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ANALYSIS OF SPATIAL GEODETIC METHODS FOR MONITORING MINING GEOSYSTEMS

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Abstract

The increasing availability of satellite and airborne technologies has changed the way mining-affected areas are monitored and analyzed. Spatial geodetic methods such as GNSS, satellite radar interferometry (InSAR), multispectral remote sensing, and UAV-based photogrammetry and LiDAR now allow continuous and accurate observation of ground behavior over large areas. This paper presents an overview of the main spatial geodetic techniques used for monitoring mining geosystems, focusing on their practical application in detecting ground subsidence, slow surface deformations, structural instabilities, and volumetric changes of waste dumps and tailings dams. The strengths and limitations of each method are discussed from a practical perspective, taking into account accuracy, spatial coverage, operational constraints, and cost efficiency. Examples from Romania and other European mining regions highlight the benefits of combining GNSS, InSAR, UAV data, and GIS platforms into integrated monitoring systems. Such approaches support early detection of hazardous processes and contribute to safer and more sustainable management of mining and post-mining environments.

Key words: *geotechnical monitoring, GIS, GNSS, InSAR, LiDAR, mining waste dumps, remote sensing, spatial geodesy, tailings dams, UAV.*

INTRODUCTION

Mining geosystems (open pits, underground operations, waste rock dumps, ash deposits, and tailings storage facilities) are dynamic engineered–natural systems that can evolve rapidly under changes in loading, groundwater, drainage, and material properties. Their deformation may remain subtle for long periods, then accelerate into hazardous states such as progressive slope failure, dam crest settlement, or wide-area subsidence. Internationally, the consequences of tailings failures have strengthened the demand for demonstrable monitoring capacity and transparent risk governance, including the Global Industry Standard on Tailings Management (UNEP, 2020). In the European Union, the management of waste from extractive industries is framed by Directive 2006/21/EC, which requires appropriate control and risk prevention measures throughout the lifecycle of tailings facilities and waste dumps (European Parliament & Council, 2006). These drivers, together with the availability of Copernicus Sentinel missions, have accelerated the uptake of spatial geodetic and Earth observation techniques for operational monitoring.

Spatial geodetic methods complement classical geotechnical instrumentation by providing geometrically consistent, often remotely acquired observations that link local deformation at critical structures to regional patterns. GNSS networks offer absolute 3D positioning with high temporal sampling, supporting early detection of deviations from expected behavior and serving as validation for remote sensing products (Scaioni et al., 2018). Multi-temporal InSAR provides dense, wide-area displacement measurements along the radar line of sight (LOS) and can reveal slow subsidence or creep processes that are difficult to capture with sparse ground points (Ferretti et al., 2001; Berardino et al., 2002; Crosetto et al., 2016; Aswathi et al., 2022). UAV-based photogrammetry (Structure-from-Motion, SfM) and UAV LiDAR deliver centimeter- to decimeter-scale 3D surface models and enable volumetric change analysis over waste dumps, tailings beaches, and open-pit benches (Westoby et al., 2012; Nex et al., 2022; Liu et al., 2023). Multispectral and hyperspectral

remote sensing add information on surface cover and mineralogical indicators that relate to erosion, dust emission, or acid mine drainage (Seifi et al., 2019; Dkhala et al., 2020).

The aim of this paper is to synthesize, from a practical perspective, the main spatial geodetic techniques used for monitoring mining-affected areas and to compare their accuracy, spatial and temporal coverage, operational constraints, and cost efficiency. We also emphasize integrated monitoring architectures that combine GNSS, InSAR, UAV-derived 3D products and GIS-based decision layers to support early warning and sustainable mine closure and post-mining management (Del Soldato et al., 2019; Poncoș et al., 2022).

MATERIALS AND METHODS

This study is a structured review and comparative analysis of spatial geodetic approaches for deformation and change monitoring in mining geosystems. The comparison follows four practical criteria: (i) geometric performance (precision, accuracy, and sensitivity to deformation components), (ii) scale (point, object, and regional coverage), (iii) temporal sampling and operational availability, and (iv) implementation effort and costs (hardware, field time, data processing, and expertise). As the literature spans multiple domains (geodesy, remote sensing, mining engineering and risk management), we focus on methods with established workflows and demonstrated applications to subsidence, slope instability, and volumetric change.

