Usage of InSAR Technology in Surface Deformations Caused by Deep Mining

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Abstract: This study investigates surface deformations at the Márkushegy Mining Facility in Pusztavám, Hungary, within the Oroszlány coal basin, from 2014 to 2019 using Interferometric Synthetic Aperture Radar (InSAR) technology. The facility, which extracted lignite, ceased operations in 2015, followed by re-cultivation by mid-2016. Sentinel-1A and Sentinel-1B radar imagery revealed vertical displacements ranging from -10 cm to +5 cm, with maximum subsidence in the central mining area during the final mining phase (2014-2015) and stabilization post-re-cultivation (2016-2019). This paper details deformation patterns, processing challenges, and validation needs, highlighting InSAR's potential for monitoring mining-induced deformations needs.

Keywords: InSAR; remote sensing; surface deformation; deep mining; lignite

1 Introduction

Previous studies by the authors explored large-scale deformations caused by earthquakes and volcanic eruptions [3], [5], [10]. However, Hungary's minimal seismic and volcanic activity necessitated an alternative application for Interferometric Synthetic Aperture Radar (InSAR) technology. Deep mining was selected due to its significant surface deformations, often reaching tens of centimeters, and the availability of validation data through traditional geodetic methods, such as precise leveling. This study focuses on lignite extraction at the Márkushegy Mining Facility in Pusztavám, located in the Oroszlány coal basin, a region central to Hungary's coal mining history since the early 20th Century.

Traditional geodetic methods, such as precise leveling, are labor-intensive, requiring extensive fieldwork and high costs, particularly in expansive or remote mining areas. InSAR offers a transformative alternative, leveraging satellite radar imagery to monitor surface deformations with high precision over wide areas [1], [2]. By processing radar phase differences, InSAR detects millimeter-scale ground movements, making it ideal for tracking the gradual subsidence and uplift associated with mining activities. This paper investigates InSAR's application in analyzing deformations during the final mining operations (2014-2015) and re-cultivation phase (2015-2016) at Márkushegy, providing insights into its efficacy for monitoring industrial impact and informing environmental management strategies.

1.1 InSAR Principles and Advantages

InSAR uses phase differences between two radar images, acquired at different times, to detect surface displacements with millimeter-scale accuracy [11]. By generating interferograms, InSAR reveals deformation patterns, capturing both sudden and gradual ground movements. Its advantages over precise leveling include cost-effectiveness, reduced fieldwork, and the ability to cover large areas, which is critical for monitoring complex deformation patterns in mining regions. However, challenges such as atmospheric interference, coherence loss in vegetated areas, and phase unwrapping errors require sophisticated processing techniques [11]. InSAR's ability to provide high-resolution, wide-area deformation maps makes it a powerful tool for environmental monitoring, particularly in industrial contexts where traditional methods are resource-intensive. Its application in mining extends beyond deformation mapping to risk assessment, infrastructure protection, and regulatory compliance.

1.2 InSAR Principles and Advantages

InSAR has been widely applied to monitor mining-induced deformations globally, offering a robust framework for assessing subsidence and uplift. Studies in Poland's Upper Silesian Coal Basin demonstrated InSAR's ability to detect subsidence up to 1 meter, providing critical data for infrastructure safety and urban planning [13]. Similarly, applications in Germany's Ruhr region highlighted InSAR's role in evaluating post-closure stability, informing land-use decisions [14]. Other studies, such as those in Australia's Bowen Basin, have used InSAR to monitor open-pit and underground mining, revealing complex deformation patterns influenced by geology and extraction methods [16]. In Hungary, InSAR research has primarily focused on seismic or volcanic applications [3], [5], [10], with limited studies on mining deformations. This study addresses this gap by applying InSAR to the Oroszlány coal basin, contributing to the sparse literature on Hungarian mining impacts and demonstrating the technology's versatility in a low-seismic context.

