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SENTINEL-1 SAR INTERFEROMETRY FOR TERRAIN MONITORING: A CASE STUDY OF MINE DYNAMICS

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Abstract: *The use of SAR (Synthetic Aperture Radar) and InSAR (Interferometric SAR) technology is very useful for monitoring changes in soil topography in industrial locations such as the Veliki Krivelj open pit mine near Bor. By analysing Sentinel-1 satellite data from January to May 2024, subcentimeter terrain changes were revealed, associated with exploitation activities and dynamic processes in the mine environment. This paper illustrates the effectiveness of InSAR methods in the detection of geodynamic changes, highlighting the potential for sustainable resource management and monitoring of topographic changes in industrial locations.*

Keywords: *Interferometric SAR (InSAR), Ground Deformation, Sentinel-1 Satellite Imagery, Open Pit Mines, Environmental Monitoring.*

1. INTRODUCTION

In today's world, where industrial and natural processes are constantly shaping our planet, monitoring and understanding changes in soil topography is becoming crucial for sustainable resource management and environmental protection. Traditional methodological approaches are often limited in their ability to provide detailed and continuous information on the dynamics of terrain changes. On the other hand, the limitation of modern photogrammetric methods is their dependence on lighting and weather conditions, as well as logistical difficulties [1]. In this context, the use of SAR images (Synthetic Aperture Radar) and InSAR (Interferometric SAR) technology stands out as a powerful tool for precise and continuous measurement of vertical and horizontal changes in the Earth's surface, especially regarding the use of publicly available data such as e.g. from the Sentinel mission.

InSAR combines the capabilities of radar with the principles of interferometry to generate highly accurate digital terrain models. This technique relies on the analysis of phase differences between multiple radar images taken from the same orbit, enabling the detection of subcentimeter terrain changes. This means that InSAR can detect even the smallest deformations that can be caused by various geodynamic processes such as seismic activity, landslides or resource exploitation. Accordingly, the application of InSAR technology for monitoring terrain topography changes in industrial locations such as mines has significant potential, and there is also a significant need for monitoring mining tailings [2]. Using the example of an open pit mine in Veliki Krivelj near Bor, this paper focuses on the demonstration of the effectiveness of InSAR methods in the detection and analysis of changes in the terrain, with the aim of showing how InSAR can be applied to monitor exploitation activities, identify potential geodynamic risks, optimize management natural resources and the method of waste disposal. Through the combination of theoretical foundations of InSAR technology, practical results obtained using Sentinel-1 mission images and analysis of the obtained results, this paper demonstrates the effectiveness of InSAR technology in monitoring changes in ground topography at industrial and other locations.

2. BASIC PRINCIPLES OF SAR

SAR is an imaging radar, which can produce high-resolution radar images of the Earth's surface from airborne and space-based platforms. By emitting microwave signals and collecting reflected waves, i.e. measured backscatter, SAR systems create a SAR image that represents a 2D representation of the measured backscatter signal [3] as shown in Figure 1.

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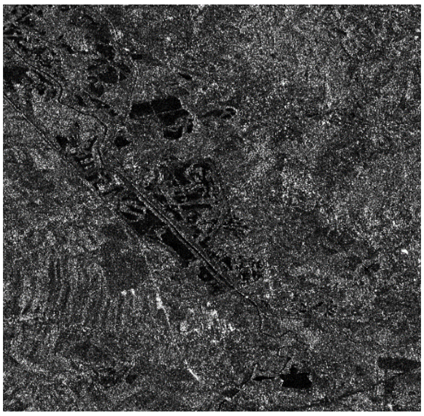


Figures 1. Example of 2D representation of SAR image

Since SAR is an active sensor and uses the microwave range within the wide radio spectrum, it can record day and night, as well as the ability to penetrate clouds and, to some extent, rain [4]. One of the key advantages of SAR technology is its ability to synthesize a large effective radar aperture, even though the physical aperture may be relatively small. This is achieved by moving the platform (whether satellite or aircraft) and recording the reflected signals over time. By combining this data, SAR can produce high-resolution images, allowing detailed analysis of surface features. These characteristics of SAR technology make it particularly interesting and useful for monitoring topography for several technical reasons:

