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The effect of advanced analytics on remote sensing products: improving user experience and mitigating risk in mining operations

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Abstract

Satellite remote sensing techniques use sensors aboard satellites to provide global coverage for monitoring entire mining areas, serving as an effective tool for analysing data at both local and regional scales at a lower cost compared to traditional in situ methods. In this article we present added value products that can be used to anticipate and mitigate potential failures that could damage the environment or interrupt the mining operations.

Synthetic aperture radar sensors allow measuring surface displacement with high level of spatial detail and can be integrated with information coming from ground sensors to get a unified view of ground displacement. These sensors provide deformation measurements with millimetric precision across the mine, including waste dumps, open pits, tailings dams, and infrastructure. Different deformation phenomena such as settlement, slope instability or subsidence can affect those areas, and all of them can be monitored through interferometric synthetic aperture radar (InSAR) technology. We demonstrate how to add value by applying specific algorithms and AI to deformation time series, providing enhanced layers of insight. These include, alert systems, based on three main indicators to guide onsite personnel to inspect and analyse the areas with major risk, and optical and multispectral sensors derived data, which can be used to delimit the areas with liquid content inside the tailings storage facilities (TSF). This latter service allows estimation of the pond size by providing the percentage of the area covered by liquid and the minimum distance to all the TSF walls. Those parameters must be monitored in some countries to comply with government regulations. The advanced products support mining operations in decision-making for daily tasks and planning. Delivered at different frequencies during the monitoring period, these products can be customised to the project's needs. Along with accumulated deformation measurements, they provide valuable insights to anticipate failures, cracks, slope instabilities, and geotechnical discontinuities.

Keywords: *InSAR, satellite remote sensing, surface deformation monitoring, tailings storage facilities, mining risk mitigation*

1 Introduction

Radar sensors onboard satellites measure differences in distance (movement) between the satellite and the terrain along the line of sight (LOS). The obtained LOS measurement is the perpendicular projection of the real movement vector on the LOS direction (line connecting satellite-surface).

Today, the numerous synthetic aperture radar (SAR) satellite constellations in orbit and the upcoming launches allow for highly favourable acquisition redundancy and the ability to establish contingency plans in case of acquisition failures. InSAR is widely used for the monitoring of mining operations as it's a highly cost-effective method for continuously tracking deformations across entire mining sites. InSAR can be used

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to perform historical analyses of ground displacements or continuous monitoring programs. However, much more can be done as described hereafter.

The satellite images used to derive InSAR measurements typically cover large areas – often the entire mine site – and can offer high spatial resolution (e.g. Spotlight mode with pixel sizes of 1 × 2 m). As a result, InSAR datasets are large, increasing the demand for big data analytics to extract actionable insights efficiently.

This paper demonstrates the application of advanced analytics algorithms on top of InSAR datasets to extract reliable and relevant information that can be used by end users to increase safety across the entire operation. These algorithms provide a clear understanding of ground behaviour enabling timely mitigative actions to prevent potential failures.

In addition to the advanced analytics, the paper also presents other remote sensing services and illustrates how integrating them with InSAR datasets enhances the overall effectiveness of a monitoring program. Together, these technologies facilitate more efficient decision-making and risk mitigation in mining operations.

2 Methodology and materials

2.1 InSAR principle

InSAR uses images taken by SAR satellites to obtain ground deformation measurements (Bamler & Hartl 1998). It is a non-invasive surveying remote sensing technique which allows users to measure millimetric motion of terrain and structures over wide areas in both urban and non-urban environments. Moreover, the large size of satellite images provides detailed information about areas outside the traditional area of investigation. For any point, satellite time series enable the follow-up of phenomena every few days during the monitoring period.

Optical satellites are passive sensors that measure the sunlight reflected by the Earth's ground. Otherwise, radar satellites are active sensors that send a signal to the ground and measure the backscattered signal. Therefore, a SAR image can be taken at night as well as through heavy cloud coverage.

InSAR comes with no (or extremely limited) installation costs (just when installing artificial corner reflector), minimal health, and safety risks and it maintains a similar monitoring accuracy to other manual systems. The use of InSAR techniques provides huge cost savings whilst maintaining most of the technical/design requirements, since in terms of technical capabilities InSAR is strictly comparable with precise levelling. However, precise levelling is carried out in one specific area and will only provide information in that area, InSAR provides a higher density of measurement points in a wider area, covering the entire asset being monitored.