2 The Test Site

The Márkushegy Mining Facility, located in Pusztavám within the Oroszlány coal basin, Hungary (Fig. 1), was the country's last operational deep coal mine, extracting lignite (brown coal with 60-70% carbon content). Mining operations ceased in January 2015, with re-cultivation completed by mid-2016, offering a unique opportunity to study surface deformations during the mine's final phase and post-closure period. The subterranean sections extend to depths of 400-500 meters, with over 50 km of underground trenches, forming a complex network that influences surface stability. Surface facilities, such as the Doba-depo excavation site, were excluded from this study to focus on underground mining impacts.

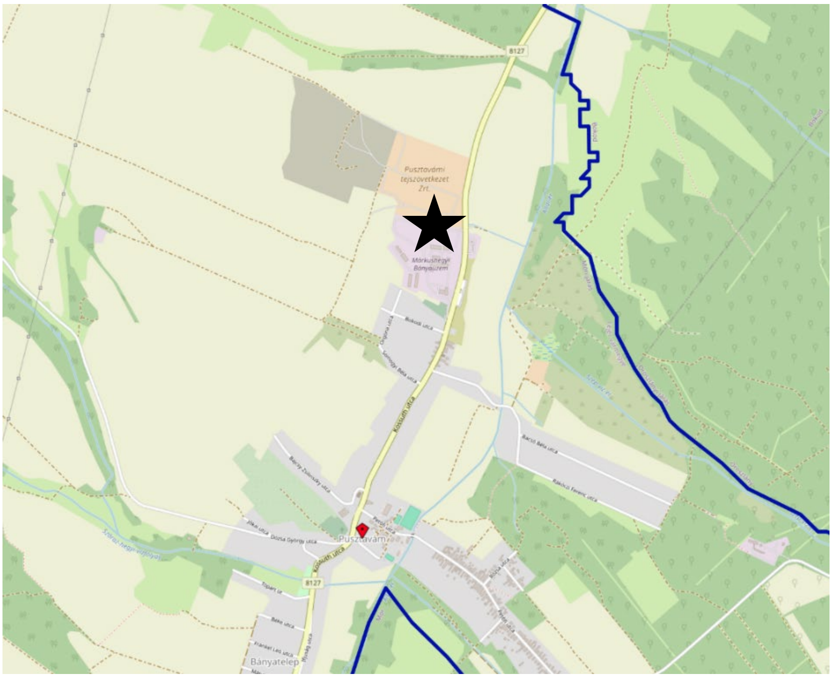

Figure 1

Location of Márkushegy Mining Facility in Pusztavám, Oroszlány coal basin, marked with a black star. The red marker indicates the village center.

Deep mining activities induce surface movements originating from subterranean voids, such as mining passages, which propagate to the surface due to extraction and re-cultivation processes. The mine closure involved:

- **Environmental remediation:** Removing or isolating contaminants to mitigate environmental impact.

- **Land reclamation:** Stabilizing terrain, restoring topsoil, and preparing the land for future use.
- **Regulatory approval:** Obtaining governmental consent to decommission mining rights, ensuring compliance with safety and environmental standards.

Despite careful closure, surface movements persist due to the properties of filler materials and surrounding geology. These movements manifest in distinct zones (Fig. 2):

- **Overlap Zone:** Strata compact without fracturing, forming surface trenches.
- **Cracked Zone:** Rock layers fracture but maintain structural integrity.
- **Crumbling Zone:** Top layers fragment heavily, risking collapse.

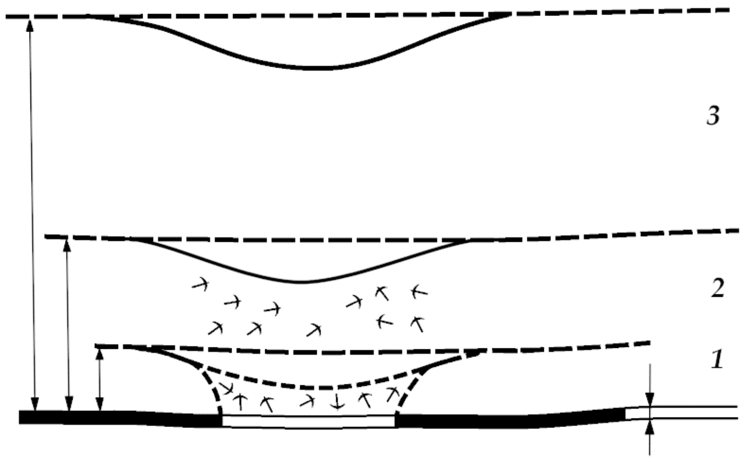

Figure 2
Schematic of deformation zones caused by mining-induced subsurface movements, illustrating Overlap, Cracked, and Crumbling Zones

