Deformation Monitoring Using Differential Interferometry Synthetic Aperture Radar (DInSAR): A Case Study of a Ghanaian Mine

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Abstract

Monitoring ground deformation in open-pit mines is crucial for ensuring safe mining operations. On site monitoring techniques such as the use of LIDAR in deformation monitoring are costly as such, Differential Interferometric Synthetic Aperture Radar (DInSAR), a satellite-based technology, provides a cost-effective solution for tracking surface deformation across expansive mining areas. However, in mining zones undergoing significant topographical changes due to excavation, the accuracy of DInSAR can be affected by insufficient digital elevation model (DEM) data. This study leverages DInSAR to analyze ground deformation of a Ghanaian mine located in the Western North part of Ghana, addressing the challenges posed by dynamic terrain shifts. The study involved acquiring Sentinel 1 SAR data, performing coregistration, generating interferograms, conducting DInSAR processing, followed by subsetting, multilooking, phase filtering, phase unwrapping, displacement calculation, and terrain corrections. The results demonstrate complex deformation patterns, with varying levels of subsidence and uplift across different sections of the mine. This approach enhances the precision of mine deformation analysis, contributing to early hazard detection and informed decision-making. By integrating DInSAR with routine safety assessments, mining companies can significantly improve hazard prediction, minimize operational disruptions, and optimize resource extraction strategies. Ultimately, this study highlights the potential of advanced satellite technology in augmenting traditional mine monitoring techniques, thereby promoting safer and more sustainable mining practices.

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1.0 Introduction

Gold mining activities can easily cause deformation and damage the surface structure which seriously threaten the sustainable development of the region. As one of the largest gold production countries in the world, Ghana's geological disasters in mining areas such as ground subsidence, ground collapse and ground water accumulation have been continuous and urgent problems for mining enterprises and local governments. Practical experience has proven that when cumulative amounts of surface deformation in a mining area reaches a certain threshold, a catastrophe will occur under numerous conditions related to weather, geological activities, or human activities (Li *et al*., 2019).

Over the last decade, Differential Interferometry Synthetic Aperture Radar (DInSAR) has become an important remote sensing tool for the estimation of temporal and spatial surface motion (Berardino *et al*., 2002). Differential Interferometry Synthetic Aperture Radar (DInSAR) is a remote sensing technique that uses radar signals to measure surface deformation with millimeter precision This technique involves comparing two or more Synthetic Aperture Radar (SAR) images of the same area taken at different times and using the phase difference between them to calculate the deformation Additionally, this technique is able to detect and quantify small deformations that could indicate potential hazards and provide early warnings to the mining operators. (Ferretti *et al*., 2001).

In recent years, compared with the traditional sparse distribution and time-consuming measurement techniques of Global Positioning System (GPS) and levelling, differential interferometric synthetic aperture radar (D-InSAR) with its continuous coverage, high accuracy, and high degree of automation, has become an effective means of obtaining surface deformation information. The GPS measurement techniques are able to measure ground deformations only at discrete points, not over a wide and continuous area. As for leveling methods, such techniques can also cover a whole territory but benchmark density is generally far lower than in DInSAR techniques. In addition, complete leveling surveys cannot be repeated frequently as the cost of carrying out the measurements is very high (Li *et al*., 2019).

Given the aforementioned context, this paper endeavours to monitor deformation areas in a Ghanaian mine using DInSAR technique.

2.0 LITERATURE REVIEW

2.1 Concept of Deformation Monitoring

Deformation monitoring involves continuous monitoring of ground movements, such as rock mass deformations and displacements, in order to detect early warning signs of slope instability. As mining activities progress, the stability and integrity of the pit walls, benches, and surrounding infrastructure can be affected by various factors such as geological conditions, mining methods, and external influences (Smith *et al*., 2020; Johnson and Lee, 2019; Brown, 2021).

However, natural and man-made slopes can be expected to record deformation, mainly due to the effect of time and stress. Slope deformations can occur as a result of geological factors, including the inherent properties of the rock mass, such as strength, jointing, and weathering (Yacoub *et al*., 2015). In addition, external factors such as seismic activity, groundwater conditions, and changes in stress distribution can contribute to slope deformations. In the context of open pit mining, man-made slopes are of particular concern due to the higher exposure of personnel and the potential economic consequences of slope failure (Ma *et al.*, 2016). Therefore, it is crucial to implement effective deformation monitoring strategies to detect and assess slope displacements.

The consequences of man-made slope failure can be severe, as it can result in injuries to personnel and significant economic losses. In an open pit mining environment, slope failures can disrupt mining operations, leading to production delays, and require costly remedial measures (Yacoub *et al*., 2015). By monitoring slope displacements, mine operators can gain insights into the behavior of the slopes and identify potential instability before it escalates into a failure. This allows for proactive planning and implementation of measures to ensure personnel safety and minimize the economic impact of slope instability.

To effectively monitor slope displacements, a range of techniques and systems are available. These include traditional surveying methods such as total station surveys, GPS monitoring, and modern technique such as satellite-based interferometry. These techniques enable the collection of measurements of slope displacements at regular intervals (Mura *et al*., 2014). Additionally, advanced technologies such as LiDAR (Light Detection and Ranging) can provide detailed three-dimensional representations of slope surfaces, aiding in the identification of potential instability zones (Ali *et al*., 2018).

In view of that, managing slope instability in an open pit mining environment requires a comprehensive approach that combines effective monitoring, accurate prediction, and timely decision-making. By integrating deformation monitoring with other risk management strategies, such as geotechnical assessments, slope design optimization, and operational controls, mine operators can minimize the risks associated with slope instability while maximizing ore extraction (Mercer, 2006).