1. Continuous monitoring - The ability to record day and night enables continuous monitoring of changes in topography regardless of weather conditions, which is crucial for timely detection and response to terrain changes.
2. Penetration through clouds and rain - SAR can penetrate clouds and rain, enabling data collection even in adverse weather conditions, which is important for continuous monitoring and analysis throughout the year.
3. High resolution - SAR provides high-resolution images that allow detailed analysis and precise measurement of topographic changes, which is crucial for identifying and monitoring small ground movements, landslides or other geodynamic processes.
4. Wide coverage area - SAR systems can quickly and efficiently cover large areas, which is useful for monitoring topographic changes in large territories, such as mines or agricultural lands.

These advantages make SAR technology essential for accurate, reliable and continuous monitoring of topographic changes, enabling detailed analysis and quick reactions. Sentinel-1 stands out as one of the important sources of satellite SAR images due to its continuous global coverage, high image resolution and open data access. The Sentinel-1 mission, part of the European Copernicus program, consists of two satellites, Sentinel-1A (2014) and Sentinel-1B (2016-2021), which carry C-band SAR sensors, which means that the wavelength of the signal is about 5.6 cm, which is suitable for topography monitoring because this wavelength enables good penetration through clouds and vegetation, which results in high reliability in obtaining data even in unfavourable atmospheric conditions. The C-SAR has four observation modes each with a different swath and resolution to suit their purpose: Stripmap (SM), Interferometric Wide swath (IW), Extra Wide swath (EW), and Wave (WV) mode. There are also 4 potential combinations of polarizations (one band VV or HH polarization, or two bands with VV+VH or HH+HV polarizations). Swath is depending on the mode, while the spatial resolution is 5m x 20m, while the height resolution is about 10 meters, which enables detailed mapping of surface features.

The mission is designed for global monitoring with a wide range of applications, including surface deformation monitoring, natural disaster management, monitoring of agricultural activities and monitoring of forest areas [5, 10]. Sentinel-1 data is open and freely available to users worldwide. The European Space Agency (ESA) provides access to this data through online platforms such as the Copernicus Open Access Hub. Users can download, analyze and use SAR data for research, scientific studies, as well as for practical applications in various industries. This open access policy encourages innovation, enhances global collaboration and enables a wide range of research and commercial activities.

3. SAR INTERFEROMETRY

Interferometry of SAR images (InSAR) is a method that uses the phase difference between two complex SAR observations taken from slightly different sensor positions to obtain information about the Earth's surface. The SAR signal contains amplitude and phase information. The amplitude represents the strength of the radar response (backscatter), while the phase is part of one complete cycle of the sinusoid (one SAR wavelength). The phase of the SAR image is determined mainly by the distance between the satellite dish and the target points on the ground.

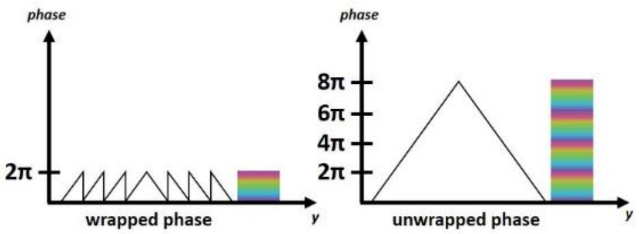
By combining the phase of these two images after co-registration, an interferogram whose phase is highly correlated with the topography of the terrain can be generated. In the case of differential interferometry (DInSAR), this topographical phase contribution is removed using a digital elevation model (DEM). The remaining variation in the interferogram can be attributed to surface changes that occurred between the two dates of image acquisition, as well as unwanted atmospheric effects [6]. The interferometric phase of each SAR image pixel is determined by the difference in the signal path from each of the two SAR sensors to the considered resolution cell. The generated interferogram contains the phase variation ϕ, caused by several factors such as the Earth's phase curvature ϕ_{flat}, topographic phase ϕ_{DEM}, atmospheric conditions ϕ_{atm}, noise ϕ_{noise} (scatterers, different viewing angles, and volume scattering), and surface deformation ϕ_{disp} between the two surveys (Equation 1).