2.2 Acquisition geometry

SAR satellites have a side-looking antenna and travel from north to south (descending orbit) and from south to north (ascending orbit) around the Earth, and pass over the same locations at approximately the same local time on each orbit. In general, an arbitrary motion will present a different measure when monitored using ascending or descending orbits. However, in the case of a pure vertical movement, it will be equally measured from the two orbits. When a movement has a horizontal component and the terrain is not flat, different magnitudes will be measured by each point of view. Terrain conditions are also a key factor to understand the obtained measurements from both orbits.

Vertical and horizontal components of the deformation vector can be obtained by processing both geometries and applying a decomposition algorithm. It is important to note that real deformation movements perpendicular to the LOS, those happening on the north–south direction, are not measured with precision due to a lack of sensibility to the movement. This is caused by the fact that satellites orbit the Earth in near-pole orbits and operate in a side-looking configuration. Hence, the obtained horizontal component is related only to movements in the east–west direction. Figure 1 shows the equations system that has to be solved to obtain the deformation components.

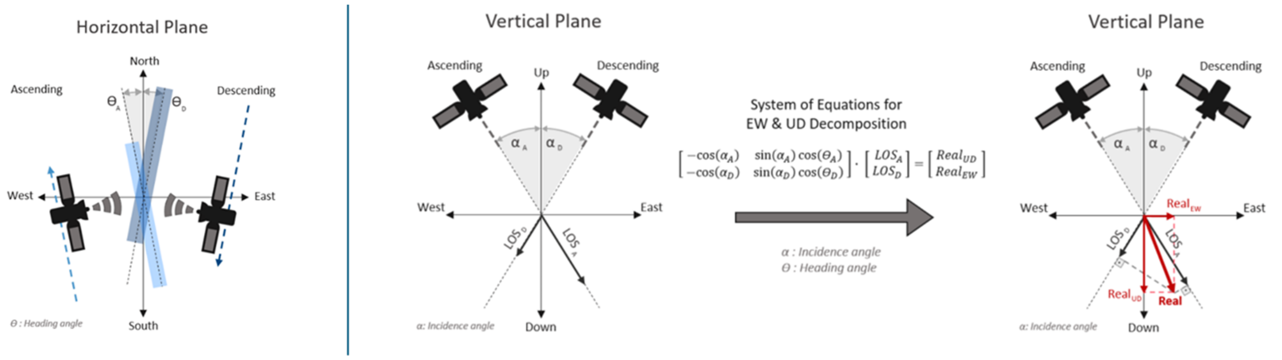


Figure 1 Schema of movement decomposition to obtain the vertical and horizontal components of the deformation

2.3 Advanced analytics

The application of advanced analytic algorithms on top of InSAR datasets is very important and becoming more popular as it helps the end user to understand, manage and extract actionable information from large InSAR datasets.

2.3.1 InSAR deformation alerts

An advanced analytics solution for monitoring and analysing ground deformation trends using InSAR time series has been developed. The solution is based on the obtention of three key indicators that can be used as an alert system, allowing for reduction in operational costs and risks, and anticipation of geotechnical events. The three indicators that are presented below to derive deformation alerts are computed using the modulus of the deformation. The modulus has proven to be the most convenient value for computing the indicators as it highlights all the areas with deformation regardless the direction, being adequate to trigger deformation alerts from InSAR time series. The mathematical expression of the modulus (M) is:

$$M = \sqrt{V^2 + H^2} \tag{1}$$

where V and H are the vertical and horizontal components of the deformation vector.

The three indicators have different and specific objectives. In one hand, the trend change indicator highlights areas with an increase of linear velocity in the latest measurement period and points out the activation of displacement processes (Figure 2a). Thus, it detects changes in deformation patterns, identifying those points transitioning from stability to upward or downward movement. The period under analysis is defined case by case, in function of the delivery frequency and project needs, with a minimum of four acquisitions per subperiod to ensure a proper fit.