2.2 Traditional Deformation Monitoring Techniques

These techniques entail measuring and analysing ground motions, which assists in identifying potential hazards and reducing risks using the conventional methods. This section will examine three commonly used traditional techniques: ground-based monitoring instruments, geodetic surveys, and visual inspections with photography.

2.2.1 Ground-Based Monitoring Instruments

One widely employed traditional technique for deformation monitoring is the installation of ground-based monitoring instruments. These instruments include survey prisms, extensometers, inclinometers, and strain gauges (Ali *et al.*, 2016). By strategically placing these instruments throughout the mining area, engineers can measure and track various ground movements, such as subsidence, heave, and lateral displacements. Data collected from these instruments provide valuable insights into the behavior of the rock mass which helps in the identification of potential instabilities.

Survey prisms, for example, are used to measure the displacement of rock faces. They consist of reflective surfaces that reflect light back to a measuring instrument, allowing engineers to precisely determine the changes in position of the prism over time (Ali *et al*., 2016). Extensometers are used to monitor changes in the length or strain of rock masses. They consist of a series of rods or wires that are anchored to the rock and connected to a measuring device. Inclinometers, on the other hand, are used to measure the angle of slope movements. They consist of a probe that is inserted into a borehole and measures the inclination of the rock mass. Lastly, strain gauges are used to measure changes in strain within the rock mass. They consist of electrical resistance elements that change their resistance in response to strain, providing information on the deformation of the rock.

2.2.2 Geodetic Survey

This monitoring technique involves the measurement of precise positions of reference points over time. Engineers can identify significant displacements and deformations within the open pit by monitoring the movement of these reference points (Mensah *et al*., 2017). Global Navigation Satellite Systems (GNSS) and terrestrial laser scanning are the two equipment that are employed in geodetic surveys.

GNSS relies on satellite signals to determine precise positions on the Earth's surface. This technique involves the use of a network of satellites that transmit signals to receivers on the ground. These receivers collect the signals and use the information to calculate the position of the reference points. GNSS provides accurate and reliable data, making it a valuable tool in deformation monitoring (Anon, 2020a).

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On the other hand, terrestrial laser scanning uses laser beams to create detailed 3D models of the terrain and then measures the time it takes for the beams to return after hitting the surface. By scanning the entire mining area, engineers can create high-resolution 3D models that accurately represent the shape and topography of the terrain. These models can then be compared over time to detect any changes or deformations (Anon, 2020b).

2.2.3 Visual Inspections and Photography

Regular site visits are conducted by engineers and geologists to visually assess any signs of deformation, such as cracks, bulges, or changes in slope geometry. These visual inspections provide qualitative information on the overall stability of the mining area. Photography is an essential component of visual inspections as it allows for the documentation of conditions and facilitates comparisons over time. Engineers take photographs of specific areas of interest, capturing details that may not be easily visible during site visits. These photographs serve as a visual record of the mining area and enable engineers to analyze and compare the conditions over different time periods. By carefully examining the photographs, engineers can identify any changes or deformations that may have occurred (Anon., 2015).

It should be kept in mind that these traditional techniques have limitations. They often require manual data collection and analysis, which can be time-consuming and subject to human error. Additionally, these techniques may not provide real-time monitoring or continuous data, limiting their ability to detect rapid or subtle changes in ground conditions.

2.3 Remote Sensing-Based Deformation Monitoring

Remote-based deformation monitoring is a vital technique in deformation monitoring, providing valuable insights into the measurement and analysis of land deformation. This approach involves utilizing various remote sensing technologies, including active remote sensors, such as Airborne Laser Scanning (ALS) and Synthetic Aperture Radar (SAR), to monitor and measure ground movements across large areas. (Anon., 2015).

2.3.1 Airborne Laser Scanning (ALS)

An instrument installed on an airplane emits light pulses (often produced by lasers) that are aimed at the ground in the shape of a scanning pattern as part of a measurement method known as airborne laser scanning (Yacoub *et al*., 2020).

ALS system, active remote sensing techniques, are employed to derive High-Resolution Digital Elevation Models (HR-DEMs) for monitoring purposes. This system provides a comprehensive displacement field for the entire landslide body, overcoming the limitations of single-point measurements from in-situ sensors. However, the accuracy of point measurements in laser scanning depends on the velocity of the observed landslide. ALS measurements typically have

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lower accuracy (approximately ±15 cm) compared to Terrestrial Laser (TLS) measurements (around ±1.5 cm at 100 m).

2.3.2 Synthetic Aperture Radar (SAR)

SAR, an active remote sensing technique, utilizes microwave signals to record the electromagnetic echo backscattered from the Earth's surface and create a 2D complex value image map representing amplitude and phase (Moreira *et al*., 2013). SAR sensors can be implemented on various platforms, including space borne, airborne, and ground-based, allowing for image acquisition independent of natural illumination and cloud coverage. Satellite SAR sensors operate in different bands, such as C-band, L-band, and X-band.

The integration of active and passive remote sensing techniques in remote-based deformation monitoring allows for a comprehensive understanding of land deformation processes. By combining the capabilities of TIR remote sensing, ALS, and SAR, researchers and practitioners can obtain detailed and accurate measurements of ground movements over large areas. This information is invaluable for assessing the stability of infrastructure, monitoring mining activities, and identifying potential geohazards (Doerry *et al*., 2004).

