique view combining vertical and horizontal components. As a result, horizontal (e.g., lateral fault motion) or vertical uplift/subsidence occurring perpendicular to the LOS may be partially or entirely undetected unless multiple look angles (ascending and descending passes) are used (Samsonov & d'Oreye, 2012).

4.2. Data Availability and Processing Constraints

Many SAR-based methods depend on dense, high-quality, and long-duration SAR image archives to construct reliable interferograms and generate accurate deformation time series. In some parts of the world, especially in developing regions, historical SAR data coverage may be sparse or non-existent. Commercial high-resolution SAR missions such as TerraSAR-X, COSMO-SkyMed, or ICEYE offer improved spatial resolution but at significant cost, limiting accessibility for researchers and institutions with limited funding.

Moreover, SAR data processing is computationally intensive and algorithmically complex, especially when working with large-scale, multi-temporal datasets. Time-series techniques like PSI and SBAS require the generation and filtering of hundreds to thousands of interferograms, phase unwrapping, atmospheric correction, and velocity estimation. These tasks necessitate high-performance computing infrastructure and specialized technical expertise, which are not always available in government agencies or non-specialist research groups (Bamler & Hartl, 1998).

Phase unwrapping remains a bottleneck in many applications. Errors in this step, especially in low-coherence areas or steep terrain, can propagate through the deformation modeling process and compromise the reliability of displacement maps.

4.3. Opportunities and Emerging Solutions

Despite these limitations, significant opportunities exist to overcome current obstacles and enhance the accuracy, accessibility, and operational value of SAR-based subsidence monitoring.

1. Dense Revisit Satellite Constellations

The deployment of SAR satellites with **short revisit times**—such as ESA's Sentinel-1A/B (6–12 days), ICEYE (~3 days), and Capella Space (~6 hours)—is dramatically improving temporal resolution. These systems allow for better detection of rapidly evolving deformation processes and more robust atmospheric phase filtering, reducing the impact of temporal decorrelation. Moreover, the upcoming NASA-ISRO SAR (NISAR) mission and RADARSAT Constellation Mission (RCM) promise to expand global SAR coverage with open-access policies.

2. Multi-sensor and Multi-platform Data Fusion

Fusing data from multiple SAR platforms (e.g., combining C-band Sentinel-1 with X-band TerraSAR-X or L-band ALOS-2) can leverage the strengths of each system in terms of wavelength sensitivity, penetration depth, and spatial

resolution. Integration with optical remote sensing, GNSS, airborne LiDAR, and UAV photogrammetry offers a more comprehensive deformation monitoring framework. Such synergistic approaches enhance the detection and interpretation of both vertical and horizontal displacements.

3. Advances in Cloud-based and Open-source Processing Tools

Platforms like Google Earth Engine, ESA's SNAP, and open-source toolboxes like StaMPS, MintPy, and PyRate are democratizing access to SAR processing tools. These platforms offer semi-automated workflows, reducing the need for extensive coding expertise. Cloud computing and distributed processing pipelines also enable scalable analysis of large SAR archives without the need for expensive local computing infrastructure.

4. Artificial Intelligence and Machine Learning

Emerging applications of machine learning in SAR interferometry include automated phase unwrapping, coherence classification, noise reduction, and deformation pattern recognition. Deep learning architectures such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs) are being used to enhance the interpretation of complex or noisy interferograms and to predict subsidence trends (Kanjir *et al.*, 2020).

5. Standardization and Interoperability

International initiatives such as GEO-GRAMED, UN GGIM, and CEOS are promoting standardization of InSAR data products and formats. This will enhance interoperability among platforms and facilitate integration into spatial planning, disaster response, and infrastructure asset management systems.

4.4. Policy and Application Opportunities

The increased maturity of SAR-based subsidence monitoring presents unique opportunities for evidence-based policymaking, especially in contexts of urban planning, critical infrastructure monitoring, climate adaptation, and land-use governance. For instance, SAR-derived subsidence maps can inform zoning regulations in cities affected by groundwater-induced subsidence, such as Jakarta, Mexico City, and Lagos. Similarly, mining regulators can use interferometric data to enforce environmental standards and evaluate compliance in resource-extraction zones.

Integration of InSAR outputs into early warning systems for landslides, sinkholes, or tectonic fault zones also offers life-saving potential in hazard-prone areas.

5. Conclusion

The use of Synthetic Aperture Radar (SAR)-based techniques for assessing surface subsidence has become an indispensable component of modern geospatial analysis and deformation monitoring. SAR interferometry enables detailed, temporally consistent, and spatially extensive observations of land deformation phenomena with millimetric accuracy, offering a cost-effective and scalable alternative to traditional geodetic techniques such as leveling and GNSS. As urbanization, groundwater exploitation, and resource extraction activities continue to intensify globally, the need for robust, reliable, and real-time subsidence monitoring systems is more urgent than ever.

The evolution of SAR methodologies—from the

foundational Differential InSAR (D-InSAR) to more sophisticated multi-temporal techniques such as Persistent Scatterer Interferometry (PSI), Small Baseline Subset (SBAS), and Coherent Pixel Technique (CPT)—demonstrates the growing capacity of SAR interferometry to address complex deformation scenarios. D-InSAR remains useful for detecting sudden or short-term displacements, especially in stable and coherent terrains. PSI, with its ability to extract long-term deformation trends from temporally stable scatterers, is best suited for urban and infrastructure-rich areas. SBAS extends monitoring capability to rural and vegetated regions by utilizing distributed scatterers and small-baseline image pairs, while CPT serves as a hybrid strategy for capturing deformation in heterogeneous landscapes. Each technique exhibits unique advantages and trade-offs related to land cover adaptability, data requirements, computational intensity, and measurement accuracy.

Despite these capabilities, SAR-based subsidence monitoring is not without its limitations. Issues such as temporal decorrelation, atmospheric phase delay, geometric constraints, and computational complexity can affect the reliability and precision of derived deformation estimates. These limitations are particularly challenging in rapidly changing or environmentally dynamic regions, such as deltaic floodplains, densely vegetated terrains, and mountainous areas where coherence may be low and atmospheric effects severe.

However, recent technological advancements have begun to address many of these challenges. The increasing temporal resolution and spatial coverage offered by new-generation SAR constellations—such as Sentinel-1, ICEYE, Capella, and the upcoming NASA-ISRO SAR (NISAR) mission—allow for more frequent observations and better characterization of subsidence dynamics. Concurrently, the integration of multi-sensor datasets, including optical imagery, GNSS, airborne LiDAR, and drone-based photogrammetry, has expanded the analytical depth and contextual understanding of SAR-derived deformation products.

Furthermore, the proliferation of open-source software tools (e.g., SNAP, StaMPS, PyRate, MintPy) and cloud-based platforms (e.g., Google Earth Engine, AWS) has democratized access to SAR processing workflows, reducing barriers for researchers and practitioners in resource-constrained settings. The application of artificial intelligence (AI) and machine learning (ML) models to automate phase processing, coherence estimation, and deformation pattern classification further enhances the utility of SAR data for operational use. These developments collectively mark a shift toward more accessible, interpretable, and actionable geospatial intelligence systems.

The operational applications of SAR-based subsidence monitoring span a wide spectrum. They include the assessment of groundwater depletion in urban centers, monitoring of infrastructure stability, hazard mitigation in mining zones, tectonic and volcanic deformation analysis, and early warning for landslides and sinkholes. The integration of SAR-derived deformation products into urban planning, disaster risk reduction frameworks, and environmental regulation systems has the potential to improve resilience, ensure safety, and optimize resource allocation in vulnerable areas.

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