For satellite radar interferometry, we adopt the standard distinction between single-pair DInSAR and multi-temporal techniques. PSI relies on stable radar targets to estimate long time-series displacement with reduced atmospheric noise (Ferretti et al., 2001; Hanssen, 2001). SBAS and related small-baseline methods exploit short temporal and spatial baselines to increase coherence over distributed targets (Berardino et al., 2002). In operational contexts, Sentinel-1 provides systematic C-band acquisitions with a 12-day repeat cycle for a single satellite and 6 days for a two-satellite constellation, with robust day-and-night and all-weather capability (Copernicus Data Space, 2025; SentiWiki, 2025). For optical remote sensing, Sentinel-2 MSI provides 13 spectral bands supporting land cover, moisture and mineral mapping at 10-60 m resolution (Copernicus Data Space, 2025; ESA, 2025).

For UAV surveys, we consider two principal data products: (a) dense point clouds and digital surface models (DSMs) from SfM photogrammetry, and (b) LiDAR point clouds acquired from airborne laser scanners mounted on UAVs. Change detection between epochs can be performed using DEM-of-difference or point-cloud-to-point-cloud approaches such as M3C2, which is well suited to rough, three-dimensional surfaces common in dumps and benches (Williams et al., 2021; Liu et al., 2023).

For GNSS monitoring, we consider both permanent stations (continuous) and campaign networks, with processing options ranging from relative positioning to PPP solutions depending on infrastructure and required accuracy (Scaioni et al., 2018).

The integrated monitoring concept is represented as a data pipeline where each observation type is quality controlled and co-registered into a consistent reference frame, then fused within a GIS platform for interpretation, thresholding, and alerting. This aligns with modern risk-based monitoring guidance for tailings facilities emphasizing defensible data, traceability, and timely escalation (UNEP, 2020).

An integrated workflow for multi-sensor spatial monitoring is summarized in Figure 1.

An effective monitoring system for mining geosystems requires the integration of several complementary data sources, because each observation technique provides different information about surface deformation and environmental change. Satellite SAR data processed through PSI/SBAS techniques allow regional detection of slow ground movements, while GNSS networks provide precise reference measurements and local validation of displacement trends. UAV photogrammetry and UAV LiDAR add high-resolution three-dimensional information, useful for analysing local changes in waste dumps, tailings dams, open-pit slopes and other unstable mining structures. The combined interpretation of these datasets within a GIS/database environment makes it possible to perform quality control, compare independent measurements, detect

abnormal deformation patterns and transform geodetic observations into practical risk indicators. Figure 1 presents the proposed integrated workflow, from data acquisition and processing to GIS-based quality assessment and early warning support.

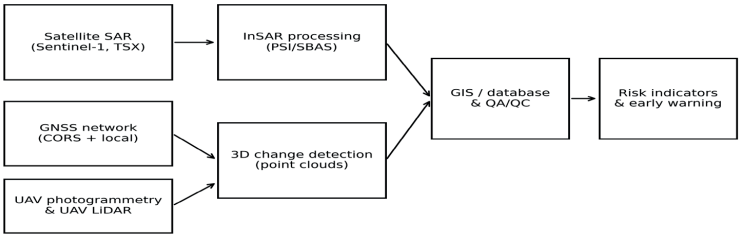


Figure 1. Integrated workflow combining satellite SAR, GNSS, UAV products and GIS decision layers

RESULTS AND DISCUSSIONS

Table 1 highlights that no single method optimally satisfies precision, coverage and update frequency simultaneously. For operational risk management, method selection should be hazard-driven and multi-scale. Regional screening (e.g., subsidence bowls and creep zones) is effectively addressed by multi-temporal InSAR (Ferretti et al., 2001; Berardino et al., 2002; Crosetto et al., 2016), while structural performance at crest monuments or critical facilities requires high-fidelity ground measurements such as GNSS or classical geodetic control (Scaioni et al., 2018). For rapidly evolving geometry (bench retreat, dump reshaping, tailings beach migration), UAV point clouds enable frequent volumetric updates and local instability mapping (Westoby et al., 2012; Liu et al., 2023).