2.4 Synthetic Aperture Radar (SAR) History and Imaging Principles

2.4.1 Overview of SAR

The Radio Detection and Ranging (RADAR) technology is used to decode electromagnetic signals that are reflected and retrieve pertinent data (Doerry *et al*., 2004). Radar has been in use since the early 1900s, when H. Ulsmeyer originally described it in a patent as the "telemobiloscope". Radar started to develop into what it is today in the 1920s and later, and it became more popular during the Second World War when it was used by the British and American scientists to see enemies from afar, even at night. Since then, it has been widely used in a number of domains, including weather forecasting, imaging of objects in space, and more recently, producing 2D pictures of ground surface displacements that can be read by humans.

Researchers found in the early 1950s that the Doppler properties of the radar echoes might be used to artificially limit the antenna beam of an airborne side-looking radar to increase its angular resolution. In order to achieve this goal, the corresponding antenna aperture was synthesized by combining many returns to produce a far smaller beam than the actual antenna transported by the aircraft. Deployment of operationally useful systems was possible as early as 1958, thanks to the speedy resolution of significant technological hurdles. Since then, the rate of advancement in the field hasn't slowed down; subsequent research has led to the creation of increasingly complex synthetic aperture radar (SAR) systems that today offer incredibly detailed images with all the benefits of a microwave radar system, including the ability to image at night and through clouds, fog, dust, bad weather, and, in specific circumstances, foliage and the ground itself. Today, more than 15 space borne SAR systems are being operated for innumerous applications (Anon., 2022).

2.4.2 SAR Imaging Principles

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SAR imaging principles involve the coherent processing of radar signals collected from different positions along the flight path (Moreira *et al*., 2013). This section aims to provide a detailed overview of the principles underlying SAR imaging.

A Synthetic Aperture Radar is a movable platform with an imaging radar placed on it. Similar to a traditional radar, electromagnetic waves are progressively sent, and the radar antenna collects the backscattered echoes and registers them in both amplitude and phase (Mura *et al*., 2014). The platform movement in the case of SAR causes the sequential times of transmission and reception to convert into various locations. The construction of a virtual aperture that is far longer than the actual antenna length is possible with the help of a suitably coherent combination of the received signals. This fundamental characteristic of SAR is where the term "synthetic aperture," which describes it as an imaging radar, originates. The radar image is produced after the raw data has been processed (after the synthetic aperture has been formed), and it serves as a measure of the scene reflectivity (Moreira *et al*, 2013).

The resolution in a final SAR image is solely determined by the integration (look) angle, signal bandwidth, and center frequency (Sjögren and Tau, 2012). This renders the resolution independent of the distance to the scene. This means that an airplane imaging the same region from a very close distance and a satellite imaging it from a far distance may both provide images with the same resolution. One important parameter that affects SAR image resolution is the range resolution (Bamler and Ramza, 2000).

The range resolution determines the minimum detectable separation between two scatterers along the radar line of sight. It can be calculated using equation below

$$\Delta r = \frac{C\tau}{2}, \qquad \text{Equation (1)}$$

Where Δr is the range resolution, c is the speed of light and τ is the pulse length and it is inversely proportional to the bandwidth meaning $\tau = \frac{1}{B}$ where B is the bandwidth of the SAR. But ground range resolution is related to slant range resolution in which the look angle, θ is taken into consideration. It is given by Equation 2.

$$R_r = \frac{C\tau}{2\sin\theta} \qquad \text{Equation (2)}$$

Substituting $\tau = \frac{1}{B}$ into the equation, it becomes

$$R_r = \frac{C}{2B\sin\theta} \qquad \text{Equation (3)}$$

Another factor that influences SAR image resolution is the azimuth resolution. The azimuth resolution determines the minimum detectable separation between two scatterers in the cross-track direction. It is determined by the antenna beamwidth and the synthetic aperture length. The azimuth resolution can be calculated using equation 3.5.

$$\Delta x = \frac{\lambda}{2 sin\beta}$$ Equation (4)

Where Δx is the azimuth resolution, λ is the wavelength of the radar signal, and β is the half-power beamwidth of the antenna. But the bandwidth is the same as the frequency. From the frequency wavelength relationship, $\lambda = \frac{C}{B}$. Substituting into equation 4, it becomes

$$\Delta x = \frac{C}{2B sin\beta}$$ Equation (5)

Where C is the speed of light which is given as 3×10^{8} m/s.

2.5 Differential Interferometry (DInSAR) for Deformation Monitoring

DInSAR has proven to be successful in identifying millimeter-level ground changes in the context of open pit mining, where the integrity of pit walls is of utmost concern. It makes it possible to identify small deformations before they become dangerous slope collapses or other geotechnical risks. By giving mining firms timely information, DInSAR enables them to put suitable mitigation measures into place and guarantee the safety of workers and equipment. One of DInSAR's main benefits is its capacity to offer extensive coverage and continuous monitoring throughout time. It is difficult to capture the complete geographic range of open pit walls using conventional ground-based monitoring methods since they sometimes have a limited scope that only includes certain locations or regions.

Standard DInSAR uses two SAR images taken at various times and from different positions on the satellite in order to quantify ground deformation (Mura *et al*., 2014). The two coregistered images were used to create an interferogram, and the topography, deformations, atmosphere, and noise all contributed to the phase's components. The topographic phase component can be subtracted from the measured deformation by knowing the satellite's location in relation to the topographic surface (Silva *et al*., 2017). What remains in the differential interferogram after the topography-related phase component has been removed is a contribution from the ground displacement between acquisitions combined with another undesired component, represented by equation 6

$$Ø_{\Delta t} = Ø_{def} + Ø_{h} + Ø_{atm} + Ø_{\beta} + Ø_{n}$$ Equation (6)

where $Ø_{def}$ is the phase change due to the displacement of the pixel in the satellite line-of-sight (LoS) direction, $Ø_{h}$ is the topographic phase error, $Ø_{atm}$ is the atmospheric phase delay, $Ø_{\beta}$ is the residual phase due to orbit errors, and $Ø_{n}$ is the phase noise.

