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Determination of Ash Dam Facility Surface Displacement Using InSAR

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Abstract - This article articulates the determination of Ash Dam Facility Surface Displacement Using InSAR at in South Africa. ADF can fail due to a variety of factors, including structural instability, seepage, or seismic activity. Therefore, using InSAR technology there is a need for threats to be identified and responded to promptly to mitigate consequences such as loss of life and property that can occur from dam failures. Interferometric Synthetic Aperture Radar (InSAR) is a powerful remote sensing technology that has proven invaluable for monitoring the stability and integrity of ash dams. The study used Vertex, which is the Alaska Satellite Facility's (ASF) data search application for remotely sensed imagery of the earth, providing convenient and powerful discovery and download of SAR data, as well as direct access to thematic datasets. ASF Data Search is an easy-to-use search tool for finding SAR data and freely processing higher level SAR products such as InSAR and Auto-RIFT products with ASF's service. The study conducted a time series analysis using Mintpy on the OpenSAR Lab server. The Mintpy toolbox is a Python 3 software for small baseline InSAR time series analysis. The input is a stack of differential interferograms that form a fully connected network. The findings were that the ash dam facility has undergone a total displacement of 200 cm vertically and 310cm laterally. The coordinates in terms of latitude and longitude of this affected area in (7145360,739280) and (7160480, 714480) respectively. In conclusion satellite remote sensing offers a cost and time effective way to monitor large infrastructure assets which would otherwise be a very resource-demanding task via conventional methods.

Key Words: Ash Dam Facility, Surface Displacement, InSAR, South Africa

1.0 Introduction

The study seeks to monitor ash dam facilities (ADF) and provide an early warning system a power generation plant. The geomatics systems monitor various data types, including water quality, structural integrity, and seepage [1]. The specific benefits of the real-time data monitoring study are aimed at improving safety, environmental compliance, and early warning of potential structural problems [2]. The project addresses the environmental concerns of coal-generation infrastructure and will contribute to assuring the safety of the ADFs.

Interferometric synthetic aperture radar (InSAR) is a radar technique used in geodesy and remote sensing which uses two or more synthetic aperture radar (SAR) images to generate maps of surface deformation or digital elevation, using differences in the phase of the waves returning to the satellite or aircraft [3]. The technique can potentially measure millimetre-scale changes in deformation over a time series [4]. It has applications in geophysical monitoring of natural hazards e.g., earthquakes, volcanoes, and landslides, and in structural/geotechnical engineering e.g., monitoring of subsidence and structural stability [4]. Civil engineering, mining, and infrastructure are activities that demand high spatiotemporal accuracy, precision, and detail in observations and measurements [5]. Satellite-borne remote sensing techniques can produce data and information of a quality that satisfies such requirements [6].

Geotechnical engineering technology and best practice have progressed significantly in the last 20 years [7]. Data capture using remote survey techniques enables discontinuity orientations and roughness to be captured in areas difficult to access [8]. Software development has progressed to a stage where numerous model scenarios can be run relatively quickly, and complex numerical 3D analysis is routinely undertaken for larger projects [9]. Unlike optical imagery, radar waves penetrate clouds and are equally effective at night [10]. InSAR compares multiple satellite radar images over time, to measure precise changes in surface displacement and can be effectively applied to monitor natural terrain or man-made surfaces [11].

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2.0 Literature Review

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3.0 Methodology

The researchers conducted a Historical displacement analysis of a three-year retrospective InSAR analysis along the ADF enables the identification of areas experiencing displacements and the establishment of ground behaviour trends. Analysing movement patterns reveals periods of stability and areas affected by acceleration in ground movement [13]. InSAR technology is favoured for its capability to provide monitoring data at all times of day or night, in all weather conditions, and particularly for wide areas with mm-scale precision as compared to other conventional methods which are laborious, costly, and sometimes unachievable [14]. Obtaining settlement data through in-situ conventional methods would have meant waiting several months to accumulate sufficient data [15]. Several years of historical settlement data can be obtained through InSAR allowing future trends to be predicted [14]. The existing conventional survey data over a long period can provide a valuable opportunity to validate the satellite method [16].

Vertex is the Alaska Satellite Facility's (ASF) data search application for remotely sensed imagery of the earth, providing convenient and powerful discovery and download of SAR data, as well as direct access to thematic datasets [17]. ASF Data Search is an easy-to-use search tool for finding SAR data and freely processing higher level SAR products such as InSAR and Auto-RIFT products with ASF's HyP3 service [16]. The ASF DAAC offers three ways for you to search and download data: on the web through Vertex, programmatically through the Python Search Module/Mintpy, and via ASF’s well-known Search Application Programming Interface [18]. ASF is also available through Earth data Search.

We conducted a time series analysis using Mintpy on the OpenSAR Lab server. The Mintpy toolbox is a Python 3 software for small baseline InSAR time series analysis [19]. The input is a stack of differential interferograms that form a fully connected network. Interferograms must be already unwrapped with small geometric perpendicular and temporal baselines for maximizing their quality [20]. For modern SAR constellations with small orbital tube and short revisit time, such as Sentinel-1, a fully connected network of interferograms can easily be formed [21] (Bonano et al., 2024). The input stack can be generated using, among other tools, the Interferometric SAR Scientific Computing Environment (ISCE) [22]. The main steps of the interferometric processing performed by ISCE are orbit correction, de-burst, co-registration, interferogram generation and adaptive filtering, subtraction of topographic phase using given Digital Elevation Model (DEM), and 2D (space) unwrapping [23].

The Mintpy toolbox consists of three main processing steps: (a) the raw interferometric phase time series calculation; (b) the correction of the raw phase time series from error sources; and (c) the noise evaluation step that

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results in the exclusion of noise SAR acquisitions and the final calculation of noise-reduced displacement time series [19]. Moreover, to have a quality index for the extracted deformation values, temporal coherence is calculated for each pixel.

The first processing step of Mintpy is the inversion of the redundant input, fully connected stack via an unbiased weighted least square estimator to acquire raw time series of interferometric phase for each date [19]. The weight information can be related to uniform behavior or no weighting, spatial coherence at pixel level, inverse of the phase variance, and nonparametric Fisher information matrix (FIM) [24]. For this study, only the inverse of the phase variance weighting was selected because, according to and for a small number of looks, the inverse of phase variance as a weighting factor gives the most robust and one of the best performances for network inversion.

The second processing step is the correction of the raw inverted phase time-series from phase error sources at the time domain. Deterministic components such as tropospheric delays, topographic residuals, and/or phase ramps are preserved after inversion and can be suppressed in the time-series domain to obtain a time series of noise-reduced displacements [25]. Moreover, a correction scheme of 2D unwrapping procedure errors with a variety of approaches is offered. The unwrapping correction method that was selected is related to the phase closure of triplets of interferograms, based on the assumption that the SAR phase field is conservative [26].

The third step is the noise evaluation of each SAR acquisition in terms of residual phase. Mintpy considers the residual phase as a combination of residual tropospheric turbulence, uncorrected ionospheric turbulence, and the remaining decorrelation noise [27]. The root mean square error of the residual phase is calculated for each SAR acquisition after a quadratic deramping over the reliable pixels that are used in the network inversion [28]. The identified noisy acquisitions are excluded, and the topographic residual and velocity estimation is performed for a second time [29]. Figure 1 to 13 shows the steps that were used to analyse displacement for the Duvha fly as dam facility.