$$\phi = \phi_{DEM} + \phi_{flat} + \phi_{disp} + \phi_{atm} + \phi_{noise} \quad (1)$$

Differential SAR interferometry (Equation 2) is used to estimate land surface contributions (ϕ_{flat} and ϕ_{DEM}), removing them from the interferogram so that the remaining phase variation can be related to changes in surface elevation between the two surveys. This works best if atmospheric contributions and other noises are kept to a minimum as they are difficult to model. Therefore, it is advisable to anticipate this when selecting images. The coherence between the reference and secondary images serves as an indicator of the quality of phase information, evaluating the degree of similarity between the images for interferometric processing, while the loss of coherence can lead to poor results and is caused by temporal, geometric and volumetric decorrelation [7].

$$\phi - \phi_{DEM} - \phi_{flat} = \phi_{disp} + \phi_{atm} + \phi_{noise} \quad (2)$$

In an interferogram, the interferometric phase is ambiguous and is known only within a range of 2π. In order to relate to the topographic height, the phase must be "unwrapped". The ambiguity height is defined as the height difference that causes an interferometric phase change of 2π after smoothing the interferogram. The phase unwrapping process resolves this ambiguity by integrating the phase difference between adjacent pixels. After removing the integer height differences (corresponding to an integer number of phase cycles of 2π), the phase variation on the smoothed interferogram provides a measurement of the actual height change as shown in Figure 2. The unwrapping results should be interpreted as the relative height or displacement between the pixels in the two images.



Figures 2. Principle of phase unwrapping [6]

The quality and reliability of the unwrapping results depend on the initial coherence. For processing Sentinel-1 satellite images, which use radar technology (SAR), coherence between two images from different dates is a key indicator for analyzing changes on the ground. Coherence measures how similar or consistent two radar images are with each other. The coherence value ranges from 0 to 1, where 1 means complete similarity (high coherence), and 0 means complete lack of similarity (low coherence). For different applications, desired coherence values can vary. For monitoring terrain deformations, a high coherence value (usually above 0.6) is desirable to accurately detect small changes on the surface. Detection of changes in vegetation or urban areas requires medium coherence values (between 0.4 and 0.6). For erosion or landslide analysis, high coherence values are also desirable, often above 0.6. In general, coherence above 0.5 is considered good for most applications, as it indicates significant similarity between two images, which can imply stability or minor changes. In this paper, a minimum coherence value of 0.3 was chosen to discard all images that are not similar. It is important to note that coherence can be low in areas with dense vegetation or changes in soil moisture, so it is crucial to contextualize the results according to the specific conditions of the terrain being analyzed..

The height resolution of 10 meters in Sentinel-1 SAR images enables detailed terrain mapping and precise detection of height differences at that level of precision. The combination of high horizontal resolution of about 5 meters and precise height resolution enables the identification of even the smallest changes in topography, which is useful for monitoring subcentimeter vertical displacements caused by geological, geotechnical or other changes in the terrain. This technology enables effective monitoring and analysis of terrain changes, which are key to understanding the dynamics and of geographic areas.

4. CASE STUDY OF MINE DYNAMICS

4.1. Geographic Context of the Mine

The subject of the analysis is the open pit of the Veliki Krivelj mine (located in the area of interest between coordinates: 44.163°N, 22.252°E and 44.049°N, 22.046°E). Veliki Krivelj is near the town of Bor in the eastern Serbia. The mine is located in an area geologically rich in copper and other minerals, which is the main reason for the development of mining operations in these locations. Its geographical position allows access to large reserves of mineral raw materials, which is key to its economic importance and continued exploitation.

