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Satellite monitoring supporting mining pipeline integrity

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Abstract

Satellite applications in the mining industry range from the exploration phase through to production and post-closure monitoring. Interferometric synthetic aperture radar (InSAR) is a satellite application commonly used to measure ground motion in mining sites.

Samarco Mineração operates 398 km of triple mining pipeline to transport its ore through the Brazilian states of Minas Gerais and Espírito Santo to the Port of Ponta Ubu. On its way, the ore pipe crosses different landscapes, and among them are hilly areas with slope stability concerns. The pipelines are mostly buried but run overground in some sections. They are costly to monitor due to their length, and as they are often located in remote areas, the use of InSAR is of high value.

Samarco Mineração´s safety management team carries out a geological and geotechnical risk analysis throughout the pipeline corridor on an annual basis. A team of people and resources are devoted to that task, and specific ground instrumentation is also in place.

InSAR has been applied to support this ground team and ensure the maintenance of the pipeline is carried out in the most effective way. InSAR detects unstable slopes and anticipates ground instabilities that can affect the pipeline infrastructure. An initial historical study has been carried out, followed by an intense monitoring plan with different types of satellite imagery.

This paper demonstrates how the combination of C-band and L-band synthetic aperture radar imagery provides valuable information to support pipeline integrity. InSAR results provide an inventory of hotspots, and the continuous monitoring of the sites supports the implementation of stabilisation works when needed.

In addition to the preventive assessment, an ATLAS InSAR long-term monitoring scheme allows the monitoring of slopes after the implementation of stabilisation works, in order to assess the behaviour over time.

This paper demonstrates how InSAR increases operational safety, reduces uncertainty, minimises onsite intervention and contributes to efficient instrumentation network planning.

Keywords: *pipeline monitoring, lnSAR, pipeline integrity*

1 Introduction

Some mining companies in Brazil rely on pipelines to transport their ores from the mine plant to the pelletising plant or the exportation port. Currently, Samarco Mineração operates 398 kilometres of a triple mining pipeline to transport its ore through the states of Minas Gerais and Espírito Santo. Along its alignment, the ore pipeline crosses varied physiographic, geological and geotechnical contexts. Potential damage to pipelines may come from landslides and ground settlement. The potential collapse of these slopes may cause not only interruption of production, which would lead to inevitable losses, but also considerable environmental damage.

At Samarco, pipeline geotechnical monitoring was performed with visual field inspections and onsite instrumentation. However, traditional ground-based monitoring involves the installation of numerous sensors, and with such large infrastructures, it can be difficult and expensive to cover the whole area of interest with enough sensors to properly understand the behaviour of the terrain. Visual field inspections present similar limitations, being difficult to cover the entire alignment of the pipelines.

These limitations can be overcome by using remote sensing techniques such as Interferometric synthetic aperture radar (InSAR). InSAR, or radar satellite interferometry, is a fully remote sensing technique based on the exploitation of synthetic aperture radar (SAR) images, able to provide centimetre- and millimetre-scale measurements of displacement over time and give the user a comprehensive, consistent, and periodic vision of a large area, without any need to access the site.

Currently, InSAR is used as a complementary technique to monitor mining pipelines worldwide because it is a large-scale, precise and cost-effective solution. It provides valuable information for short- and long-term planning, safety and risk management. InSAR mitigates risks associated with ongoing pipeline operations by:

- Highlighting deformations, perimeters of the deformation and their evolution over time.
- Identifying acceleration sectors and precursor movements.

The purpose of this paper is to present how Samarco uses ATLAS, Sixense´s InSAR processing chain, to support mining pipeline integrity. The pipeline’s alignment has been monitored with ATLAS using a set of Sentinel-1 (C-band) images and a set of ALOS-2 (L-band) images, acquired between January 2021 and December 2022 and between August 2021 and September 2022 respectively.

2 Methodology and data

2.1 InSAR technique

InSAR is a non-invasive remote sensing technique capable of monitoring wide areas of terrain with millimetric precision, making it ideal for the monitoring of infrastructures over wide areas in both urban and non-urban environments (Bamler & Hartl 1998). This technique brings to the user a comprehensive, consistent and periodic vision, without any need to access the site. Moreover, the large size of satellite images provides detailed information over thousands of kilometres. By using more than one footprint, InSAR can cover entire mining pipelines and detect many thousands of potential hazards with millimetre- to centimetre-level precision. Using satellite time series, ground displacements can be analysed at any point every few days throughout the monitoring period.

A SAR image contains amplitude and phase information recorded as a complex number. The phase of a SAR image is related to the distance the electromagnetic pulse travels from the satellite to the ground and back to the satellite. Solutions based on InSAR exploit phase differences of a stack of SAR images acquired over the same area at different times to obtain ground displacement information. The final output is a ground displacement map of the area over the period of SAR image acquisition, as well as deformation time series (Figure 1).