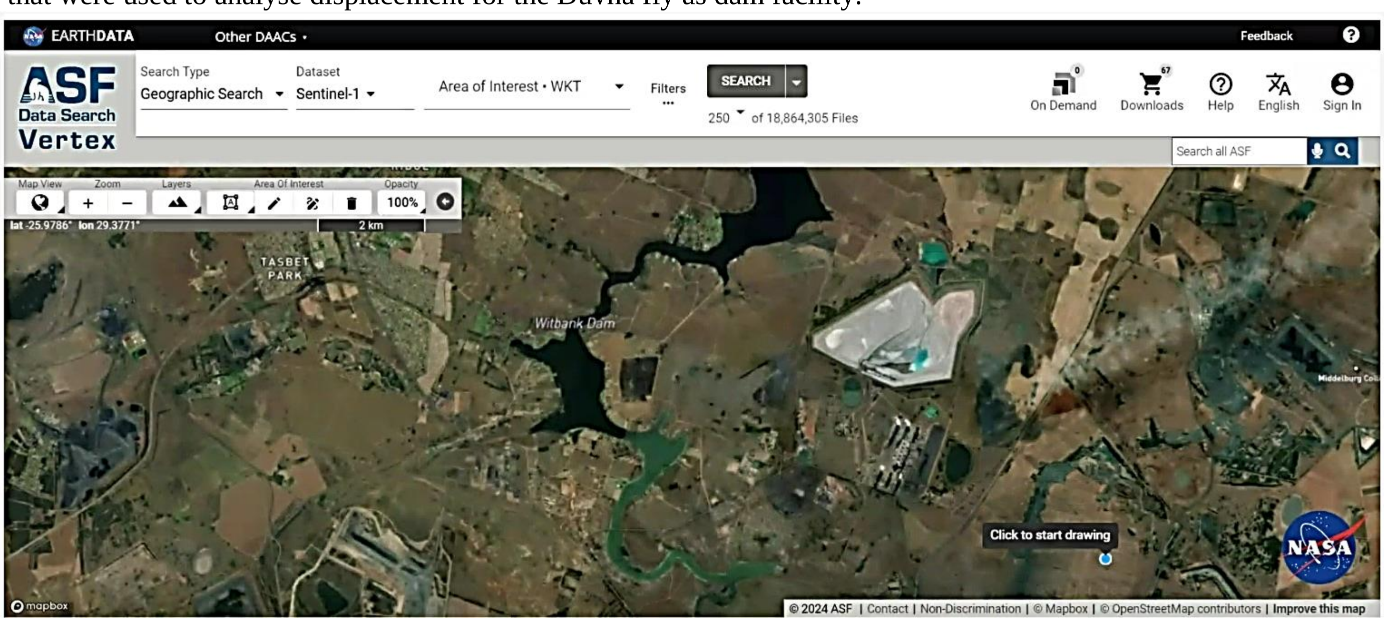

Fig.1: Data set being analysed – 1. (Source: Researchers).

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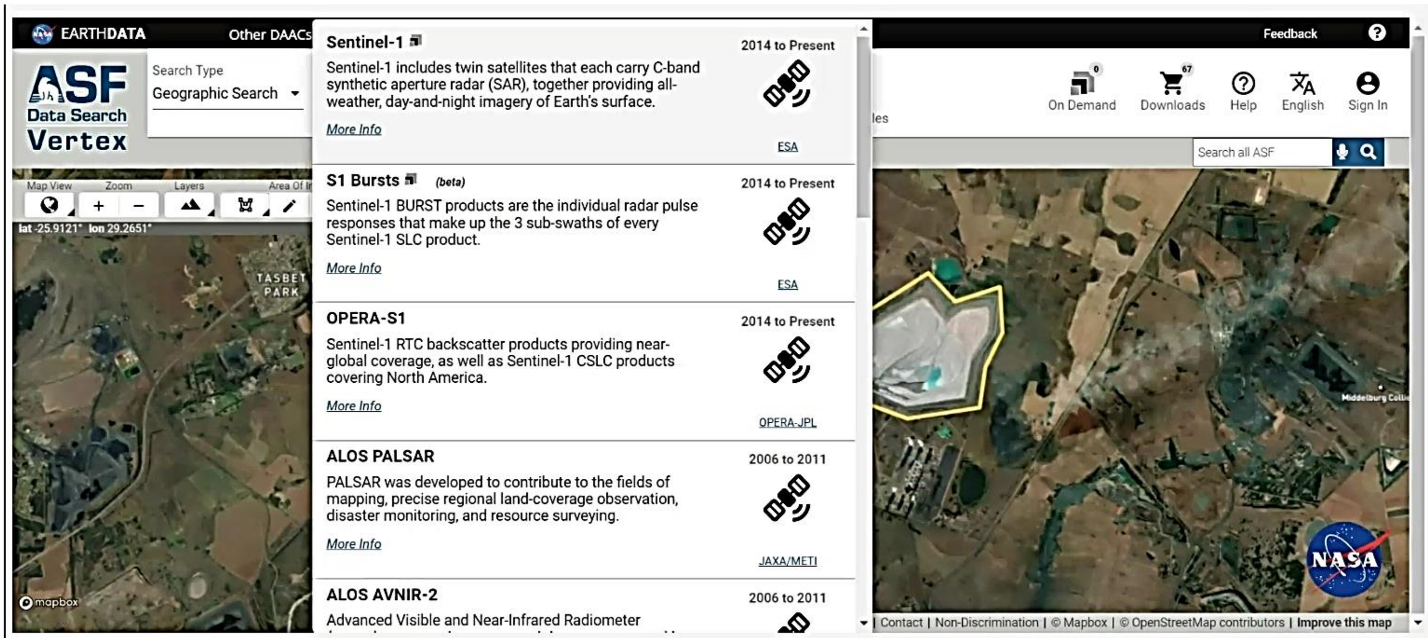

Fig.2: Data set being analysed – 2. (Source: Researchers).

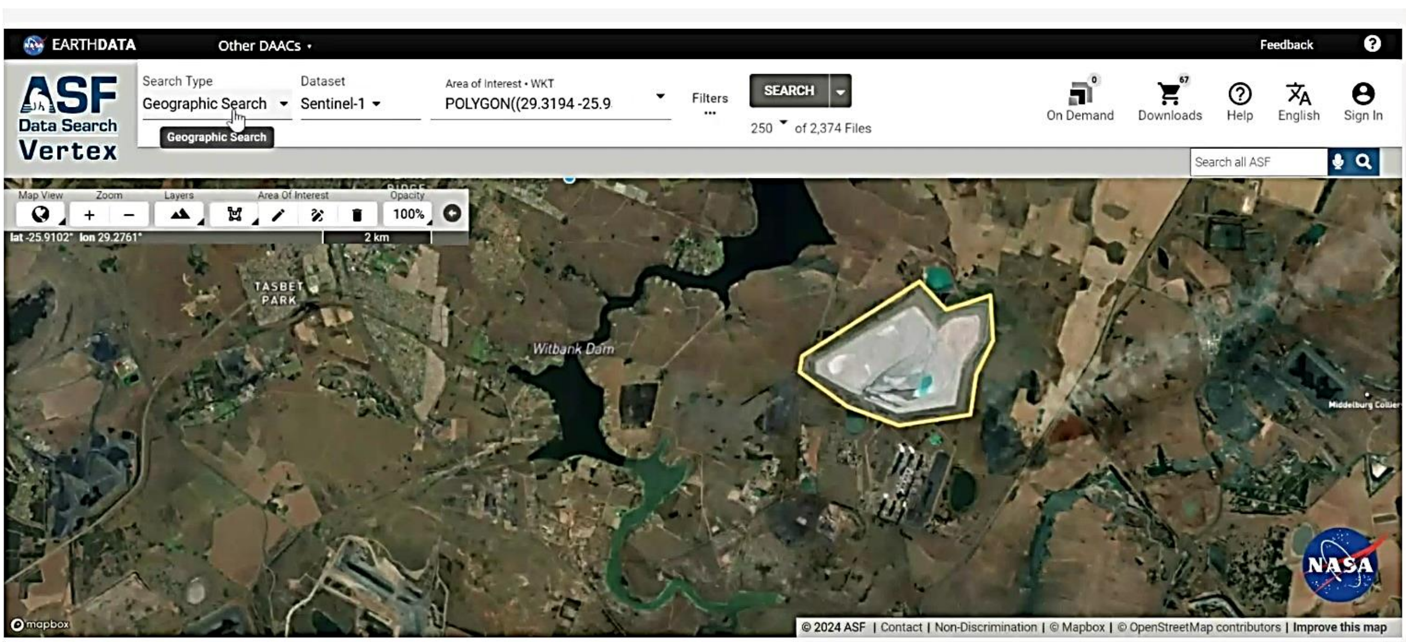

Fig.3: Drawing a polygon around the arear of interest. (Source: Researchers).