2.1 Geological Context

The Oroszlány coal basin, formed during the Miocene, hosts lignite deposits within sedimentary layers of clay, sandstone, and marl. The basin's geology, characterized by low permeability and high compressibility, amplifies surface deformations as subsurface voids collapse or compact under the weight of overlying strata [15]. The Márkushegy mine's depth (400-500 m) and extensive trench system exacerbate these effects, creating a dynamic interplay between subsurface extraction and surface stability. Geological surveys indicate that the basin's sedimentary structure, combined with fault lines and varying rock densities, contributes to uneven deformation patterns, making precise monitoring critical. These factors, coupled with the mine's long operational history (decades of extraction), make Márkushegy an ideal case for InSAR monitoring, as the basin's unique characteristics produce detectable surface movements. Table I summarizes key mine characteristics.

Table 1
Characteristics of Márkushegy Mining Facility

Parameter	Value
Depth	400–500 m
Trench Length	>50 km
Mineral	Lignite (60–70% carbon)
Closure Date	January 2015
Re-cultivation Completion	Mid-2016

3 Data Processing

Data were sourced from Sentinel-1A and Sentinel-1B satellites via the Copernicus Open Access Hub (until October 2023) and the Copernicus Data Space Ecosystem, delivering 16 terabytes of data daily [7], [8]. The study period (2014-2019) covers the final mining year, re-cultivation, and post-closure stabilization at Márkushegy. March was selected to minimize seasonal variations in vegetation and atmospheric conditions, which can degrade radar signal coherence (Fig. 3).

Single Look Complex (SLC) data with VV polarization, spaced 12 days apart, were used due to the 175-orbit cycle required for image overlap [3], [10]. The area of interest was defined using a rectangular window around Pusztavám, ensuring coverage of the primary mining-affected area. Downloading older recordings (pre-2014) was challenging, requiring a 24-hour wait for secondary server access and a 3-day access window, with only two recordings retrievable simultaneously, necessitating meticulous planning to maintain data continuity.

Processing was conducted using the Sentinel Application Platform (SNAP), an open-source tool developed by the European Space Agency (ESA) in collaboration with Brockmann Consult, Array Systems Computing, and C-S [9]. The Sentinel-1 Toolbox within SNAP handled most tasks, with phase unwrapping performed using the Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping (SNAPHU). The processing workflow required careful parameter tuning, particularly for coherence thresholds, unwrapping settings, and noise filtering, to mitigate errors from vegetation, atmospheric effects, and low signal quality in complex terrain.