On the other hand, the acceleration indicator highlights those measurement points where the time series of deformation has experienced an acceleration during latest acquisitions (Figure 2b). It is based on a second-order regression over the latest samples of the time series, assuming a uniformly accelerated displacement, always considering a minimum of four images. Finally, an inverse velocity fit is applied over those measurement points highlighted by the acceleration indicator, with the objective to forecast a potential failure date, under a purely cinematic point of view using the deformation values measured using the latest acquisitions (Figure 2c).

Finally, the use of clustering algorithms allows identification of groups of points that have the same behaviour, thus minimising the probability of false alarm, and providing alerts only when there are a significant number of points that show the same deformation pattern or trend. Artificial intelligence algorithms can be trained with this information to enhance the detection of critical areas in future monitoring.

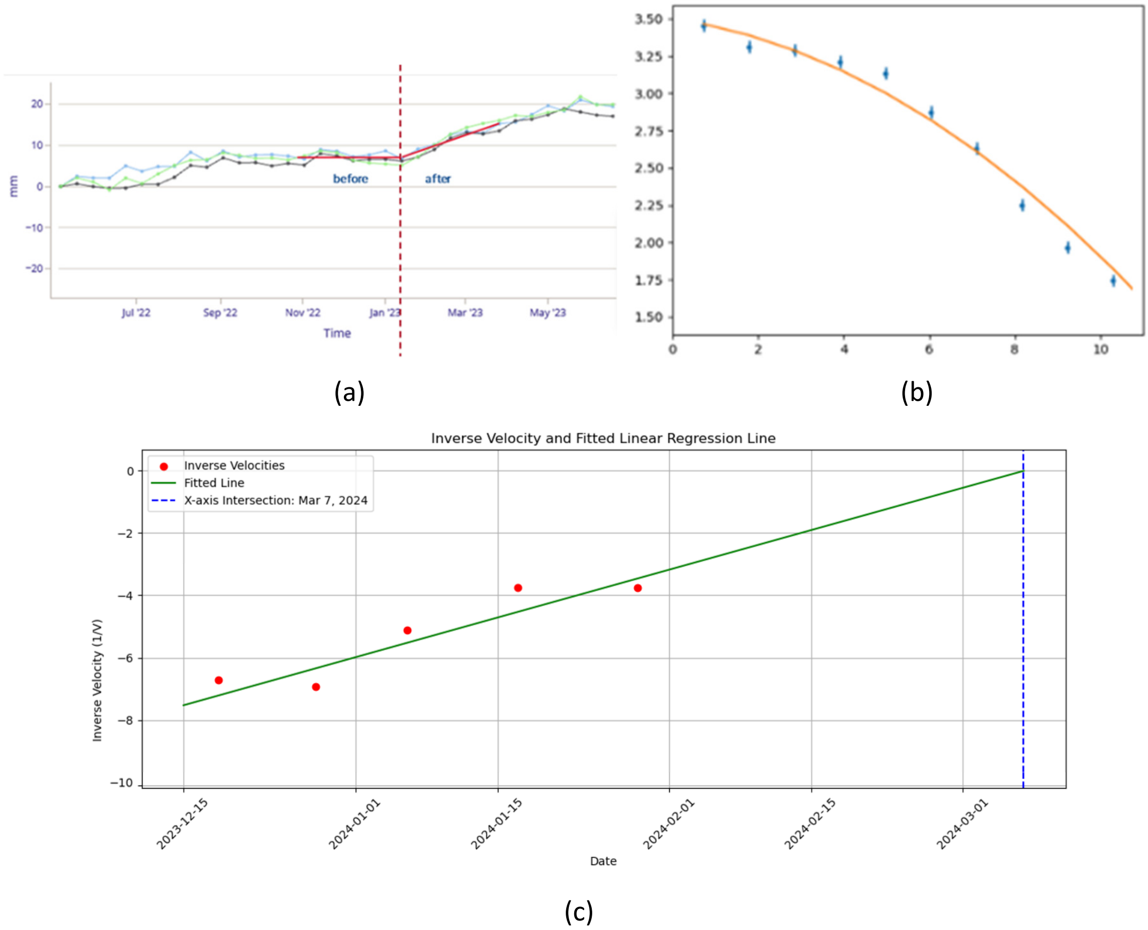


Figure 2 Indicators produced. (a) Comparison between linear fits of previous and latest monitoring period for linear trend change detection; (b) Quadratic fit for acceleration detection; (c) Linear regression over inverse velocity

2.3.2 Pond size indicator

To obtain the percentage of liquid tailing present inside a pond, firstly the perimeter of the water part on its maximum capacity needs to be known. For this, a polygon corresponding to the maximum extent has to be defined either by using a real-colour composite of an optical image, or by using data provided by the asset owner. The normalised difference water index (NDWI) can then be used to obtain the pond area.