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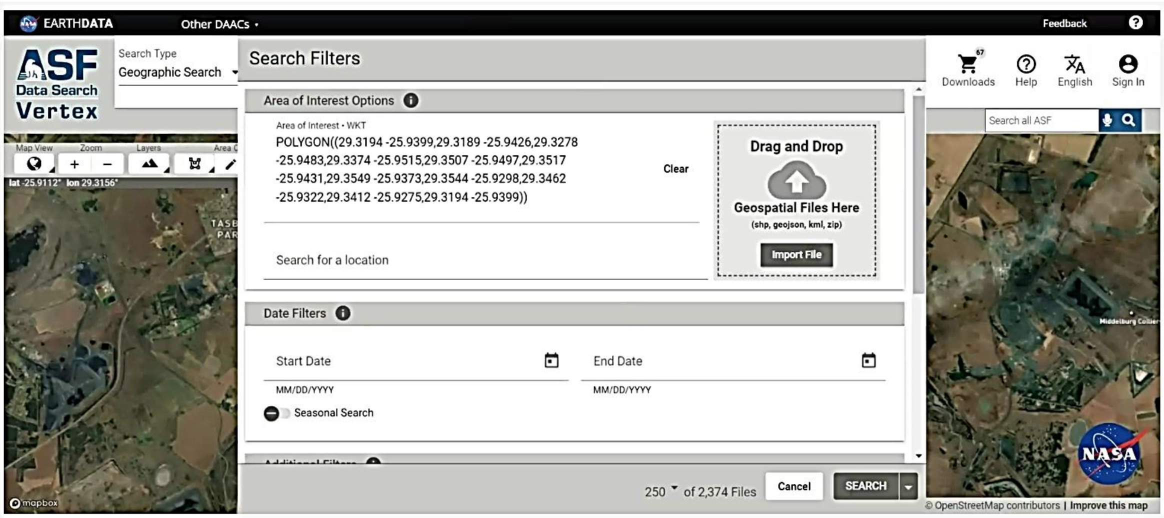

Fig.4: Filters. (Source: Researchers).

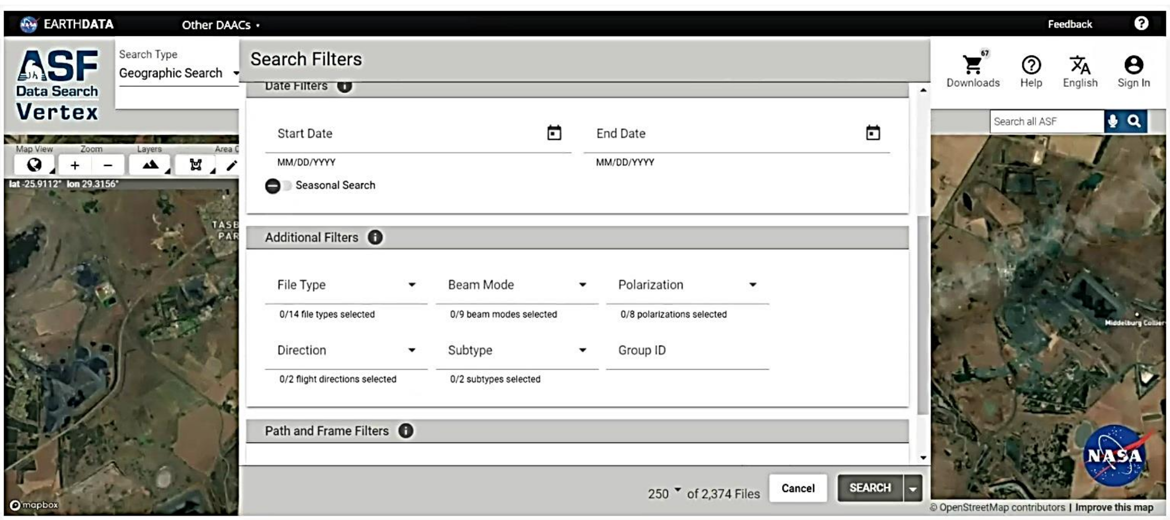

Fig.5: Three years period analysis selection. (Source: Researchers).

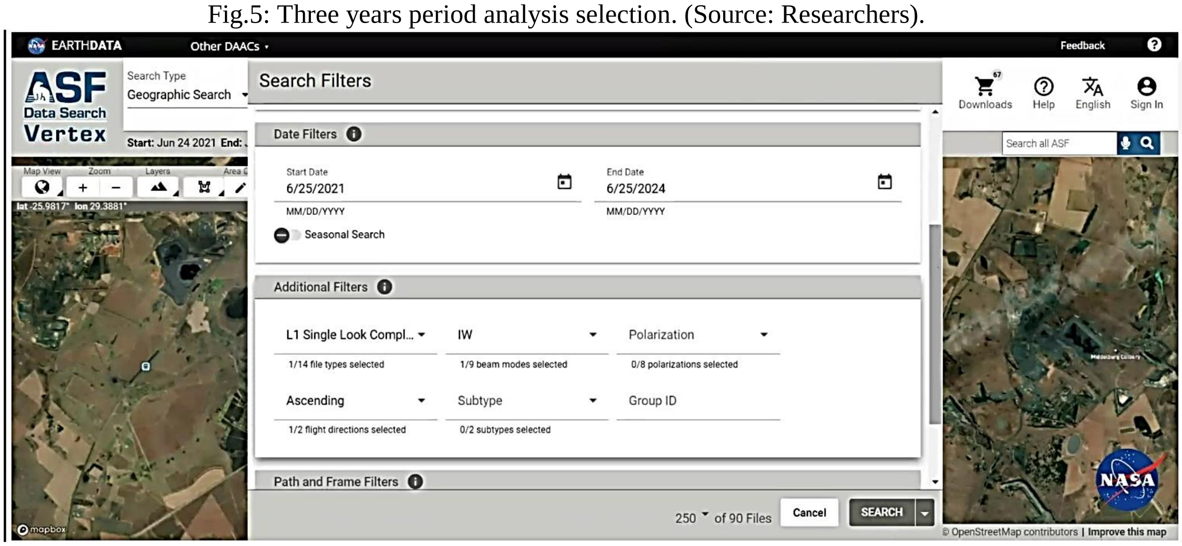

Fig.6: Selection of appropriate filter. (Source: Researchers).

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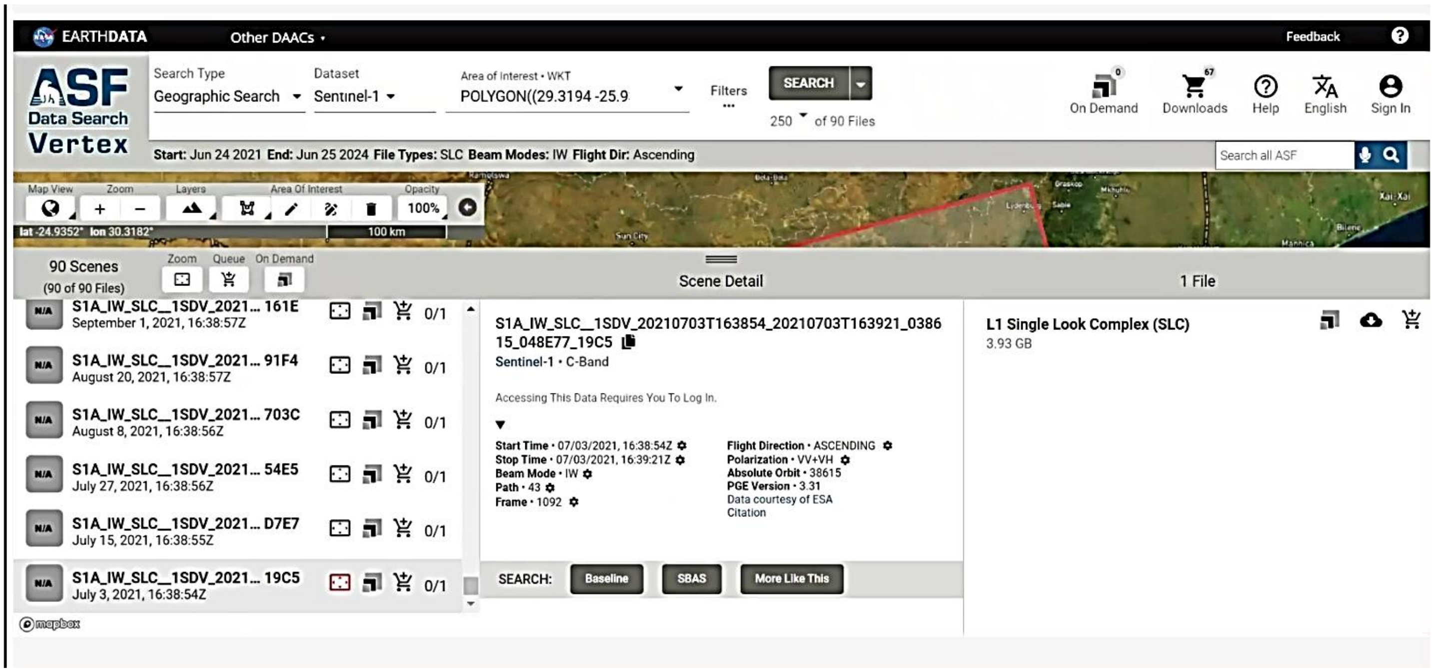