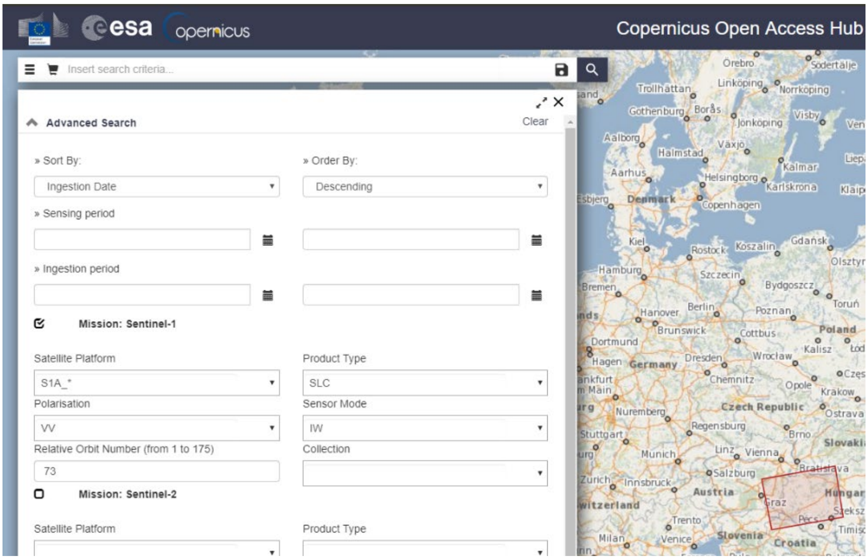

Figure 3
Data selection criteria for Sentinel-1 imagery, specifying the area of interest (Pusztavám, 2-km radius), time frame (2014-2019), and VV polarization settings

Key processing steps included:

- **S1 TOPS Coregistration:** Aligning master and slave images, selecting sub-swaths and bursts to ensure precise overlap (Fig. 4).
- **Apply-Orbit-File:** Using Sentinel Precise orbits with SRTM 3Sec for elevation correction, improving geometric accuracy.
- **Interferogram Formation:** Applying corrections for:
  - Flat Earth phase (curvature effects).
  - Topographic phase (elevation variations).
  - Surface deformation (displacement signals).
  - Atmospheric effects ($\Delta\varphi_{atmosphere}$, phase differences due to weather).
  - Noise (temporal scatterer changes & look angle variations) [11].
- **S1 Tops Deburst:** Merging adjacent stripes to reduce visible bursts in the interferogram.
- **Topographic Phase Removal:** Using a Digital Elevation Model (SRTM) to simulate and subtract reference phases.

- **Goldstein Phase Filtering:** Reducing speckle noise from temporal and geometric decorrelations.
- **Phase Unwrapping:** Converting ambiguous phases (0 to 2π) to displacement using SNAPHU, a critical step prone to errors in low-coherence areas.
- **Phase to Displacement:** Converting phase values to vertical displacement (meters).
- **Geographical Conversion:** Applying Update Geo Reference and Ellipsoid Correction for accurate spatial mapping.

The interferometric geometry is illustrated in Figure 4, where:

- **M, S**: Radar antennas on moving platforms.
- **P(x,y,z)**: Ground surface point.
- $\mathbf{B_n}$: Normal baseline (antenna separation).
- **R**: Distance from radar to target.
- $\mathbf{\Delta_h}$: Altitude difference.
- **s**: Slant range displacement.
- **θ**: Incidence angle.

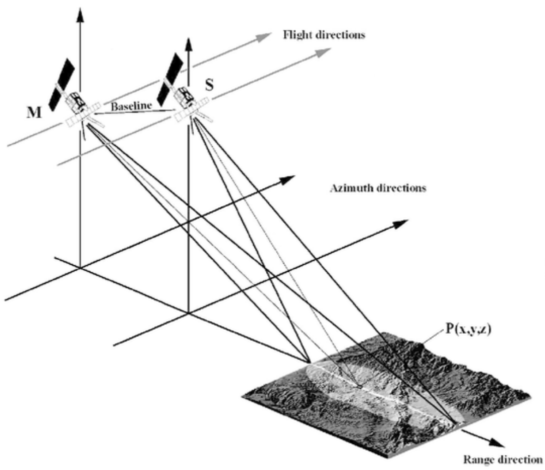

Figure 4
Schematic of InSAR geometry, showing radar antennas (M, S), baseline (Bn), and ground point P(x,y,z). Adapted from [12]

3.1 Processing Workflow

The SNAP workflow, illustrated in Figure 5, involves sequential steps from data import to displacement mapping. Coregistration aligns images with sub-pixel accuracy, critical for interferogram quality. Interferogram formation corrects for multiple phase components, while SNAPHU's phase unwrapping converts ambiguous phases to meaningful displacements. This step is particularly sensitive to coherence loss in vegetated areas or regions with complex topography, requiring optimized settings (e.g., minimum cost flow algorithm) to minimize errors [11]. The workflow's complexity, combined with the need for iterative parameter adjustments, underscores the importance of computational resources and expertise in achieving reliable results. Challenges such as low coherence in peripheral zones and atmospheric noise further complicate processing, necessitating robust error mitigation strategies, such as multi-looking or advanced filtering techniques.