2.6 Data Processing and Analysis Techniques for DInSAR

InSAR is primarily used to register the phase information between two coregistered radar images. The D in DInSAR refers to "Differential," which implies it is used to track variations in phase over time between two SAR images (Anon., 2022). It is used to monitor subsidence/uplift or lateral deformation. To be independent from topograpy, the topographic phase is simulated using a

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reference DEM and then removed from the interferogram. This section provides an overview of some commonly used techniques in DInSAR data processing and analysis. Figure 3.1 shows a basic technique of DInSAR where the phase difference between satellite 1 and satellite 2 data acquired at different times can be used to compute the deformation.

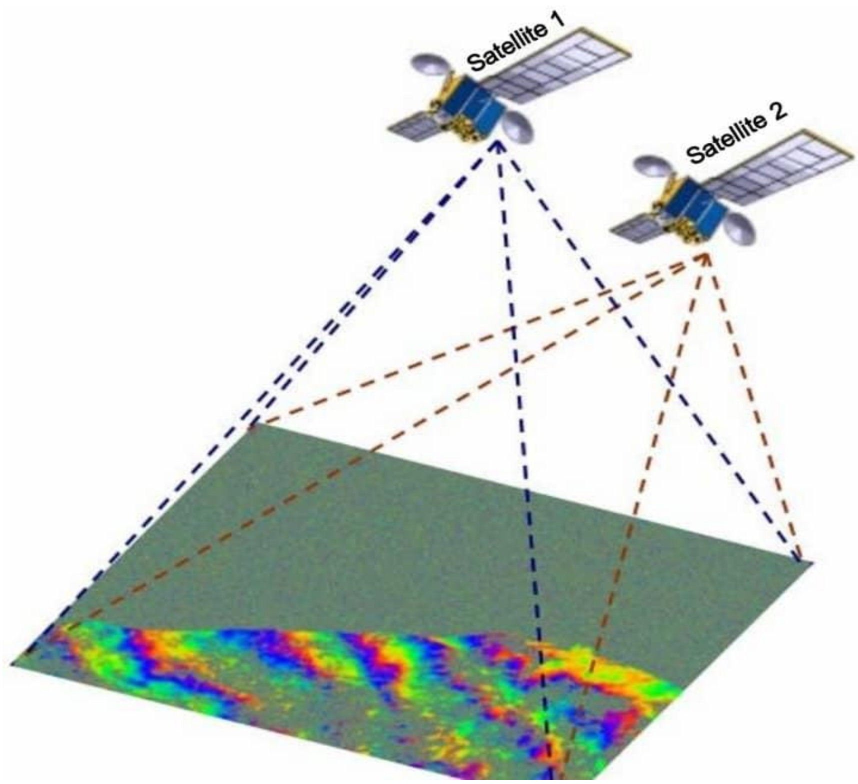

Figure 1 Basic DInSAR Technique (Mora, 2006)

4 MATERIALS AND METHODS USED

4.1 Data source

In this study, Sentinel-1 SAR data in the ascending mode was acquired. Four sets of Sentinel-1 SLC - IW data were downloaded from the Copernicus website for the study. The acquisition dates for each dataset were as follows: Dataset 1 (2nd April, 2022.), Dataset 2 (2nd May, 2022.), Dataset 3 (2nd June, 2022.) and Dataset 4 (2nd July, 2022.). The SLC - IW data format contains both amplitude and phase information, providing essential data for interferometric analysis.

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4.2 Methods

4.2.1 Coregistration

In the second method of the project, coregistration is performed on the acquired Sentinel-1 SAR data. The coregistration process involves aligning the pixels of the two radar images so that corresponding features in the scenes are precisely matched. This alignment is necessary because slight geometric variations, atmospheric conditions, and platform instabilities can introduce image displacements and distortions. By aligning the images, these discrepancies can be corrected, enabling accurate interferogram generation. Various algorithms can be employed for coregistration, including feature-based matching, intensity-based matching, phase correlation, cross-correlation. The algorithm used for this project is the cross-correlation, which calculates the similarity measure between two images based on their pixel intensities. The displacement vector that yields the highest correlation value represents the optimal shift required to align the images.

4.2.1 Interferogram and DInSAR Formation

The third step in this project involves Interferogram Formation and Differential Interferometric Synthetic Aperture Radar (DInSAR) processing. A two coregistered Single-Look Complex (SLC) images acquired at different times helped in the interferogram generation. The interferogram captures the phase information related to ground displacement between the two acquisitions. DInSAR processing involves comparing the phase values from the interferogram formed. It can be computed using Equation 7.

$$\Delta\phi = \phi 2 - \phi 1 \qquad \text{Equation (7)}$$

This phase difference, $\Delta\phi$, is proportional to the Line-of-Sight (LOS) displacement of the ground.

4.2.2 Subset to Study Area

In this study, the fourth method involves Subset Extraction from the interferogram to focus on a specific study area of interest. This process allows for a more targeted analysis of the deformation phenomena within the selected area.

Subset extraction is necessary for two main reasons. Firstly, it reduces computational requirements by working with a smaller portion of the interferogram, optimizing processing time and resource usage. Secondly, it enables a focused analysis of specific areas where deformation patterns and trends are of particular interest.