Fig.7: Scene selection. (Source: Researchers).

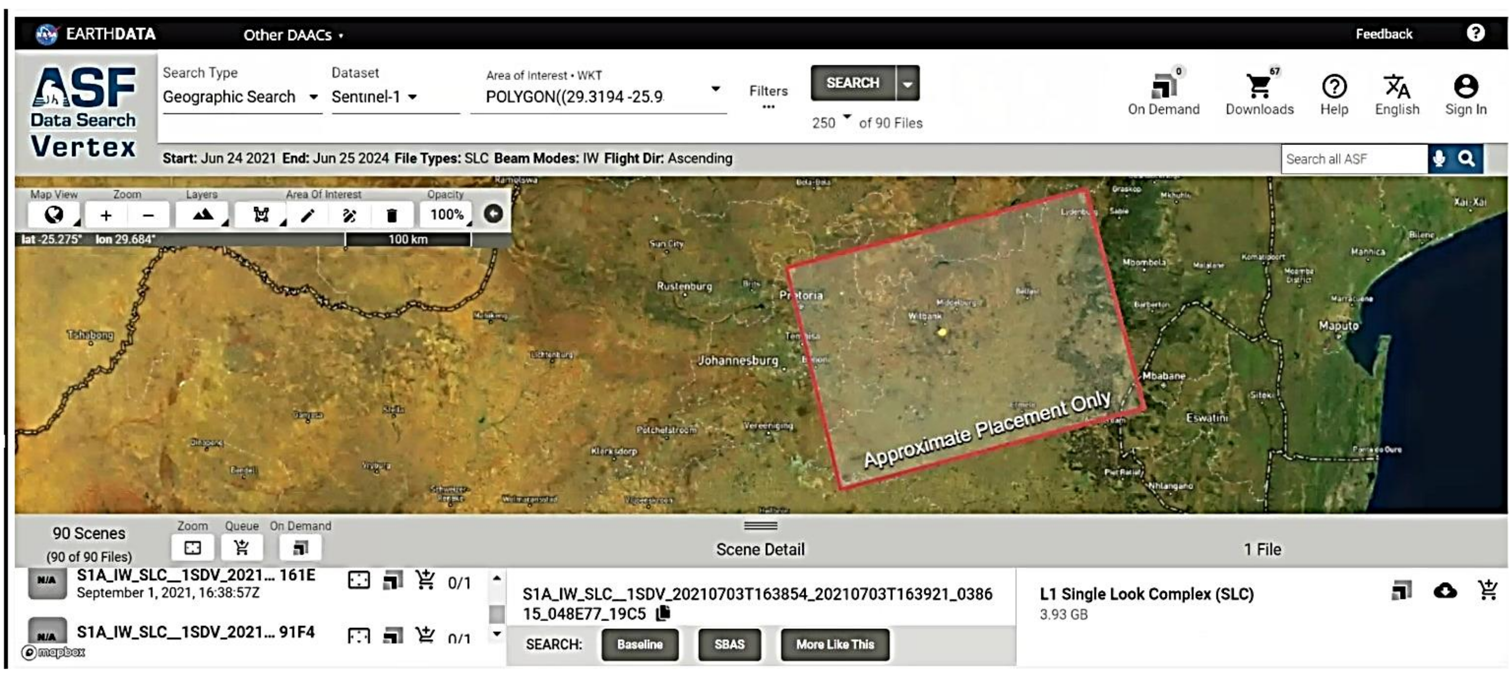

Fig.8: Approximate placement and only scene available. (Source: Researchers).

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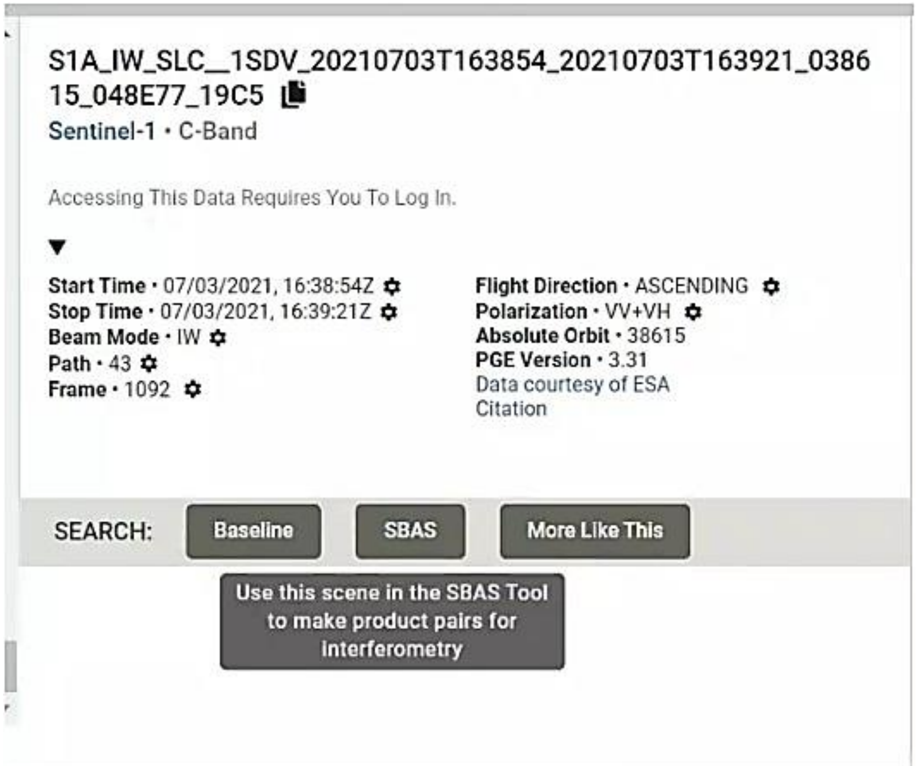

Fig.9: Short baseline subsets screen availability. (Source: Researchers).