This mine at national-level of Serbia is particularly significant to monitor due to the dynamic nature of their mining operations and their impact on the environment, and it goes through continuous changes in the exploitation of resources, which affects the topography and stability of the terrain. Monitoring these changes provides a deeper understanding of how mining activities affect the local ecosystem, water resources and surrounding communities. Also, the dynamics of exploitation can have long-term consequences on the local economy and social structure, which emphasizes the importance of systematic monitoring and management of this location.

4.2. Data

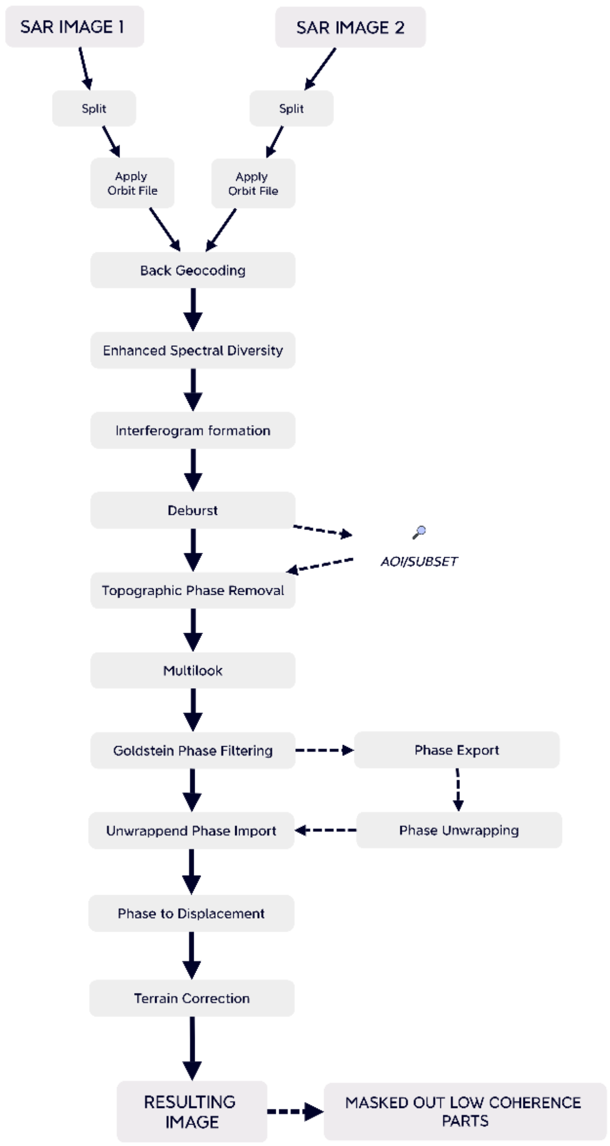
For the analysis of deformations in the territory of the mine, Sentinel-1 A images were used in pairs of adjacent acquisitions with the same swath shown in Figure 3. These are IW images, with a relative orbit number of 80 in the descending direction and VV&VH polarization, which is generally used in such analyses.

Figure 3. SAR Images footprint [8]

In this study, 12 images were used, in the period from 04.01.2024. to 15.05.2024. (the images in between are from 16.01, 28.01, 09.02, 21.02, 04.03, 16.03, 28.03, 09.04, 21.04. and 03.05.2024), which makes 11 interferometric analyses with a time window, i.e. a frequency of about 12 days. The selected period for SAR interferometric analysis enabled the use of fresh and recently available data from the Copernicus platform, which is crucial for the topicality of the research. Although seasonal changes may affect the coherence due to the growth of vegetation beginning in March and April, this period was chosen to make the most of the limited time for data collection and processing. IW types of images were used, which imply a wider observation zone and enable the coverage of a wider geographical area in one pass. The Sentinel-1 IW mode provides a wide coverage area in a single pass of the satellite, useful for observing large territories. The high spatial resolution of the images enables detailed mapping of the Earth's surface, crucial for the analysis of geological changes and urban development, as well as for monitoring the environment and disasters. The interferometric capabilities of IW mode support accurate measurement of ground displacement and deformation, making IW imagery a key tool for geoinformation studies. The images were processed in the open software SNAP, which is a free software developed by ESA.