This spectral index uses reflectance information for the green and near-infrared (NIR) bands to:

1. maximise the typical reflectance of water features by using green light wavelengths
2. minimise the low reflectance of NIR by water features
3. take advantage of the high reflectance of NIR by terrestrial vegetation and soil features.

It ranges between -1 and 1, with positive values associated with water features and zero or negative values associated with soil and terrestrial vegetation features (McFeeters 1996).

The NDWI is calculated by Equation 2:

$$NDWI = \frac{Green - NIR}{Green + NIR} \quad (2)$$

Applying a segmentation algorithm to the NDWI values, following well known threshold that allows to differentiate between water and no-water pixels, the pond mask can be obtained. Values above this threshold correspond to 'water' or liquid, and those below to 'no-water'. Once the water mask is obtained, a vector layer corresponding to this mask can be created.

Finally, the percentage of liquid tailings present in the embankment is obtained by comparing the area of the mask with the maximum extent of the TSF.

2.4 Summary of case studies

Two mining case studies are presented to show the benefits of using Atlas+ advanced analytics on InSAR datasets. In both studies, InSAR ground deformation analyses have been obtained by using Sentinel-1 mid-resolution images in ascending and descending geometries. The images were processed using Sixense in-house Atlas InSAR processing chain. Accumulated deformation maps were obtained for both geometries over persistent and distributed scatterers (Ferretti et al. 2000). With the results, vertical and horizontal components of the actual deformation vector were computed from which the modulus of the accumulated deformation was obtained to generate the alerts map.

A third case study is presented to show how the use of multispectral images can complement the InSAR results on TSFs by adding an extra layer of information that allows delimitation of the liquid content and detection of humidity. Sentinel-2 multispectral images have been used over a mining site with several TSFs to calculate the NDWI and then produce polygons indicating areas with liquid tailings. Table 1 summarises the images used, their characteristics, and the period analysed for each case study.

Table 1 Characteristics of the images used to produce the results for each case study and the period analysed

	Satellite/type	Spatial resolution	Period analysed
Case study 1	Sentinel-1/SAR	20 × 5 m	January–November 2024
Case study 2	Sentinel-1/SAR	20 × 5 m	September–December 2024
Case study 3	Sentinel-1/SAR	20 × 5 m	November 2023–December 2024
	Sentinel-2/Optical	10 × 10 m	October–December 2024

3 Results and discussion

The results from the three case studies are presented in this section, highlighting the benefits they provided to the end users.

3.1 Detection of accelerating motion on waste dumps

3.1.1 Case study 1

A high density of measurement points was retrieved along the whole mine site, allowing for a good movement characterisation.

The algorithms to produce the InSAR deformation alerts were computed using the modulus of the accumulated deformation time series, classifying the points in three alert levels: points with a linear trend change, points showing acceleration during the last acquisitions, and finally points that present a probability of collapse in the following days.

Figure 3 shows that all the eastern area of the waste dumps presents a linear trend change (Figure 3c), with a deformation velocity increase during the last period analysed. This movements can be explained by the fact that the mine activity was continuously dumping waste material which was consequently experiencing a rapid compaction. Moreover, a cluster of measurement points showing an acceleration pattern on its deformation time series has been found on the southern part (Figure 3d). Those points show a similar behaviour with deformation exceeding 30 mm of accumulated settlement during the last month, showing a significant increase on the deformation rate than the previous months.

As a result of the InSAR analysis and the alerts produced, it was easy to identify those areas at major risk and remediation plans were activated to prevent possible failures.