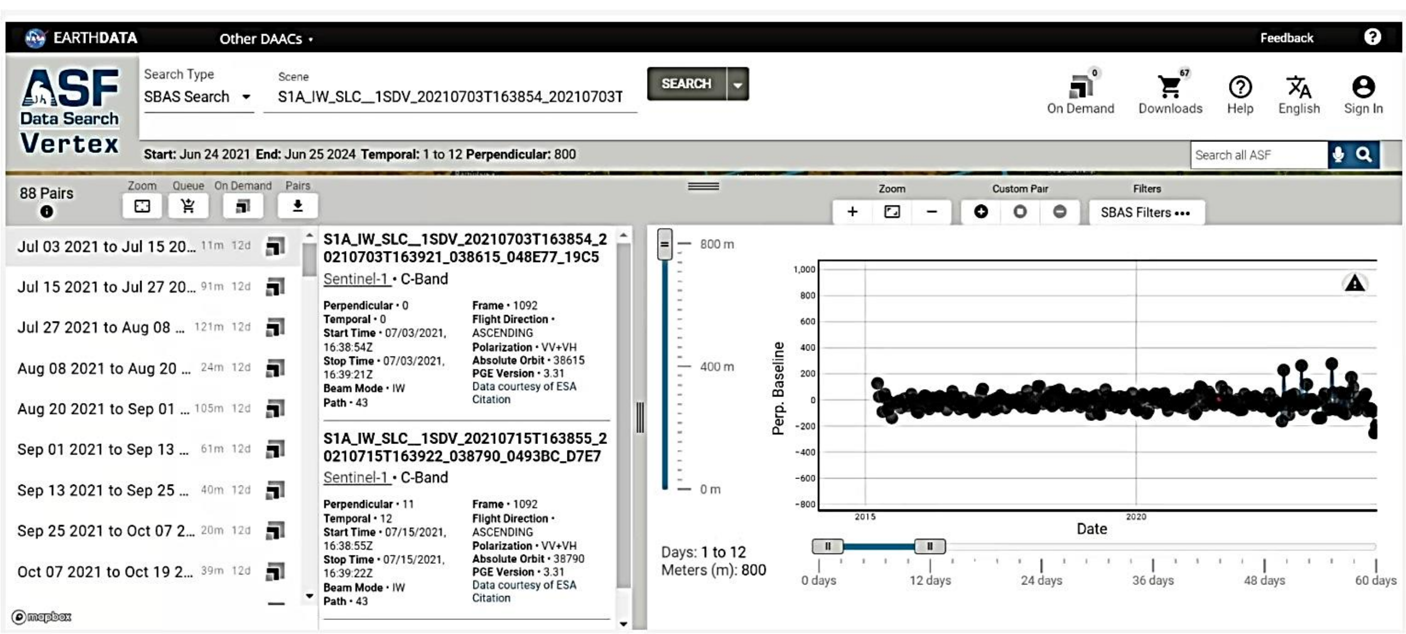

Fig.10: Short baseline perpendicular subset. (Source: Researchers).

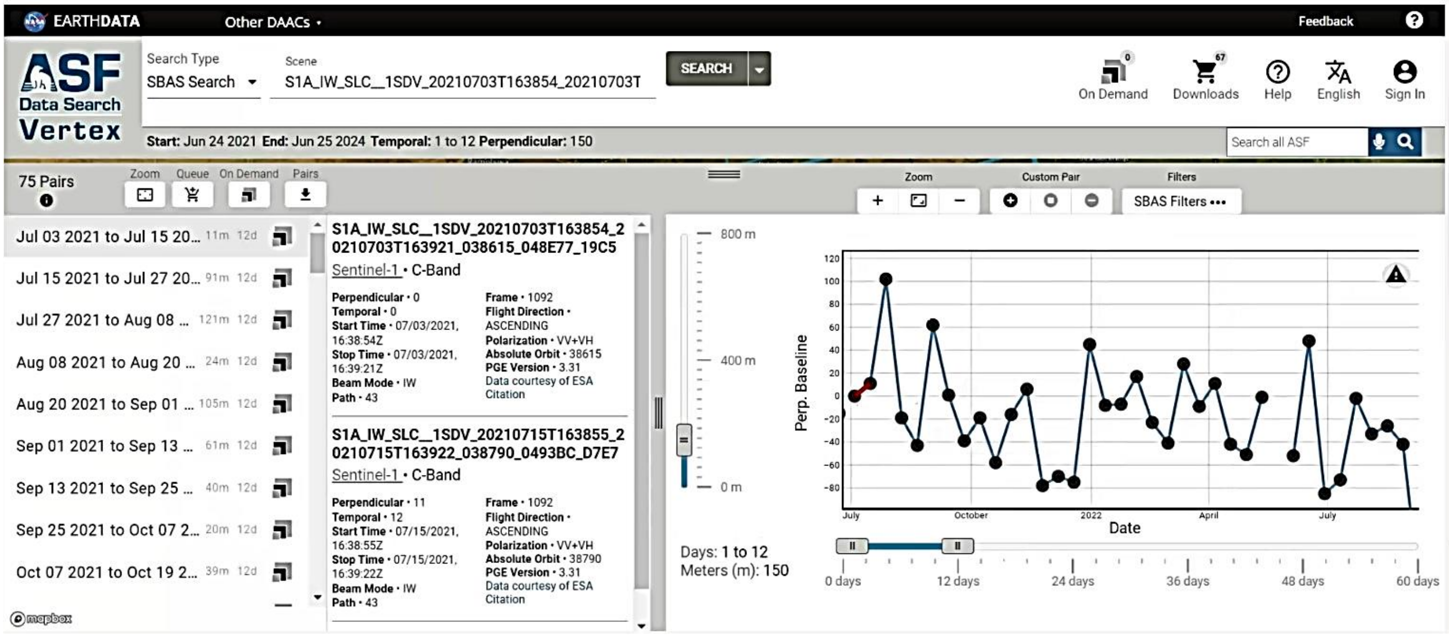

Fig.11: Short subset baseline. (Source: Researchers).

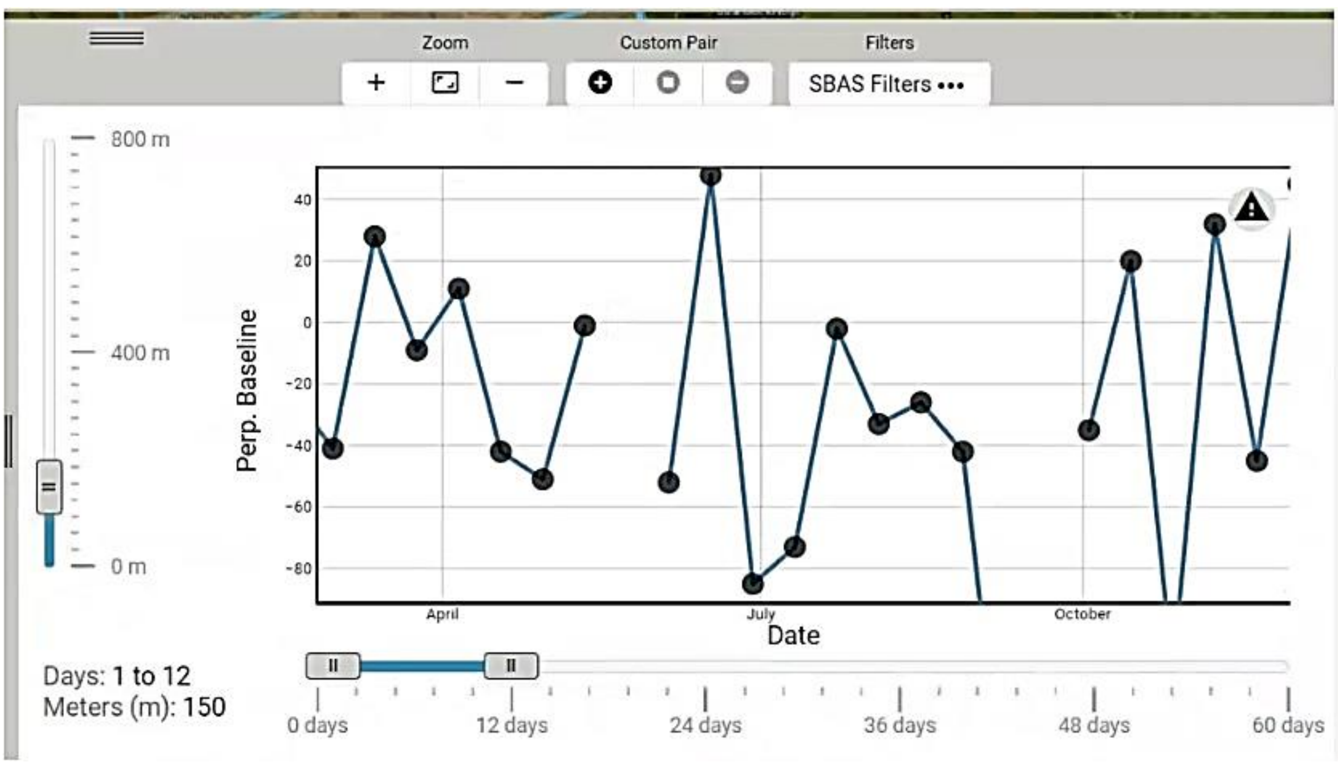

Fig.12: Custom pairs. (Source: Researchers).