4.3. Methodology

SAR data was processed using interferometric techniques to generate interferograms, a basic tool for terrain deformation analysis. Data processing includes differential interferometry - DInSAR (Differential Interferometric Synthetic Aperture Radar), which enables the detection and quantification of vertical movements of the Earth's surface between two different moments in time. Data calibration was performed to eliminate atmospheric effects and other artifacts that may affect the accuracy of the results. The processing steps are shown as a flowchart in Figure 4. First, two adjacent SAR images from the same orbit from two temporally adjacent acquisitions were used. After downloading, they were "split" to extract the corresponding bursts from the images. Precise orbits were then applied to ensure maximum geolocation accuracy. The next step was "back geocoding", which enables correct alignment of SAR images in geographic space. Then the "enhanced spectral diversity" method was applied to improve the quality of spectral coherence. After that, an interferogram was formed that represents the phase difference between two SAR images, which enables the analysis of deformations in the field. The interferogram went through a "deburst" process to remove discontinuities. A "subset", i.e. an area of interest, was selected, in this case the Veliki Krivelj open pit territory, to reduce the amount of data for further processing. After that, topographic phase removal is applied, which could introduce errors in the analysis, in order to isolate and analyse only changes in phases that are caused by real surface deformations or other phenomena of interest, and not changes which are the result of differences in terrain height. Further, "multi-look filtering" is applied to reduce noise and increase the signal-to-noise ratio. "Goldstein phase filtering" was additionally used to remove remaining phase noises. After phase filtration, phases were exported ("Snaphu phase export") and then unwrapping was performed ("Snaphu phase unwrapping") to eliminate phase cycles. The unwrapped phases are then loaded and converted to displacements ("phase to displacement"), which enables the detection of metric displacements. Finally, "terrain correction" was performed to ensure the precise geolocation of the resulting data. Finally, the resulting image was masked, removing parts of the image with coherence less than 0.3 to ensure valid data. Together, these enable a detailed analysis of terrain deformations using the DInSAR (Differential Interferometric Synthetic Aperture Radar) method, providing valuable insights into changes in the mine area.



Figures 4. Processing workflow of SAR images

4.4. Analysis Results

Analysis of DInSAR interferometry over the Veliki Krivelj open pit reveals significant changes in ground level during different time periods. Despite the lack of detailed information on geological and mining processes, as well as the dynamics of mine operation, it is possible to draw useful conclusions by analyzing the coherence of interferograms and identifying specific patterns in ground level changes. The open pit proved to be highly coherent on the interferograms, which enables precise detection of changes. In some periods, activities were observed that indicate a decrease in the ground level, while in other periods, changes suggest an increase in the ground level. This analysis focuses on the identification and interpretation of these changes, using custom legends for each time window to highlight extreme displacement values. Based on the obtained results and visualizations for each time period, we can try to draw conclusions about the dynamic processes taking place in the open pit.

In DInSAR analysis, the phase difference conversion between two SAR images and the ground displacement value is crucial. The phase of the radar signal depends on the distance between the satellite and the ground surface, and the phase differences between two time-separated images detect the change in that distance.

Table 1. Extreme displacement values across interferograms

Dates of acquisition (Image 1 - Image 2)	Decreased Terrain Level [cm]	Increased Terrain Level [cm]
04.01-16.01. (Pair 1)	**-4.5**	**1.9**
16.01-28.01.	-3	4.2
28.01-09.02.	Not detected	3.2
09.02-21.02.	Not detected	3.9
21.02-04.03.	Not detected	6
03.04-03.16.	-3.2	1.3
16.03-28.03.	-2.4	3.8
28.03-09.04. (Pair 2)	**-4.3**	**2.6**
09.04-21.04.	Not detected	3
21.04-03.05.	-3	2.4
03.05-15.05. (Pair 3)	**-2.2**	**7.9**