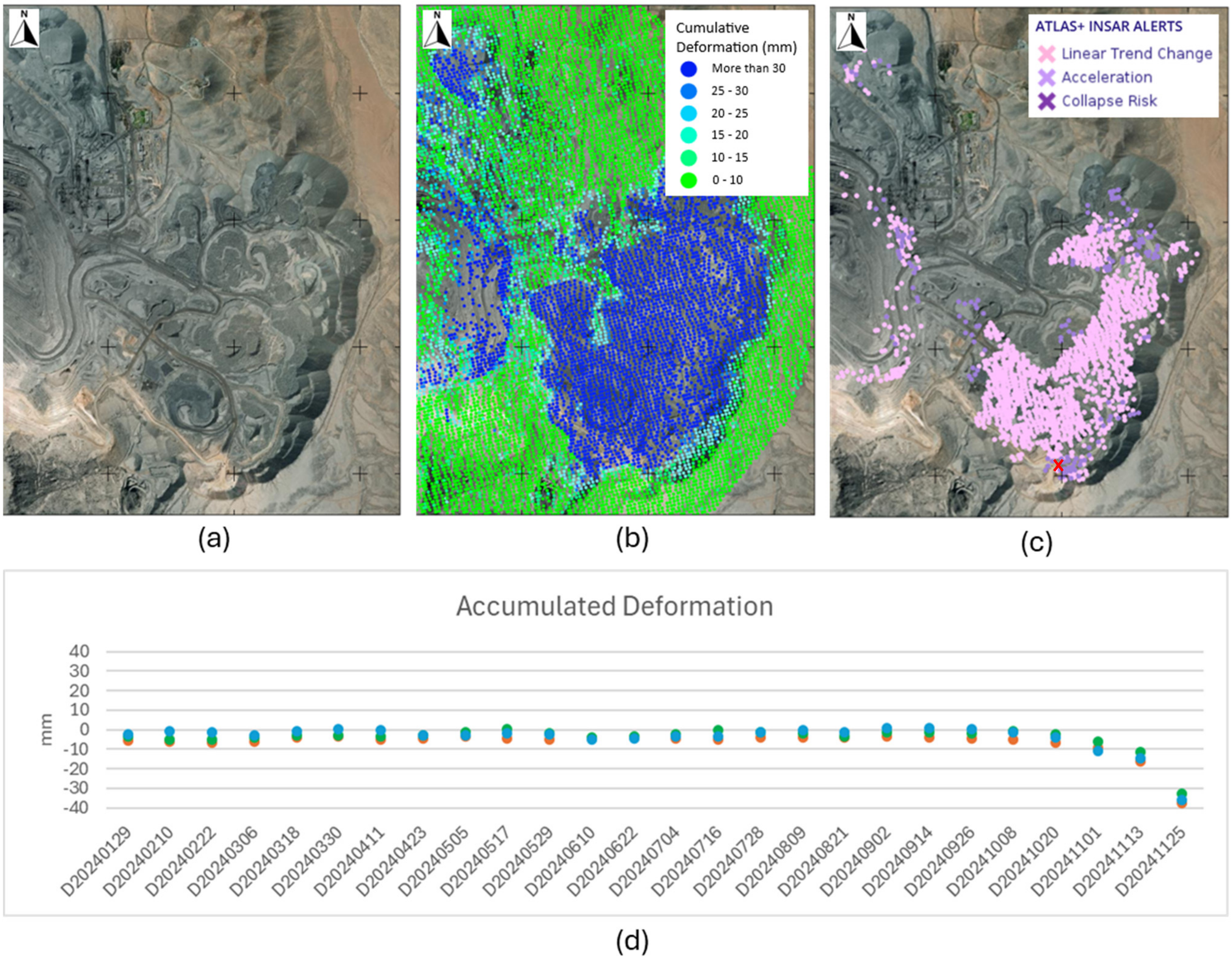


Figure 3 (a) Optical image or the area of interest; (b) Modulus of accumulated deformation; (c) Alerts map; (d) Time series of points showing acceleration during the last period analysed. The points represented here are located on the southern part of the dump area in (c), marked with a red X