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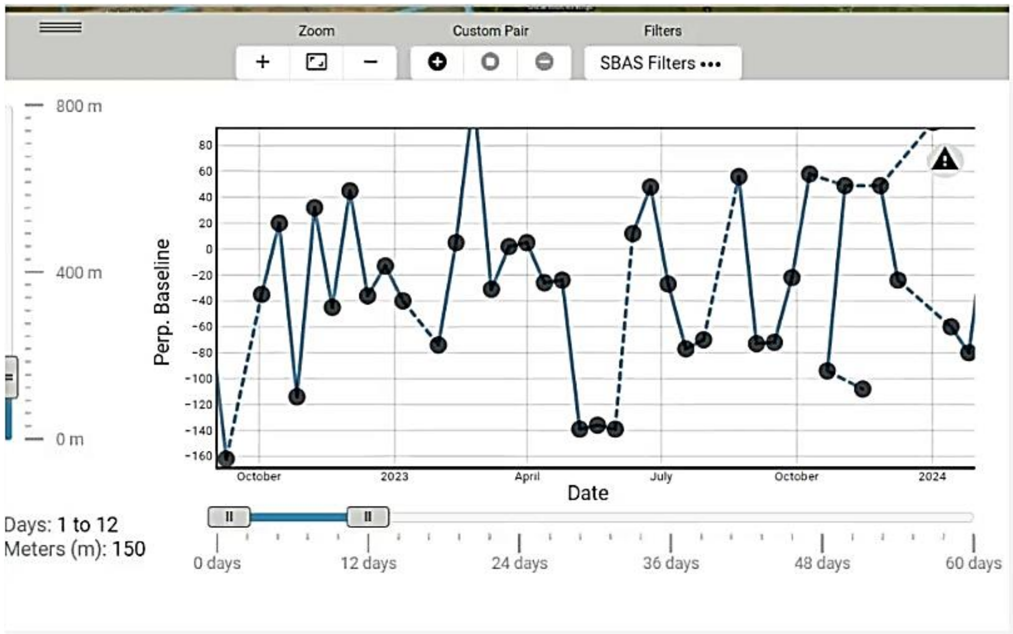

Fig.13: Joined custom pairs. (Source: Researchers).

4.0 Findings

To gauge displacement, wrapped images are uploaded to InSAR, where coherence is determined through baselines and interferograms are them analysed for errors and later displacement is determined. The same applies to moisture content analysis.

The InSAR monitoring relies on images and these images need to be wrapped. Why? Because in so doing, it allows one to effectively model large areas of interest with a high level of precision. Figure 14 shows a wrapped image of the ash dam facility.

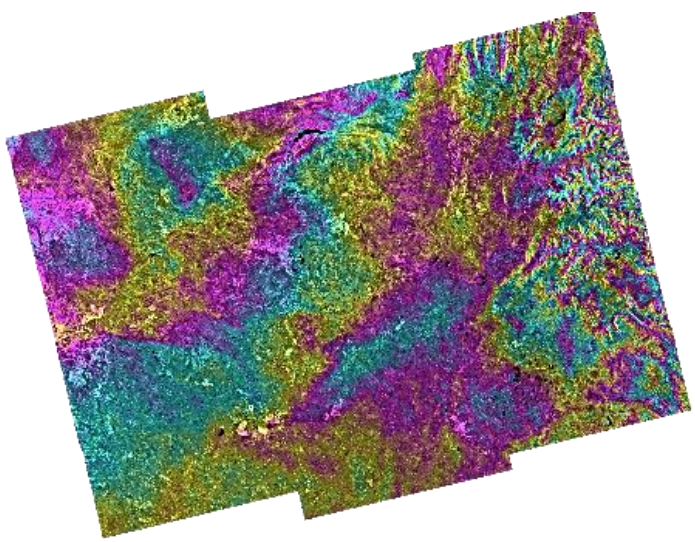

Fig.14: Wrapped images. (Source: Researchers).

Running plot_network.py gives an overview of the network (fig.15 and fig.16) and the average coherence of the stack in fig.19. The programme created multiple files as follows:

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- ifgramStack_coherence_spatialAvg.text: containing interferogram dates, average coherence temperoral and spatial baseline separation (that is fig.15). Here deformation estimation is carried out through unwrapping of the interferometric phase.
- Network.pdf: displays the network of interferograms on a time baseline coordinates, color-coded by average coherence of the interferograms (that is fig.16). Here also deformation estimation is carried out through unwrapping of the interferometric phase.
- CoherenceMatrix.pdf shows the average coherence pairs between all available pairs in the stack (that is fig. 17 and 18)

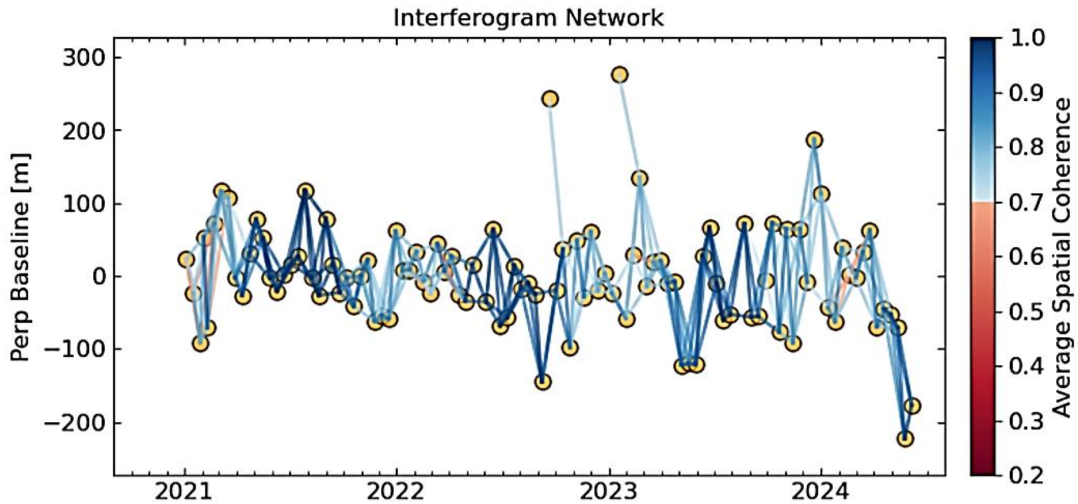

Fig.15: The comparison of the perpendicular baseline and the average spatial coherence. (Source: Researchers).

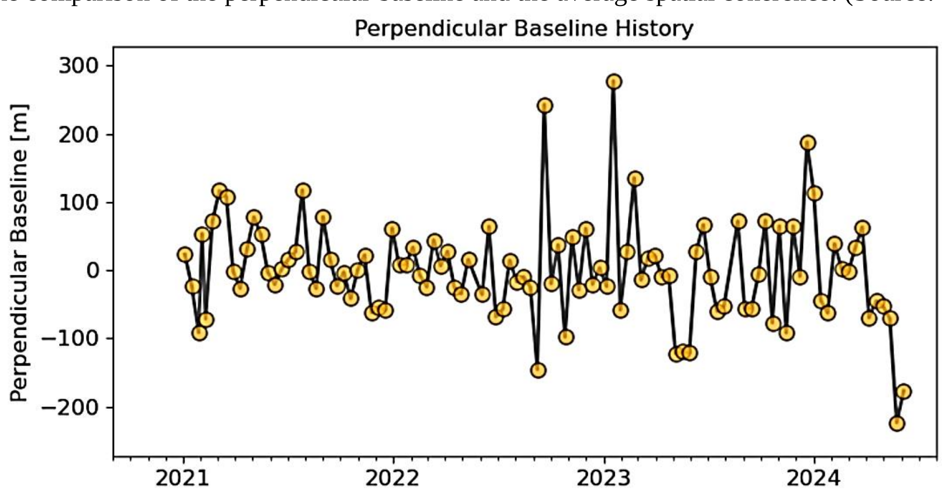

Fig.16: Perpendicular baseline history of displacement for 3 years. (Source: Researchers).