The "phase to displacement" value represents the change in distance between the radar on the satellite and the ground surface between two SAR images, quantifying ground displacement in millimetres or centimetres. This value is relative, showing how much the distance between the satellite and a certain place on Earth has changed between two SAR images, depending on the position of the satellite and the geometry of the image. It does not give the absolute height or depth of a point on the ground, but only the change in height as an indication, which is useful for detecting ground movement dynamics. The phase differences are first converted to displacement and then used to create maps that show changes over time windows. Positive values indicate an uplift of the ground, while negative values indicate a lowering of the ground. The analysis of these values enables the detection and monitoring of changes due to mining activities or natural processes in the Veliki Krivelj mine, providing insight into relative ground movements during the analysed time periods.

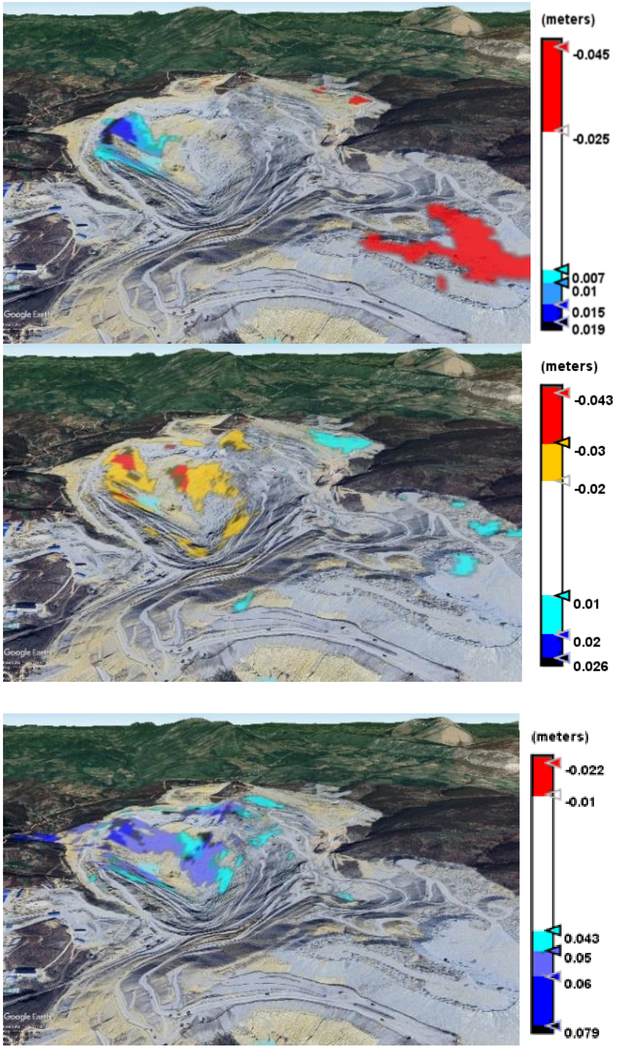


Figure 5. DinSAR Results: Pair 1 (top), Pair 2 (middle), Pair 3 (bottom)