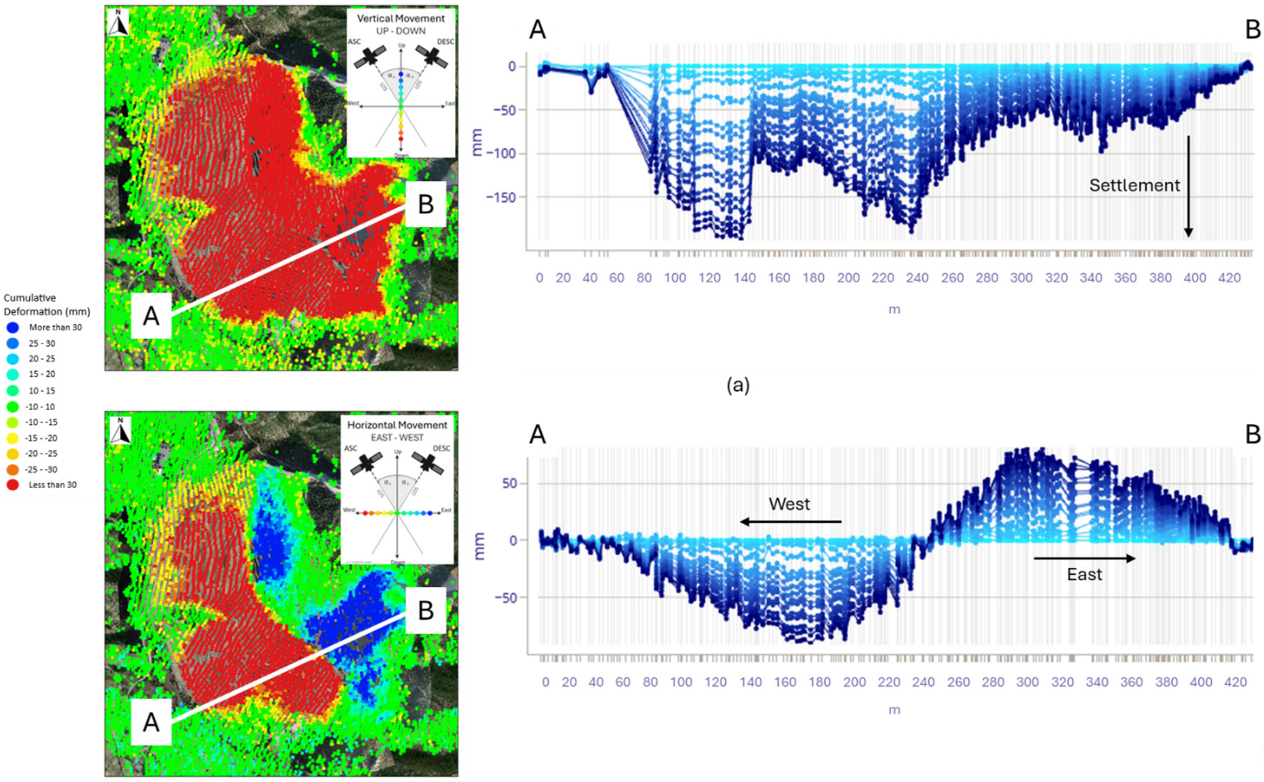
3.1.2 Case study 2

This case study presents an Atlas InSAR analysis of a large waste dump area with a geometry resembling an irregular pyramid, with two main slopes; one facing to the northeast and the other one facing southwest (Figure 4).

Figure 4 Photo of the western slope of the waste dump

As in the previous case study, a good density of measurement points has been retrieved throughout the whole area under analysis. Figure 5 shows how this acceleration patterns can be also defined using spatial profiles or transects. Those graphs help to understand the behaviour of the movement and the location of the areas with more deformation. The graphs show the deformation of each InSAR measurement point at different dates, with lighter lines showing older dates and darker lines showing recent dates. These graphs represent a different approach to detect acceleration by looking at the line's separation. Non-uniform spacing between lines means an increase or decrease of the deformation rate between the dates.

The following image shows a first transect (Figure 5a) showing the accumulated vertical deformation (up–down) along a waste dump section, where it can clearly be seen that the strongest and more active vertical deformation is located at the centre part of the dump, and both extremes are mostly stable. Figure 5b plots the same transect but using the horizontal (east–west) deformation dataset, where downslope movement can be identified in both sides of the dump.



(b)

Figure 5 **(a) Spatial profile of the vertical component; (b) Spatial profile of the horizontal component, both obtained from the movement decomposition of the line of sight (LOS) measurements in ascending and descending geometries**

Trend change and acceleration indicators were also obtained, highlighting clusters of InSAR measurement points showing an acceleration pattern on the southeastern side of the dump (Figure 6).