Table 1. Comparative overview of spatial geodetic methods for mining geosystem monitoring

Method	**Main outputs**	**Typical deformation sensitivity**	**Spatial/temporal coverage**	**Strengths**	**Key limitations**
GNSS (campaign/continuous)	3D point displacement; velocity; reference frame control	mm–cm at monitored points (daily–subdaily for permanent stations)	Points to networks; high rate possible	Absolute 3D; real-time options; strong for validation and critical structures	Sparse spatial sampling; requires installation and maintenance
InSAR (PSI/SBAS, Sentinel-1 or high-res SAR)	LOS displacement maps and time series; regional deformation patterns	mm–cm along LOS for coherent targets	10^2-10^5 km²; revisit 6-12 days (Sentinel-1)	Wide-area, dense measurements; retrospective analysis; cost-efficient at scale	LOS-only; decorrelation on vegetation/water; atmospheric artefacts; phase unwrapping issues
UAV photogrammetry (SfM)	Dense point clouds, orthomosaics, DSM/DTM; volumetric change	cm-dm (site dependent)	0.1-10 km² per flight; on-demand	Very high spatial resolution; flexible survey geometry; low equipment cost	Requires safe access/flight permissions; lighting/wind constraints; GCP/direct georeferencing needed
UAV LiDAR	LiDAR point clouds; vegetation-penetrating surface; change vectors	dm to few cm (platform dependent)	0.1-10 km²; on-demand (lower speed than photogrammetry)	Performs in low texture; less sensitive to illumination; better in vegetation	Higher sensor cost; calibration/boresight; point density depends on flight plan
Multispectral / hyperspectral EO (Sentinel-2, airborne)	Land cover, moisture proxies, mineral/contamination indicators	Indirect (not deformation); complements geometric monitoring	10-60 m (Sentinel-2); revisit days	Supports environmental context: erosion, seepage, AMD indicators	Cloud sensitivity; mixed pixels; requires field validation for mineralogical interpretation

The relationship between spatial coverage and vertical precision is an important criterion when selecting monitoring techniques for mining geosystems. Methods such as levelling, GNSS and terrestrial laser scanning provide high vertical accuracy, but their spatial coverage is

usually limited to points, profiles or local areas (Calina et al., 2021). In contrast, satellite-based InSAR offers regional coverage over very large surfaces, although the vertical precision is influenced by radar geometry, coherence, atmospheric effects and the need to convert line-of-sight displacement into vertical deformation. UAV photogrammetry and UAV LiDAR occupy an intermediate position, providing high-resolution spatial products over site-scale areas, which makes them particularly useful for monitoring waste dumps, tailings dams and open-pit slopes. Therefore, the choice of method should not be based only on precision, but also on the required monitoring scale, update frequency, accessibility of the site and the type of deformation process being investigated. Figure 2 illustrates this practical trade-off between typical spatial coverage and vertical precision for the main geodetic and remote-sensing techniques used in mining-area monitoring.

The practical value of spatial methods depends on uncertainty communication. InSAR products, for instance, are susceptible to atmospheric artefacts and may exhibit spatially correlated errors (Table 2); multi-temporal processing and the use of stable reference areas are therefore essential (Hanssen, 2001; Crosetto et al., 2016).

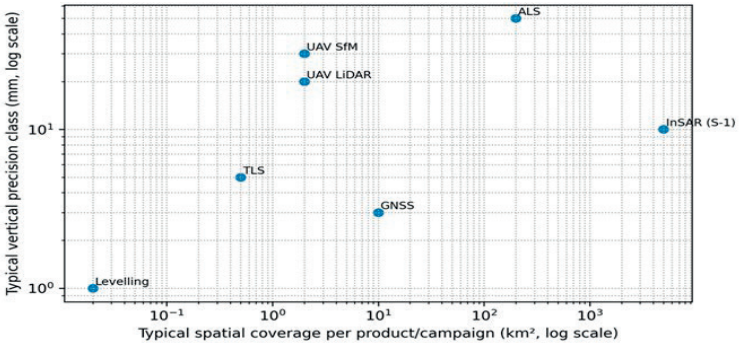


Figure 2. Trade-off between typical spatial coverage and precision class for common monitoring approaches (illustrative)

Table 2. Major error sources and mitigation strategies for spatial geodetic monitoring in mining areas