To perform subset extraction, the geographic coordinates or pixel indices defining the boundaries of the study area are carefully selected. These boundaries should encompass the desired region while ensuring that the coherence and phase information essential for deformation analysis are preserved.

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4.2.3 Multilooking and Phase Filtering

To improve the quality and interpretability of the data, two essential processing steps were employed: multilooking and phase filtering.

Multilooking

SAR images often suffer from a granular noise artifact known as speckle, which can hinder the analysis and interpretation of the data. To address this issue, a technique called multilooking was applied. Multilooking involves averaging neighboring pixels within a defined window to reduce the noise and improve the signal-to-noise ratio**.**

Interferograms often contain noise that can obscure the desired phase information related to ground motion or deformation. To enhance the visibility of the desired information and suppress unwanted noise, the Goldstein filter, a widely used phase filtering technique, was applied.

By incorporating multilooking and phase filtering techniques, the SAR data were processed to obtain smoother images with reduced speckle noise, as well as filtered interferograms with enhanced visibility of the desired phase information. These improved data sets formed the basis for subsequent analysis, such as phase unwrapping and accurate measurement of ground motion or deformation patterns.

4.2.4 Phase Unwrapping

Phase unwrapping is a critical step in the analysis of DInSAR data, allowing for the accurate measurement and interpretation of ground motion or deformation. For this project, SNAPHU method, a widely used and efficient algorithm for phase unwrapping was utilized. The SNAPHU (Statistical-cost Network Approach to Phase Unwrapping) method is based on a statistical-cost network optimization framework. It leverages the relationships between neighboring pixels in the interferogram to determine the unwrapped phase values. By applying the SNAPHU method to the interferograms, it effectively resolved the phase ambiguities and obtained a continuous representation of the phase differences.

4.2.5 Phase to Displacement

After phase unwrapping, the unwrapped phase values obtained from the interferograms need to be converted into meaningful displacement measurements. This process, known as phase to displacement conversion, allows for the analysis of ground motion or deformation.

The formula for phase to displacement conversion is given by equation 8;

$$D = (\lambda * \Phi) / (4\pi * B) \qquad \text{Equation (8)}$$

Where D represents the displacement,

λ is the wavelength of the radar signal,

Φ is the unwrapped phase and B is the baseline distance.

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By incorporating the phase to displacement conversion into the processing workflow, the unwrapped phase values obtained from the interferograms was successfully converted into meaningful displacement measurements. This enabled a comprehensive understanding of the ground motion or deformation processes occurring within the study area.

4.2.6 Terrain Correction

Terrain correction involves adjusting the orientation of the acquired SAR data to align with a common geographic reference system, allowing for accurate measurement and analysis of ground motion or deformation.

The original SAR data is acquired with a sensor-oriented coordinate system, which may not align with a standard geographic reference system. To address this misalignment, terrain correction was applied to reorient the data to a consistent geographic coordinate system.

The terrain correction process involved geocoding and geolocation of the SAR data. Geocoding refers to the transformation of the sensor-oriented data to geographic coordinates, ensuring proper alignment with a standard reference system. Geolocation, on the other hand, involves assigning precise geographic coordinates to the SAR data based on accurate positioning information. The change in orientation facilitated the accurate identification and characterization of ground motion or deformation within the study area.

5.0 Results and Discussion

To monitor deformation areas within the study area, DInSAR technique was applied during various periods (i.e., from April 2022 to May 2022, from May 2022 to June 2022, and from June 2022 to July 2022). This results into generation of displacement maps and histograms, where different areas are color-coded based on their displacement values. Displacement maps (Figs. 2, 4, 6) and corresponding histograms (Figs. 3, 5, 7) illustrate the spatial distribution and magnitude of ground deformations.

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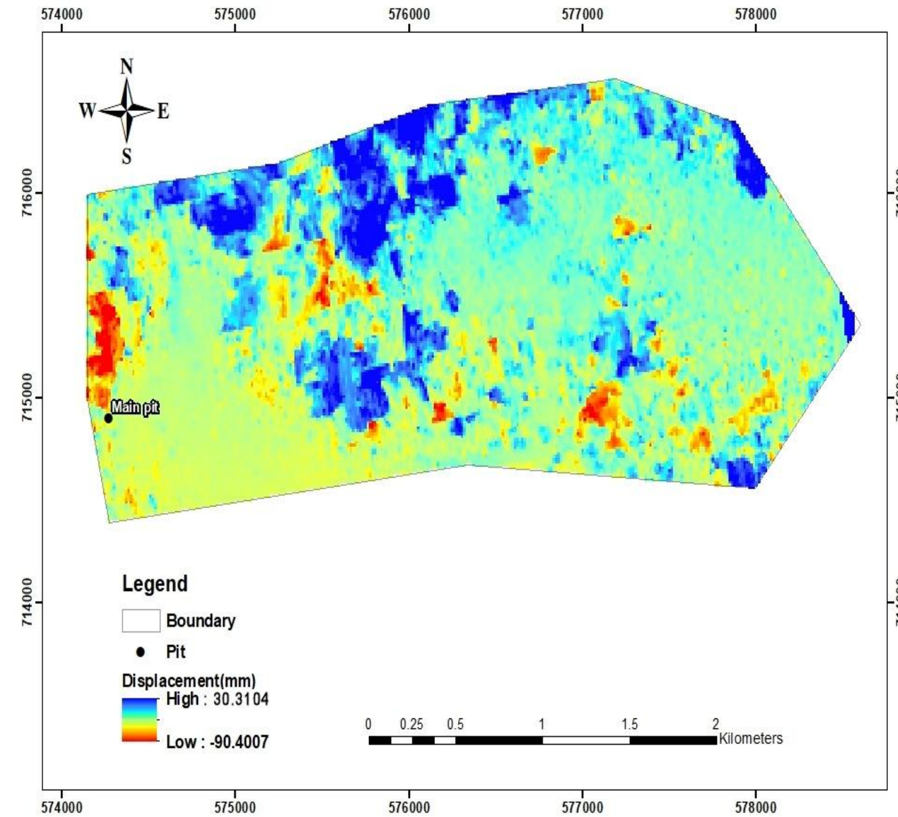