Figure 5

Flowchart of SNAP processing workflow for InSAR deformation analysis

4 Results

Processed data revealed vertical displacements ranging from -10 cm (subsidence) to +5 cm (uplift) across the study area from 2014 to 2019. Maximum subsidence occurred in the central mining area during 2014-2015, corresponding to the final phase of active lignite extraction, when underground activities were at their peak. Post-re-cultivation (2016-2019), deformations stabilized, with minor uplift observed in peripheral zones, likely due to the compaction of filler materials and geological adjustments following mine closure. The study area was trimmed to a 2-km radius around Pusztavám, isolating regions directly impacted by underground mining activities and excluding external influences, such as surface excavations.

Results were visualized using ESRI ArcGIS, with displacements standardized and presented in 3D (Fig. 6) and 2D (Fig. 7) formats. Figure 6 provides a three-dimensional view, emphasizing the topographic context of deformation patterns and highlighting the pronounced subsidence in the central mining area. Figure 7 offers a planimetric overview, mapping displacements geographically and illustrating the spatial distribution of subsidence and uplift. Both figures include a colorbar indicating displacement values: red (-10 cm, subsidence), yellow (0 cm, neutral), and blue (+5 cm, uplift). These visualizations underscore the spatial variability of deformations, with the central area showing the most significant subsidence and peripheral zones exhibiting stabilization or uplift. All of which areconsistent with the expected impacts of mining and re-cultivation.

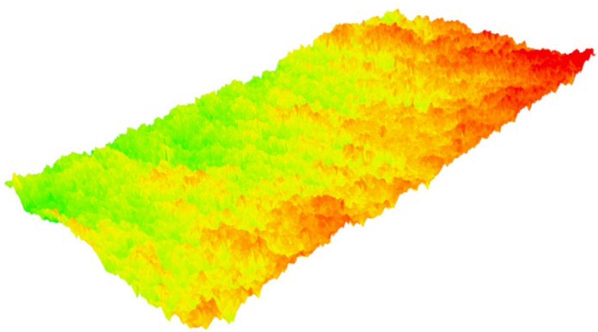

Figure 6
3D representation of vertical displacements (2014-2019), with colors (red: -10 cm, yellow: 0 cm, green: +5 cm)