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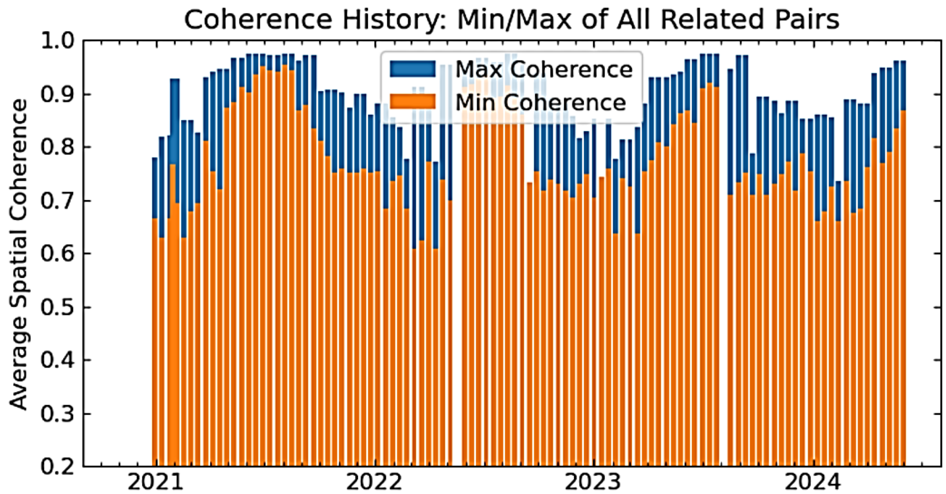

Fig.17: Coherence history. (Source: Researchers).

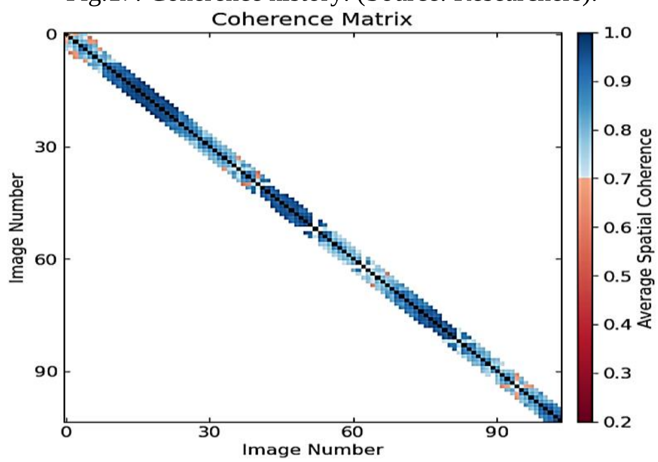

Fig.18: Coherence matrix. (Source: Researchers).

We had to examine the number of interferogram triplets with non-zero phase closure. For an interferogram triplet (DQij, DQjk and DQik) unwrapping errors will introduce a non-zero integer component Cijk int in the closure phase Cijk. therefore, the number of interferogram triplets with non-zero integer ambiguity T_{int} can be used to detect unwrapping errors.

$C^{ijk} = DQ^{ij} + DQ^{jk} - DQ^{ik}$ (1)

$C^{ijk}{}_{int} = [C^{ijk} - wrap\ (C^{ijk})]\ /2\ \pi$ (2)

$T_{int} = \sum C^{ijk}{}_{int!=0}$ (3)

Where warp is an operator to wrap to input number into [-π, π]; T is the number of interferogram triplets. Like we said before, errors must be removed, and these are through analysis and removal of unwrapped errors. In fig.19, a plot of histogram for the number of triplets with non-zero integer ambiguity is carried out and from it, the take home messages from T_{int} map and histogram are that:

1. Areas with $T_{int} > 0$ have unwrapping errors
2. The areas sharing the common positive T_{int} Value could be corrected
3. The areas with wide – distributed T_{int} values indicates random unwrapping errors which are difficult to correct so we did not correct these.

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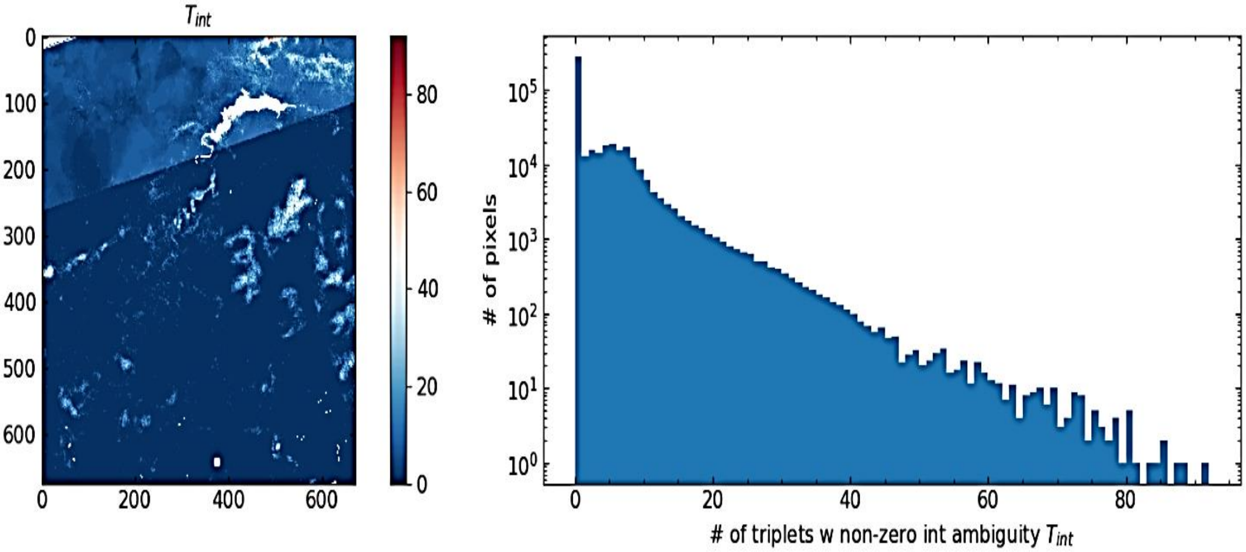

Fig.19: Histogram of zero ambiguity. (Source: Researchers).

To calculate displacement, a velocity map must be plotted. It should be noted that the min/max values in this plot must be adjusted to our earlier data set. The output of following plot that is figure 20 and figure 21 shows the data range discussed earlier in the coherence and baseline adaption. This plotting can be done once to collect information and then re – run to carry out adjustments. We updated the V_{min} and V_{max} to match our range of data. The V_{min} and V_{max} values that were assigned can also be used for additional plots. On the colour scale of this displacement/velocity maps, green denotes zero deformation while the blue denoted deformation below Zero. In the figure 20 below, the blue spots highlight the problematic area with noted displacement. Figure 21 shows that it has undergone a total displacement of 200 cm vertically and 310cm laterally. The latitude and longitude of this affected area in (7145360,739280) and (7160480, 714480) respectively.

The negative values showed areas where the ground was depressed while the positive values show areas where the ground level was elevated. On the colour scale of this displacement/velocity maps, green denotes zero deformation while the blue denoted deformation below Zero. In the figure 20 below, the blue spots highlight the areas where the highest deformation is observed. Since the deformation us negative, this implies that the moisture content in these areas is high. These areas could represent the ashing points where the deformation observed could be problematic. Fig.21 shows that it has undergone a total displacement of 200 cm vertically and 310cm laterally.