Figure 2 Displacement Map between the Months of April and May

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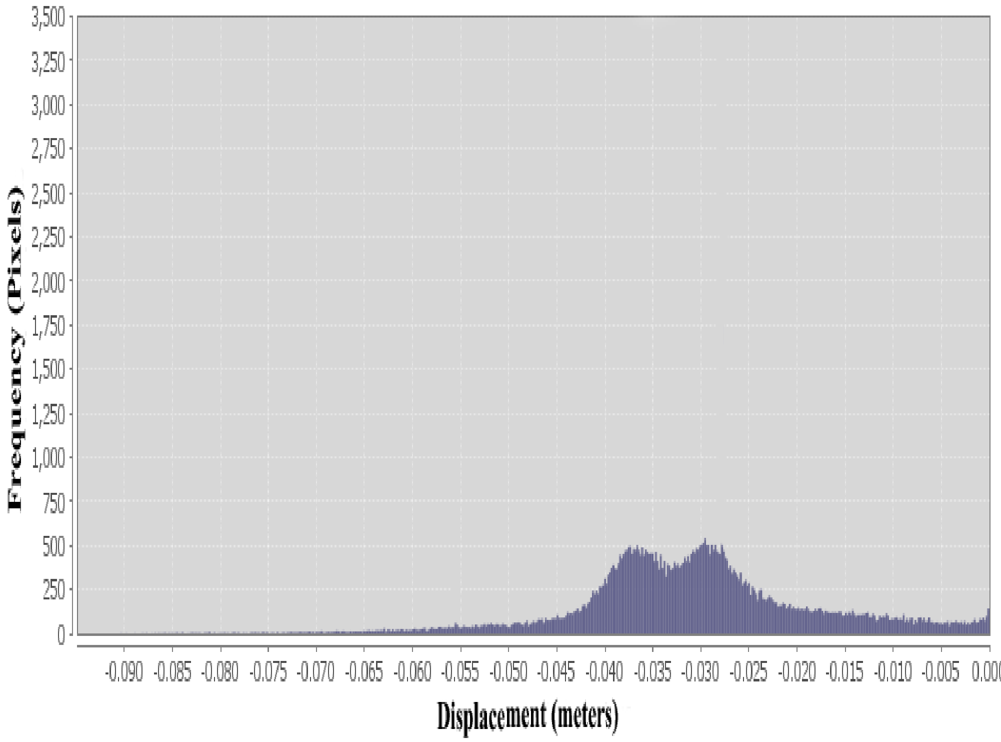

Figure 3 Histogram between the Months of April and May

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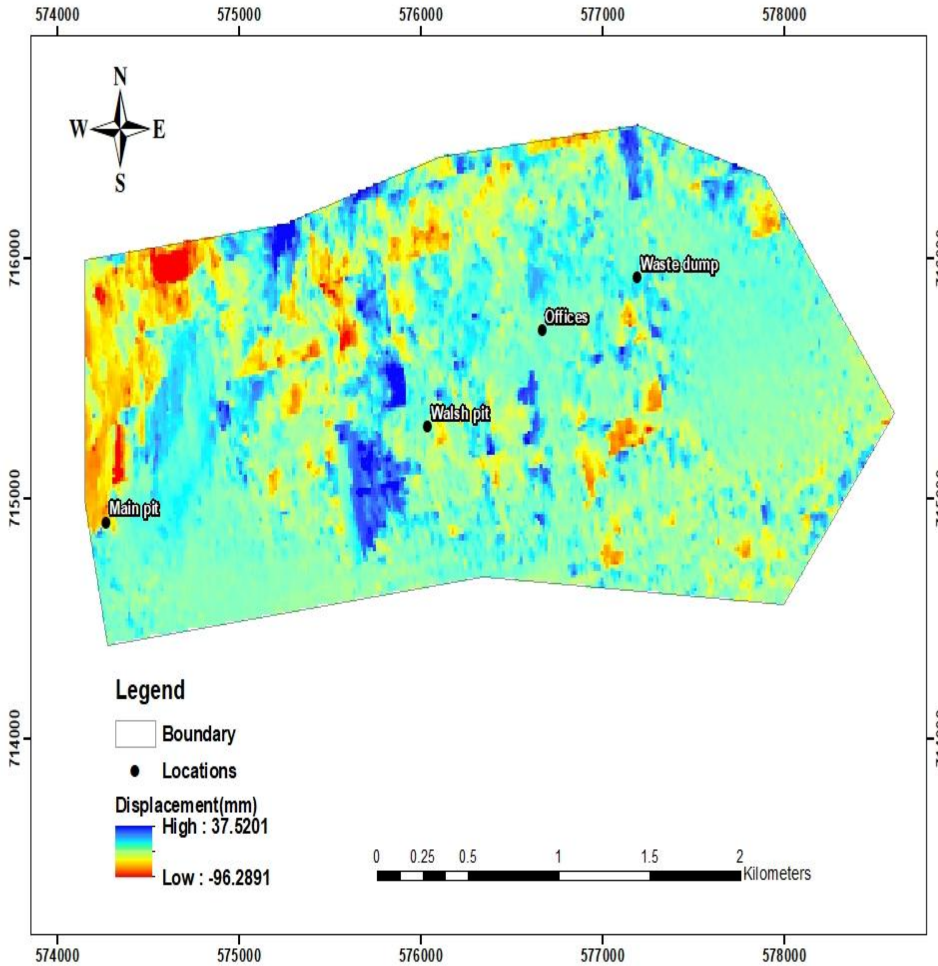