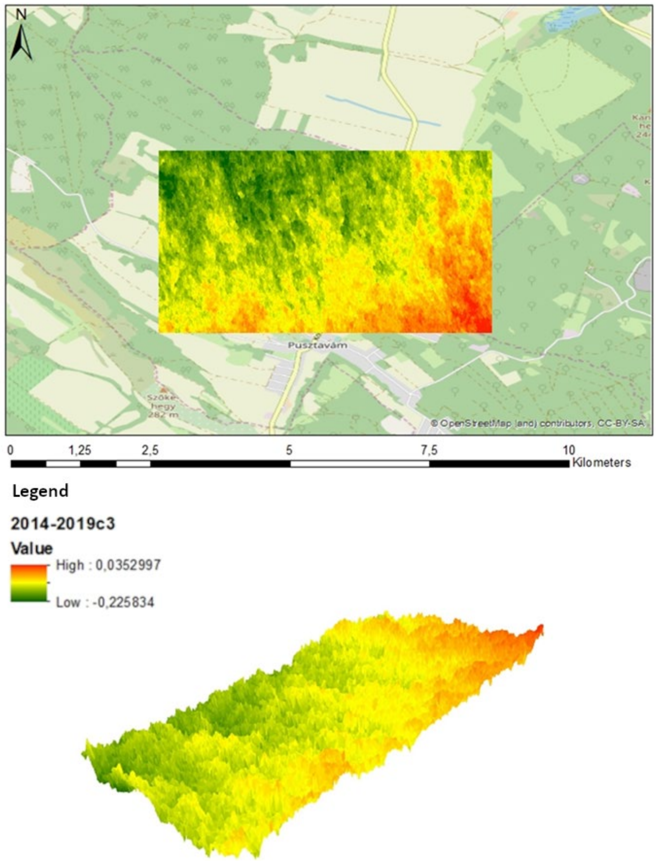

Figure 7
2D map of displacements, covering Pusztavám and a 2-km radius

4.1 Temporal Deformation Trends

Analysis of available interferograms indicates significant subsidence (-10 cm) in the central mining area during 2014-2015, driven by the intensive extraction of lignite and the collapse of subterranean voids. This period corresponds to the mine's final operational phase, when underground activities maximized subsurface disturbance. Post-closure (2016-2019), subsidence rates decreased markedly, with deformations stabilizing in the central area (reaching -2 cm) and minor uplift (+5 cm) observed in peripheral zones. This uplift is attributed to the compaction of backfill materials used during re-cultivation, which counteracted earlier subsidence, and to natural geological processes, such as sediment rebound following the cessation of extraction. Table II summarizes these displacement patterns by zone, based on aggregated data from key interferograms.

The lack of complete annual datasets prevented a detailed time-series analysis, limiting the ability to quantify year-by-year changes with high precision. However, the observed trends are consistent with the expected impacts of mining and re-cultivation, where active extraction causes rapid subsidence, followed by gradual stabilization as subsurface voids are filled and the terrain is restored. These findings align with patterns observed in other mining regions, where post-closure stabilization often results in localized uplift due to backfilling or geological recovery [13], [14]. The spatial and temporal variability of deformations highlights the importance of continuous monitoring to assess long-term stability and inform land-use planning in mining-affected areas.

Table 2
Displacement by Zone (2014-2019)

Zone	2014-2015	2016-2019
Central (Mining)	-10 cm	-2 cm
Peripheral	-3 cm	+5 cm

4.2 Validation Considerations

Precise leveling measurements, conducted concurrently with the study period (2014-2019), provide a valuable opportunity for validating InSAR-derived displacements. Preliminary comparisons suggest that InSAR results are accurate within ±2 cm when compared to leveling data in select areas, particularly in non-vegetated zones with high coherence. However, systematic errors, possibly due to coherence loss in vegetated areas or unwrapping issues in complex terrain, require further investigation. Access to comprehensive leveling datasets and a detailed mining map, specifying the exact locations of underground trenches, would significantly enhance validation efforts. Such data would allow for a more precise correlation between InSAR measurements and ground truth, improving the methodology's reliability and enabling the identification of error sources [7].

5 Discussion

The results of this study align closely with prior InSAR applications in mining regions, reinforcing the technology's efficacy for monitoring deformation [13], [14]. The observed -10 cm subsidence in the central mining area during 2014-2015 reflects the intense extraction activities typical of deep coal mining, consistent with findings in Poland's Upper Silesian Coal Basin, where subsidence reached up to 1 meter in active mining zones [13]. The post-closure uplift of +5 cm in peripheral zones suggests effective re-cultivation practices, mirroring observations in Germany's Ruhr region, where backfilling and land restoration mitigated subsidence over time [14]. These parallels underscore InSAR's ability to capture both active and post-mining deformation dynamics, providing actionable data for environmental management.

Limitations of the study include coherence loss in vegetated areas, which reduced the reliability of interferograms in peripheral zones, and errors during SNAPHU phase unwrapping, particularly in regions with complex terrain or low signal quality. The incomplete dataset for annual interferograms further restricted the ability to conduct a detailed time-series analysis, limiting temporal resolution. These challenges highlight the importance of site selection, data preprocessing, and data availability in InSAR studies. Future research should prioritize:

- Monitoring non-vegetated or sparsely vegetated mining areas to improve coherence and data quality.
- Integrating precise leveling data for robust validation, ensuring alignment between satellite and ground-based measurements.
- Extending the methodology to other Hungarian coal basins, such as the Mecsek or Borsod basins, to assess its scalability and adaptability.
- Exploring advanced InSAR techniques, such as persistent scatterer InSAR (PSInSAR), to enhance accuracy in challenging environments.