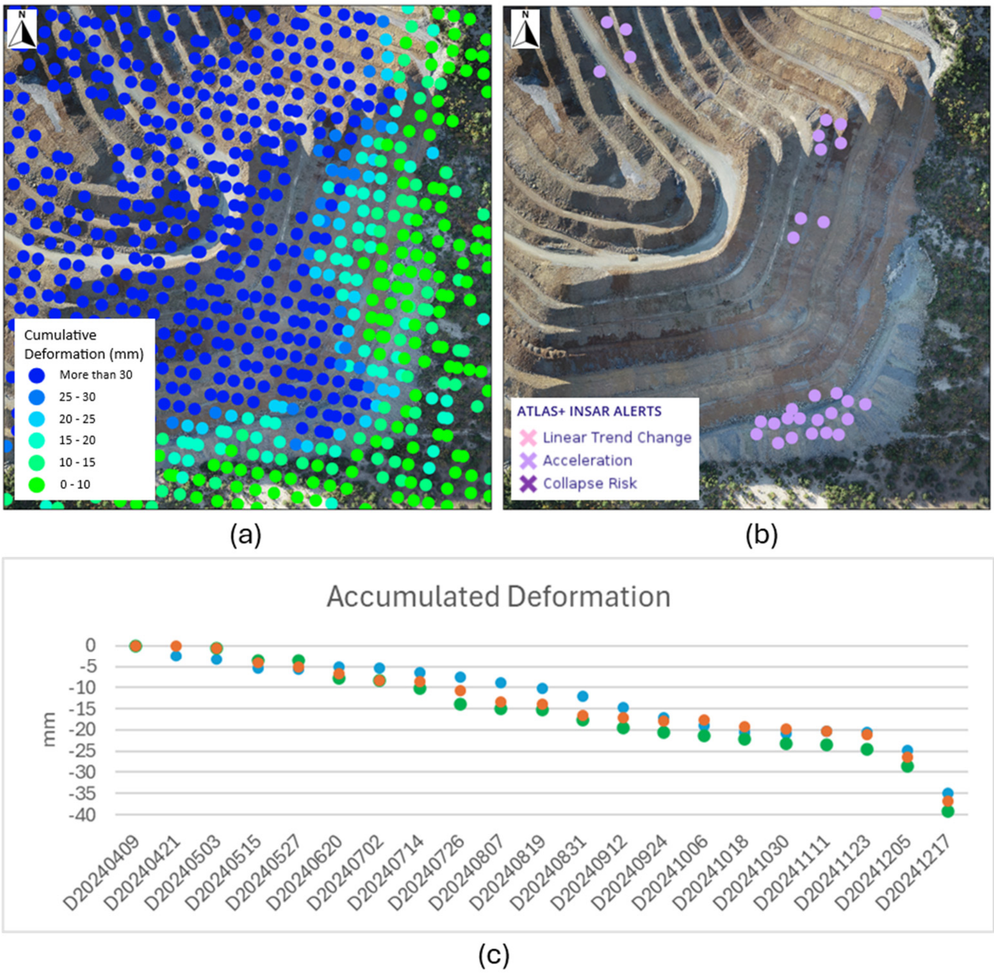


Figure 6 (a) Modulus of accumulated deformation; (b) InSAR alerts map; (c) Time series of deformation of a cluster of points that show an acceleration in the last month analysed

3.2 Detection of accelerating motion on tailings storage facilities

3.2.1 Case study 3

The third case study presents a tailings storage facility (TSF) where acceleration in the InSAR time series was detected over a dam wall concurrently with the approach of the liquid tailings to the area. Analysis of the liquid content masks showed how the liquid tailings were getting closer to one of the TSF walls month by month, and that correlates with the area where the acceleration alert has been triggered by the InSAR advanced analytics (Figure 7). For confidentiality reasons, the location of the area is not shown.

Given the correlation between the two methodologies, the routine InSAR monitoring of the mine was complemented by adding Sentinel-2 multispectral images to compute the percentage of liquid tailings and the distance to the walls to use them as an additional early warning alert that will allow them to take action when the liquid content exceeds a predefined threshold.