Figure 4 Displacement Map between the Months of May and June

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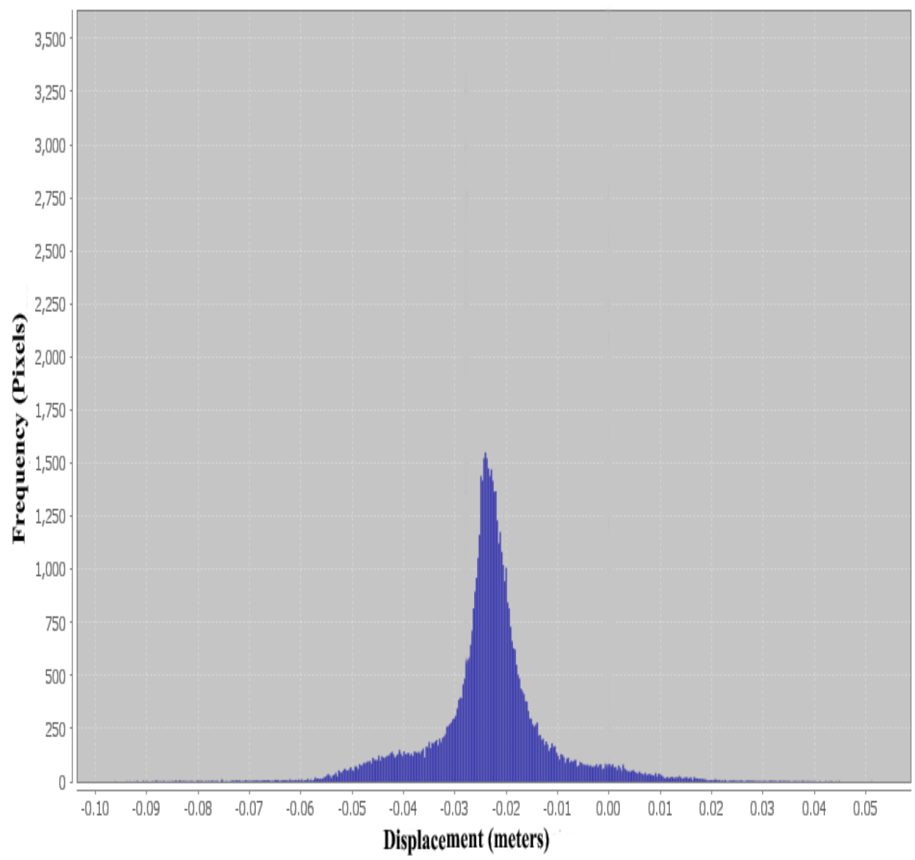

Figure 5 Histogram between the Months of May and June

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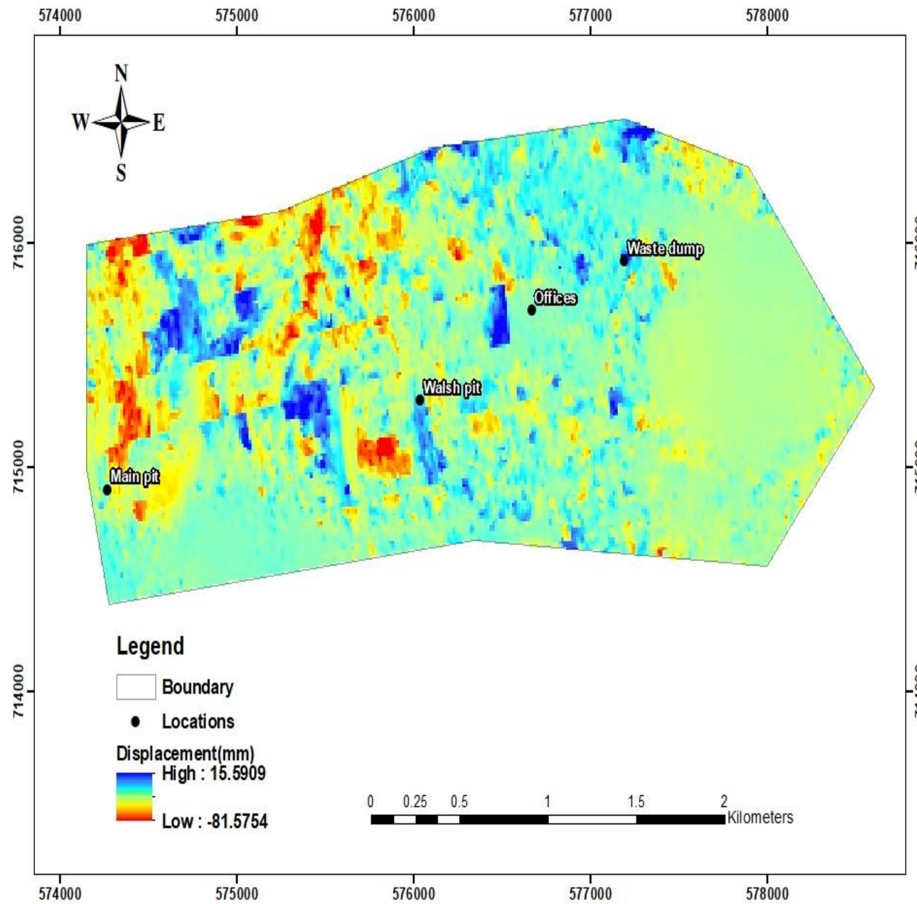