Table 1 shows the results of interferometry with minimum and maximum values of the phase differences of the images converted to lengths (displacement). All extreme values are located in the open pit of the mine in all 11 interferograms. In order to ensure the accuracy and relevance of the results, values with a low level of coherence between images (less than 0.3) were neutralized. Only extreme displacement values are presented in the results, while small displacement values are not included in the visualization. This approach reduces the impact of possible noises caused by possible atmospheric effects and vegetation, enabling better identification and analysis of significant changes in the ground level. The visualization of the results was exported in KMZ format for display and verification on the digital terrain model in Google Earth. The results show significant changes in the ground level in the Veliki Krivelj open pit. Negative values of displacement (lowering of terrain or digging of material) vary up to -4.5 cm, while positive values (raising of terrain or accumulation of material) reach up to 7.5 cm. These changes indicate active geodynamic processes and mining activities. By neutralizing low coherence and focusing on extreme values, the obtained data provide a clear insight into significant ground movements, useful for further analysis and monitoring of the mine's condition. In the table, the interferograms that have been specially selected are bolded, and the visualization for them is shown in Figure 5, providing a clearer insight into the extreme values for each time window. Orange and red colors represent areas where there is less material, i.e. where there is a noticeable decrease in the level of the ground (from higher to lower, respectively), while the shades of blue and black colors indicate the areas where material has been dumped, i.e. increase in ground level (from lower to higher values, respectively) in between two adjacent acquisitions of about 12 days. Such visualization helps to monitor natural processes, such as erosion or sedimentation, as well as mining activities, which may include tailings disposal or ore exploitation. For Pair 1, a decrease in the ground level of 2.5 to 4.5 cm is noticeable along the perimeter of the mining pit, while a slight increase of 0.7 to 1.9 cm is observed on the interior of the mine on the northwest side in a place that can be assumed to be a temporary dumped material. This may indicate processes such as sedimentation or redistribution of material due to mining activities or natural factors. The results for Pair 2 show more significant changes. An increase in the soil level of 1 to 2 cm was observed along the perimeter of the pit, while a decrease of 2 to 4.3 cm was detected inside the pit. This may suggest more complex geological processes or changes in the mining method during that period. Pair 3, as the last interferometer in the investigated period, shows the most pronounced changes. On the northern side of the interior and on the northern perimeter of the pit, a significant increase in the ground level from 4.3 to 7.9 cm was observed, while in other places there were no significant changes. These results indicate activities that may be related to mining processes or geological features, especially along the perimeter of the mine where consistent increases and decreases in ground level have been observed. Variations within a mine may be the result of local geological conditions or specific technological processes. Further research, with additional data on the dynamics of mining activities, geological features and weather conditions, is necessary to fully understand the causes of these changes in topography. This research provides the basis for further terrain analysis within the Veliki Krivelj mining area.

When analyzing the results that show maximum and minimum displacement values in the context of the DInSAR method, it is possible to point out that the interpretation of these changes as a consequence of mining activities has an intuitive logic, bearing in mind the known processes of depositing and removing materials in mines. However, since there are no additional sources available to support these findings, it is important to emphasize that the next phase of research should include more detailed verification and confirmation of the results. This need for further research may be a key aspect of the discussion, highlighting the importance of expanding the literature and additional studies that would confirm and deepen the understanding of the links between DInSAR results and specific mining processes.

The integration of this argument not only enhances the discussion, but also lays the foundation for future work aimed at improving the scientific validity and wider application of the results in practice.

5. CONCLUSION

In this research, which deals with the application of SAR technology for monitoring soil deformations in industrial locations such as open pit mines, the important role of Interferometric SAR (InSAR) in the analysis of these changes is highlighted. Using the example of Veliki Krivelj mine in Serbia, the research demonstrated the ability of Sentinel-1 satellite images to accurately detect vertical displacements of the terrain, which is essential for understanding the impact of mining activities on the environment. The analysis of the InSAR technique indicated the effectiveness of its use in the identification and quantification of soil deformations caused by exploitation, as well as in monitoring their long-term changes. This methodology enables detailed monitoring of areas of high coherence such as open pit mines, where complex processes such as subsidence, material accumulation or topographic changes often occur. The study highlights the importance of continuous monitoring of mining sites for sustainable resource management and environmental protection. By analyzing time series of interferograms, researchers were able to identify and characterize different phases of changes in soil deformations, which provides valuable insights into exploitation dynamics.

At the same time, despite challenges such as seismic activity or changes in vegetation that can affect the quality of the interferogram, SAR technology has shown indications of even subtle changes. This research highlights the need to integrate geologic, meteorological, and operational data to better understand the factors influencing soil change in mining environments. and additionally confirmed the results, which would be the subject of further research as well as application on examples of other open pits in Serbia to compare the results.

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