Technique	Dominant error sources	Mitigation / QA-QC	Practical notes
InSAR (PSI/SBAS)	Atmospheric delay; temporal/spatial decorrelation; unwrapping errors; geometry (LOS)	Use multi-temporal methods; atmospheric filtering; ascending/descending decomposition; GNSS tie points	Best for slow deformation; interpret LOS; validate locally where possible
GNSS	Multipath; antenna stability; reference frame drift; troposphere modelling	Stable monuments; choke-ring antennas; network adjustment; PPP/relative processing; redundancy	High temporal sampling; critical points on crests and abutments
UAV SfM	Camera calibration; GCP quality; poor texture; wind; rolling shutter; time-varying shadows	Robust GCP network or RTK/PPK; calibration checks; overlap planning; independent checkpoints	Excellent for geometry and volumes; repeatable flight plans improve consistency
UAV LiDAR	Boresight misalignment; IMU drift; scan geometry; strip adjustment	Calibration flights; strip adjustment; ground truth targets; stable control points	Better than SfM on low-texture surfaces and in vegetation; higher sensor cost.

Where deformation vectors are needed, combining ascending and descending tracks allows decomposition into vertical and east–west components, although the north–south component typically remains weakly observed (Crosetto et al., 2016). For UAV change detection, point-cloud-to-point-cloud techniques (e.g., M3C2) reduce bias introduced by gridding and are well suited for rough quarry and dump surfaces (Williams et al., 2021; Liu et al., 2023).

A typical integration pattern is to use GNSS time series to validate InSAR trends and to strengthen interpretation of low-rate deformation (Figure 3).

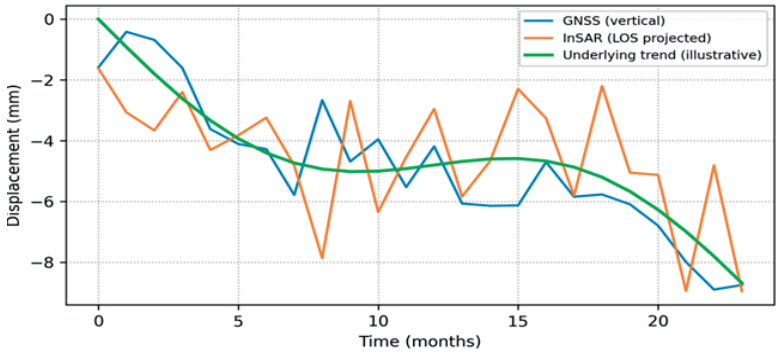


Figure 3. Example of GNSS-InSAR time series consistency for slow deformation

Integration is most effective when each method is assigned a clear role. In mining subsidence, for example, InSAR can provide long-term regional context and reveal residual subsidence beyond the footprint of active panels, while GNSS and classical control networks constrain absolute displacement at infrastructure points. This complementarity has been demonstrated in multiple European mining regions. In Poland's Upper Silesian Coal Basin, multi-decadal InSAR analysis revealed both active subsidence troughs and residual deformation zones over thousands of square kilometers (Przyłucka et al., 2022). In southeast Spain (La Unión), advanced DInSAR was used to map small-scale subsidence affecting built-up areas within historic mining districts (Herrera et al., 2007).

Romania provides diverse mining settings where integrated approaches are increasingly relevant (Stefan et al., 2009). A Sentinel-1 based study in the Călimani area demonstrated the use of interferometric processing for terrain reconstruction and monitoring in a former sulphur quarry, motivated by high costs and accessibility constraints of terrestrial surveys (Gheorghe & Vodă Marc, 2020). National-scale services have also been developed: a ground motion monitoring product for Romania highlighted the potential of InSAR to detect subtle deformation patterns and to support infrastructure and environmental assessment (Terrasigna, 2020). More recently, integrated EO monitoring of the Roșia Poieni copper mine has been discussed as a pathway to link geomorphic evolution and environmental indicators to operational decision-making (Herban et al., 2024; Kirsch et al., 2025).

From an operational point of view, decision makers often need a simplified comparison of method attributes; a qualitative scoring example is shown in Figure 4.