Figure 6 Displacement Map between the Months of June and July

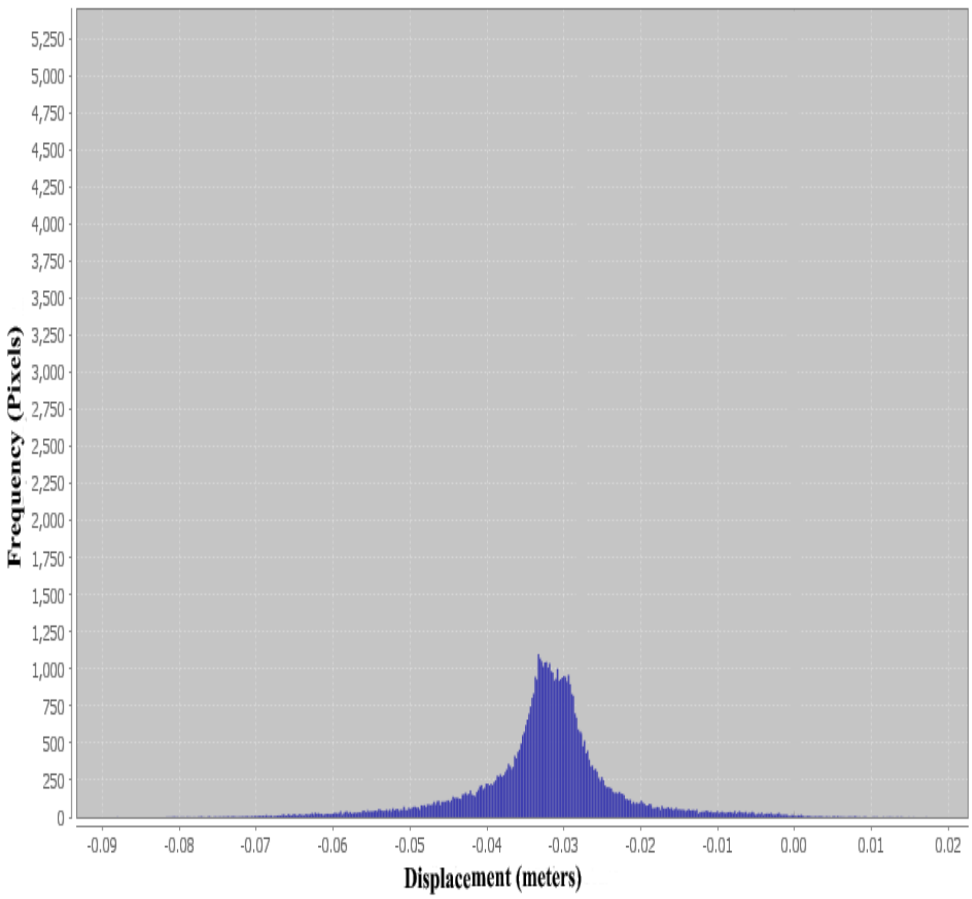

Figure 7 Histogram between the months of June and July

The displacement maps (Figures 2, 4, 6) reveal significant spatial variations in ground movement across the study area, with color-coding indicating areas of uplift (blue) and subsidence (red/yellow). Notably, the highest uplift recorded was 37.52 mm between May and June, while the most substantial subsidence occurred during the same period at -96.29 mm. Additionally, between April and May, an uplift of 30.31 mm and subsidence of -90.40 mm were observed. From June to July, the uplift was recorded at 15.59 mm, alongside subsidence of -81.58 mm. These results highlight a dynamic environment in which both uplift and subsidence occur at varying magnitudes, underscoring the necessity for continuous monitoring to ensure the stability and safety of mining operations. However, figure 3, 5, and 7 illustrate the distribution of displacement values, exhibiting a bell-shaped curve characteristic of normal distribution. Most areas within the mine experienced relatively low deformations, primarily within the range of -40 mm to -20 mm. The presence of extreme displacement values was less frequent, indicating that while significant movements do

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occur, they are localised rather than uniformly distributed across the mining area. This distribution pattern suggests variability in the response of different sections of the mine to operational activities.

Geological factors, such as rock properties and geological structures, and environmental factors, like changes in groundwater levels or weather conditions, may contribute to the observed ground deformations. Understanding these factors is crucial for developing effective mitigation strategies. The mine generally exhibits stable behavior with low deformations. However, areas with significant uplift or subsidence require close monitoring and targeted interventions to ensure ongoing stability.

6.0 Conclusions

Displacement maps and histograms for the respective months have been produced and analysed. The analysis of displacement maps and histograms provided valuable insights into ground deformations within the mine area. The results indicate that the mine area exhibits dynamic behaviour, with areas experiencing both uplift and subsidence at different magnitudes. Based on the findings, it can be concluded that most areas within the mine experience relatively low deformations. The authors recommend that continuous monitoring and detailed risk assessment should be carried out to evaluate the potential hazards associated with the observed ground deformations. Moreover, future research should focus on integrating geological assessments with DInSAR data to enhance risk mitigation efforts and ensure the ongoing safety and sustainability of mining operations.

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