The methodology presented offers a scalable and cost-effective framework for monitoring industrial-scale deformations, with significant implications for environmental management, infrastructure safety, and regulatory compliance. By providing high-resolution deformation maps, InSAR can inform land-use planning, risk assessment, and policy development in mining regions, reducing the potential for structural damage or environmental degradation. Its versatility extends beyond mining to other industrial activities, such as oil and gas extraction or geothermal energy production, where subsurface changes induce surface deformations.

5.1 Data Limitations and Future Data Needs

The incomplete dataset for annual interferograms, due to limited Sentinel-1 data availability and coherence issues from vegetation cover and atmospheric noise, restricted the study's temporal analysis. These limitations underscore the challenges of applying InSAR in regions with diverse land cover and variable data access. To address these issues, future studies should focus on:

- Acquiring additional Sentinel-1 images to ensure uninterrupted temporal coverage, particularly for critical periods of mining and re-cultivation.
- Implementing advanced techniques, such as PSInSAR, to mitigate coherence issues by focusing on stable reflectors (e.g., buildings, bare soil).

- Collaborating with local mining authorities to access proprietary data, such as detailed trench maps or operational logs, to refine deformation zone delineation.
- Developing automated processing pipelines to streamline data retrieval and analysis, reducing delays associated with secondary server access.

These improvements would enable a more comprehensive analysis of temporal deformation patterns, strengthening the methodology's applicability to other mining contexts and enhancing its utility for long-term monitoring.

6 Data Processing Challenges

Processing faced significant technical hurdles due to SNAP's high computational demands. Program freezes and shutdowns occurred on systems with insufficient processing power, particularly during the resource-intensive tasks like phase unwrapping and interferogram formation. A minimum 8-core processor with substantial RAM is recommended to ensure stability and efficiency. Additionally, downloading older Sentinel-1 recordings (pre-2014) was time-consuming, requiring a 24-hour wait for secondary server access and a 3-day access window, with only two recordings retrievable simultaneously. These constraints necessitated careful planning to maintain data continuity. Addressing these challenges requires investment in robust hardware infrastructure, optimized software configurations, and streamlined data access protocols to support large-scale InSAR studies.

Conclusions

This study demonstrates the potential of InSAR technology for monitoring surface deformations caused by deep mining, using the Márkushegy Mining Facility in Pusztavám, Hungary, as a case study. Sentinel-1A and Sentinel-1B data revealed vertical displacements ranging from -10 cm (subsidence) to +5 cm (uplift) between 2014 and 2019. Significant subsidence occurred during the final mining phase (2014-2015), particularly in the central mining area, while minor uplift was observed in peripheral zones post-re-cultivation (2016-2019). These findings are summarized as follows:

Despite promising results, systematic errors, likely due to coherence loss or unwrapping issues, were observed, necessitating further investigation to identify their sources. Future research will focus on mining-affected areas with minimal vegetation to enhance data quality and coherence. Validation against precise leveling measurements, conducted during the study period, is recommended to confirm the reliability of InSAR-derived displacements. Access to a detailed mining map would improve the delineation of impacted zones, enabling more precise spatial analysis.

Implications and Applications

The scalability of InSAR makes it a valuable tool for monitoring other Hungarian mining sites, such as the Mecsek or Borsod coal basins, as well as global coal mining regions facing similar deformation challenges. Its integration into regulatory frameworks could enhance environmental oversight by providing timely data on ground stability, informing policies to mitigate risks to infrastructure, such as roads, buildings, or pipelines. Beyond mining, the methodology could be adapted to monitor other industrial activities, such as oil and gas extraction, geothermal energy production, or underground storage, where subsurface changes induce surface deformations. By offering a cost-effective, high-resolution monitoring solution, InSAR supports sustainable land management, risk mitigation, and environmental protection in industrial landscapes, contributing to safer and more resilient communities.

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