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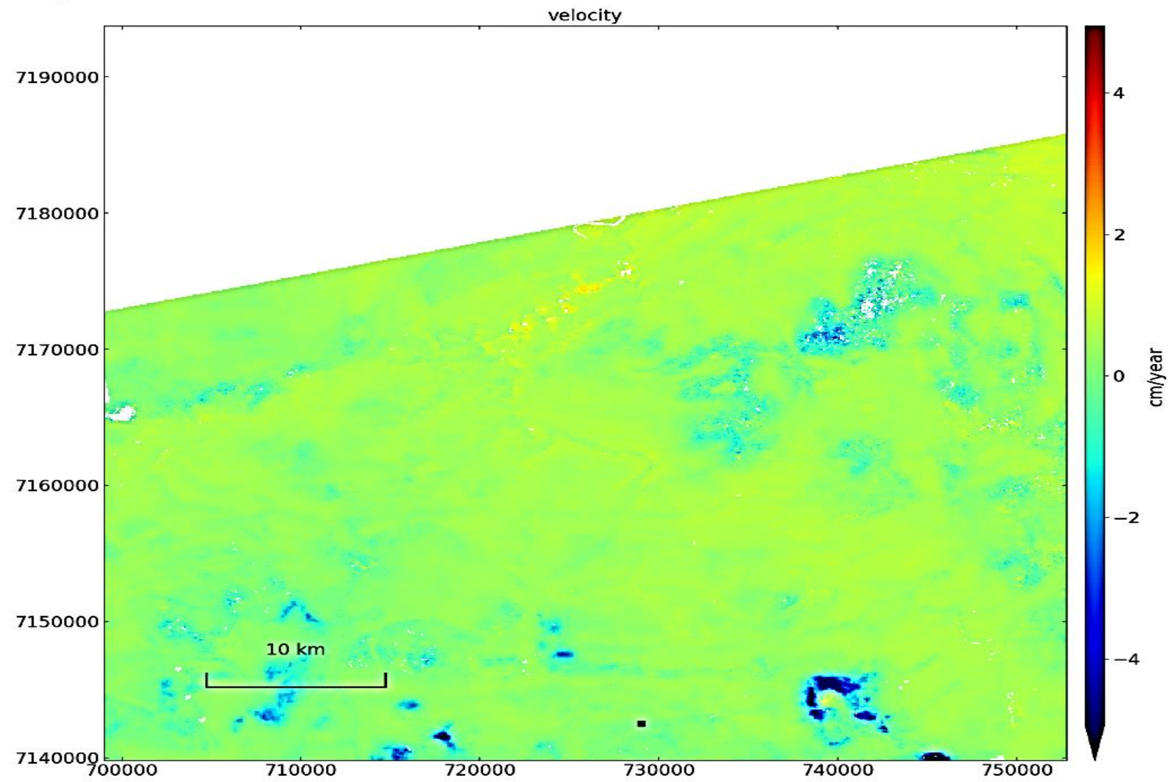

Fig. 20: Displacement/velocity map. (Source: Researchers).

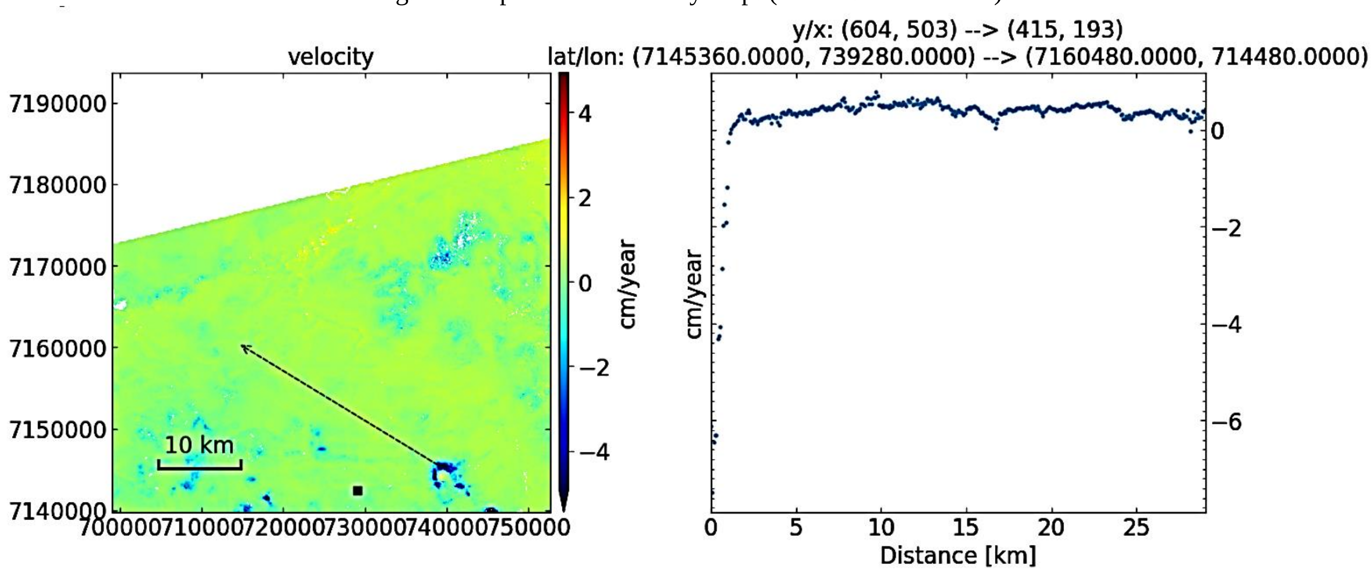

Fig.21: Zoomed in displacement map. (Source: Researchers).

5.0 Implication InSAR

- InSAR historical analysis will provide valuable insight in terms of ground behaviour trends.
- Ongoing InSAR monitoring will help monitor a power station and surrounding area in a proactive way and identify early on any deformations which are worth looking into and investigating further before they become serious and more costly.
- InSAR complements in-situ monitoring and helps to target and prioritise riskier areas. This results in better use of

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resources and reduction in carbon footprint.
- There is no need to shut down operations for monitoring, this is a remote method.
- Geotechnical interpretation of the outputs to assess the level of impact of the identified trends.
- Operators and dam safety officers can simultaneously access results using a secure web-based platform without the need to manage disparate data sources or to visit instrument locations.
- Automatic alerts can be set up in cases where ground displacement, exceed an agreed threshold, this will help identify and rectify issue early on which is always a more cost-effective approach.
- Finally, satellite remote sensing offers a cost and time effective way to monitor large infrastructure assets which would otherwise be a very resource-demanding task via conventional methods
- **Further benefits of using InSAR technology comprise:**
  -a high spatial resolution of monitoring points,
  -more accuracy than LiDAR or UAV surveys,
  -regular weekly updates possible,
  -the safest method for monitoring assets,
  -no site inaccessibility issues,
  -no fixed monitoring devices required,
  -historical modeling possible, and
  weather independent

6.0 Conclusions and recommendations

The researchers wanted to **develop a proof of concept for ash dam monitoring (geomatics) using** Interferometric Synthetic Aperture Radar (InSAR). Since this is the case, the recommendations should be limited to the proof of concept of INSAR for ash dam monitoring. However, we sought to effectively model large areas of interest with a high level of precision so that we could determine surface displacement for historical/current monitoring of the ash storage facility, identify problematic locations for further local investigation and provide effective risk management of the site and assets dependent on the calculated displacement trends. The area in figure 21 and 22 marked as blue on the velocity/displacement map that has undergone a total displacement of 200 cm vertically and 310 cm horizontally possess a risk. However, there are no infrastructures nearby and the motion might not affect large slopes. The latitude and longitude of this affected area in (7145360,739280) and (7160480, 714480), should be braced/pinned/strengthened. This needs close monitoring.

In summary:
1. There is a need to better understand the triggers of the movements, as well as accelerations due to a change in the border conditions.
2. In addition, there is need to investigate whether the triggering parameters have changed with time, to correlate the change in trend of displacements.

InSAR is a powerful remote sensing technology that has proven invaluable for monitoring the stability and integrity of ash dams. InSAR can deliver frequent, regular monitoring, allowing for early detection of any changes that could compromise the structural integrity of the ash dam. InSAR works by measuring the phase change between two radar images of the same area, allowing it to detect even millimetre-scale surface displacements. This high sensitivity makes InSAR a particularly useful tool for monitoring potential ground deformation or settling around ash dams, which could indicate structural instability.

A major advantage of this technology is that a single radar image can cover a major area of up to 100 km by 100 km or more as, for example, satellite data covers a 250 km wide swath. InSAR methodologies provide a large amount of data that are easily comparable with other classical geodesic measurements. InSAR has the advantage of effectively covering large spatial areas at low cost, a regular acquisition of measures over time, and the availability of large historical data archives to perform retrospective studies. However, this technology is yet to be adopted by the South African industry.

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