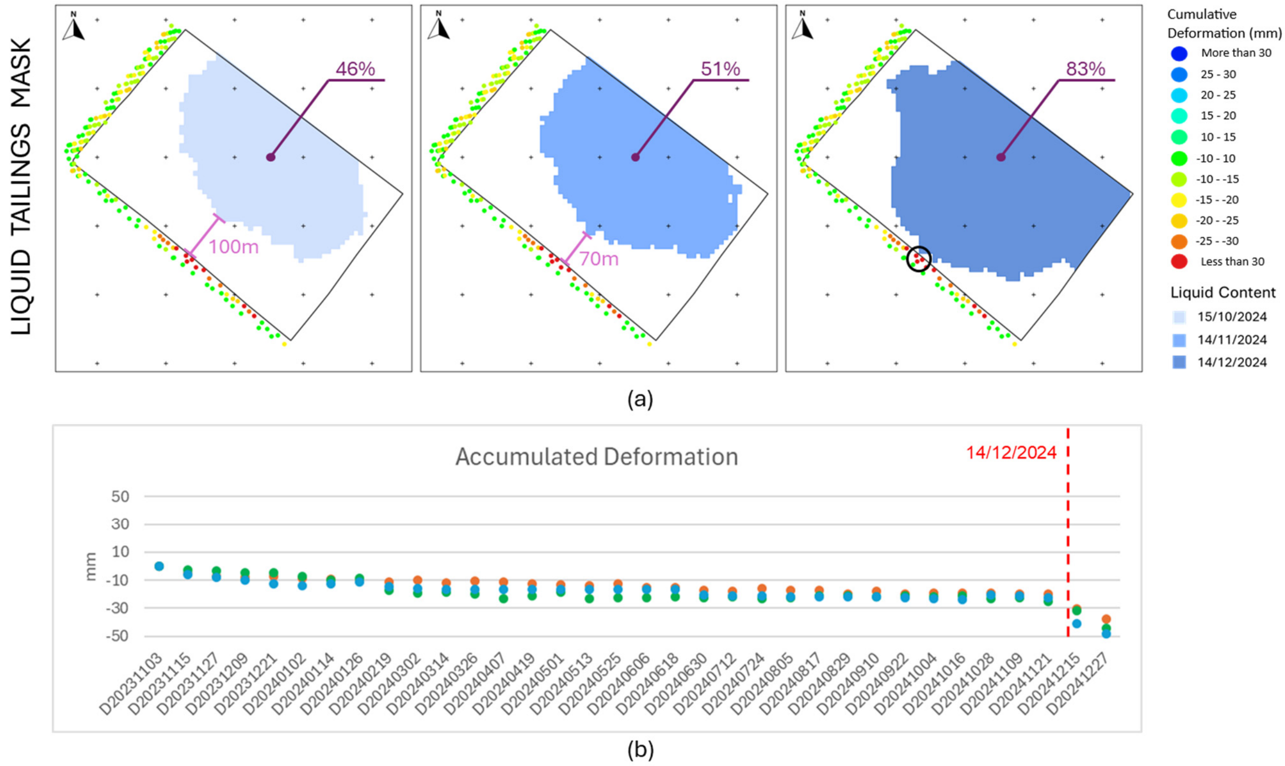


Figure 7 (a) Evolution of the liquid tailings inside the tailings storage facility (TSF) and the accumulated displacement obtained from the InSAR analysis; (b) Time series of a group of points located in the wall of the TSF and showing acceleration when the liquid tailings approaches

4 Conclusion

It has been demonstrated how advanced analytics provide potential failure alerts that can be used as early warning systems to proactively inform about potential failures of mining critical structures.

It is essential to complement standard InSAR datasets with advanced analytic packages and additional remote sensing services in order to gain a comprehensive understanding of the situation at each update, enabling timely response and the implementation of preventive measures to mitigate deformation.

Understanding the needs, potential hazards, and criticality of the asset/structure is essential for developing the appropriate algorithms, capable of uncovering hidden patterns and enabling early detection of potential failure indicators. Powerful algorithms have been designed and developed to integrate InSAR datasets with other sources, such as ground-based instruments, weather forecasts, and other remote sensing products. A clear understanding of each system's limitations is key to ensuring the delivery of a reliable and meaningful advanced analytics service.

5 References

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