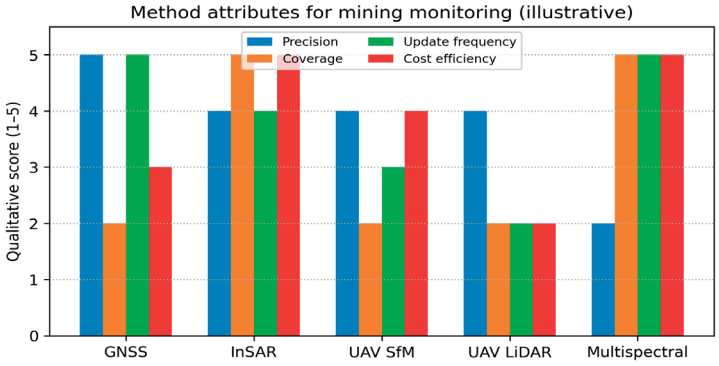


Figure 4. Qualitative comparison of method attributes relevant for mining monitoring

Table 3 summarizes practical configurations that align method capability with hazards. For tailings facilities, integrated schemes are increasingly coupled with numerical modelling and risk assessment. For instance, combining InSAR with modelling has been shown to improve interpretation and to support early detection of slope instability patterns in tailings ponds (Lu et al., 2025). InSAR-based ground motion services can also support prioritization, directing limited field resources to zones showing acceleration or anomalous trends (Del Soldato et al., 2019; Poncoș et al., 2022).

Table 3. Recommended integrated monitoring configurations by mining object and dominant hazard

Object / hazard	Regional screening	Local high-resolution monitoring	Decision layer
Tailings dam: crest settlement, slope instability	InSAR (PSI/SBAS) + optical change detection for seepage indicators	GNSS on crest/abutments + UAV LiDAR/SfM for beach and slope geometry	Thresholds on velocities/accelerations; integration with geotechnical readings and GISTM controls
Waste rock dump: creep, erosion, runout susceptibility	InSAR + multispectral (moisture/vegetation) for surface condition	UAV SfM for frequent 3D updates; TLS for critical scarps; GNSS targets where needed	Change maps and volume budgets; trigger surveys after intense rainfall or operational regrading
Open pit slopes: bench instability, rockfall precursors	InSAR where coherent; regional context for surrounding infrastructure	UAV SfM/LiDAR + TLS for detailed discontinuity mapping and change detection	Spatial zoning of deformation; hazard maps; coupling with operational plans
Underground mining: subsidence bowls and infrastructure impact	InSAR time series (long-term)	GNSS/levelling lines along critical assets; UAV mapping for local cracks	Subsidence prediction vs observations; maintenance prioritization; public safety communication

Beyond deformation, multispectral and hyperspectral remote sensing provides environmental context relevant for post-mining management, such as the spatial pattern of mineralogical anomalies in tailings and surrounding soils (Dkhala et al., 2020; Milut et al., 2020), or the mapping of acid mine drainage potential using spectral information (Seifi et al., 2019). Early Romanian work using Landsat data demonstrated the feasibility of mapping mining waste deposits across large areas in Romania and Slovakia (Vîjdea et al., 2004), while more recent local studies have applied Landsat and Sentinel imagery to monitor land-cover change around Roșia Poieni (Herban et al., 2024).

The main limitation of integrated monitoring is not data availability but operationalization: stable reference frames, repeatable acquisition plans, and transparent uncertainty reporting are required to avoid false alarms or missed detections. The monitoring chain should therefore include (i) a well-defined geodetic reference network anchored in stable ground, (ii) standardized processing and metadata, (iii) cross-validation between independent methods, and (iv) governance rules for escalation and documentation consistent with risk-based standards (Scaioni et al., 2018; UNEP, 2020).

CONCLUSIONS

Spatial geodetic monitoring has become central to mining geosystem risk management because it links point-scale structural observations to regional deformation patterns.

Multi-temporal InSAR is the most cost-efficient option for wide-area screening of slow deformation, but it requires careful treatment of LOS geometry, coherence and atmospheric artefacts, and benefits from local GNSS validation.

GNSS remains indispensable for absolute 3D control at critical structures (e.g., dam crests) and for near-real-time trend detection at selected points.

UAV SfM photogrammetry and UAV LiDAR provide high-resolution 3D geometry and volumetric change estimates, enabling detailed assessment of dumps, benches and tailings beaches when flights can be conducted safely and repeatably.

Integrated monitoring architectures combining InSAR, GNSS, UAV products and GIS decision layers support early warning, efficient field prioritization and defensible reporting aligned with modern tailings governance standards.

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