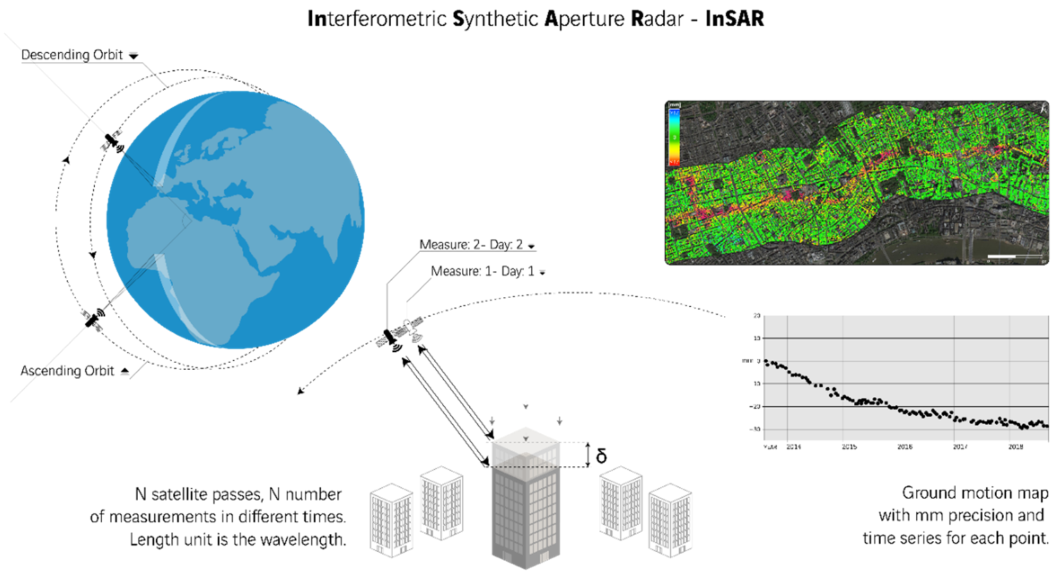


Figure 1 SAR interferometry working principle

2.2 Qualitative and quantitative assessment of ground deformations along Samarco's pipelines using differential InSAR and persistent scatterer interferometry

Sixense has developed its InSAR processing chain called ATLAS, which is able to perform both the conventional differential InSAR (DInSAR) and persistent scatterer interferometry (PSI) analysis.

In conventional DInSAR, phase measurements from two images captured at different times over the same region are utilised to obtain deformation in the satellite line of sight (LOS; Massonnet et al. 1993). The processing involves co-registering paired images and generating a differential interferogram between them, which displays the phase change information. Subsequently, the coherence of the data is estimated, serving as an indicator of data quality. Coherence ranges from zero to one, with zero representing low similarity and poor data quality, while one represents high similarity and excellent data quality. Finally, ground displacements are estimated based on the phase differences between images (Figure 2). However, the effectiveness of DInSAR in accurately quantifying displacement can be hindered by challenges such as data decorrelation, atmospheric distortions and phase saturation, which can arise due to significant changes in surface or imaging characteristics over time (Mohr & Madsen 1999).

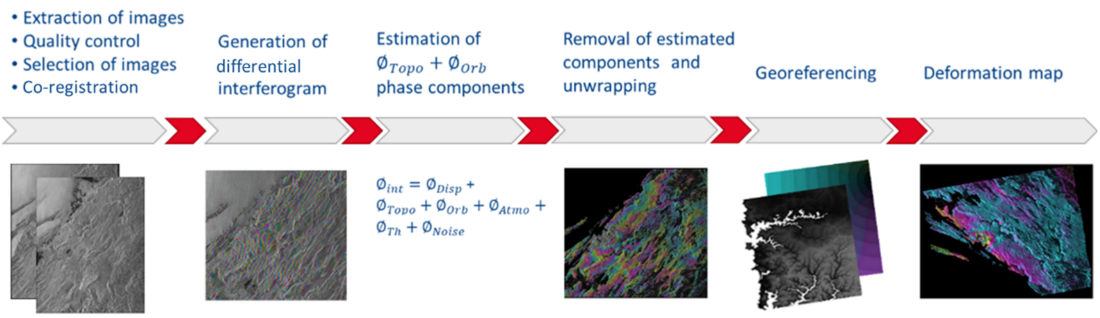


Figure 2 Block diagram of the DInSAR processing chain workflow

The PSI technique requires a database of more than 15 SAR images and involves several key steps (Ferretti et al. 2000, 2001). First, the algorithm identifies common points in each pixel of the SAR image that persistently reflect the radar signal back to the sensor. These targets, called persistent scatterers, can be man-made structures, rocks, arid terrains or other features with characteristics that enable optimal radar wave reflection. Then, the PSI processing sequence includes co-registration of images to produce an interferogram stack, generation of differential interferograms, selection of measurement points, ground-motion estimation, precise estimation of deformation time series, geocoding of the measurement points and final quality control.

2.3 Area of interest and SAR data

Samarco operates 398 kilometres of a triple mining pipeline, which runs from the Germano mine located in Mariana until Ponta Ubu, cities located in Minas Gerais and Espírito Santo, respectively. Along its course, the ore pipe crosses different landscape scenarios, and among them are hill areas with slope stability concerns. In general, the area is mainly vegetated, with minor urban zones. The mining pipelines, with a general NNW-SSE orientation, are mostly underground but run overground in some sections.

Annually, the slopes of the pipeline are evaluated by Samarco's geotechnical team to map situations of geological-geotechnical risk and rank them according to the level of risk involved. This prioritisation allows for better planning of preventive and corrective actions on these slopes. During this risk analysis, a series of important factors regarding the slopes are evaluated, of which among them are the following:

- Weighting of geological-geotechnical profiles carried out based on maps of erodibility (Rizzato et al. 2020), susceptibility (Peçanha et al. 2020) and vulnerability (Simões et al. 2019) of soils to water erosion in Brazil. These maps were made and published by Embrapa, the Brazilian Agricultural Research Corporation, in 2019 and 2020. This weighting takes into account intrinsic factors of the soil, land use and protection, relief, and climatic conditions.
- Physical characteristics, such as height and inclination of the slopes; presence of surges, erosion or subsidence; and existence of retaining walls.
- Damage indicators, including evaluating the potential for damage in terms of range and the impacts on safety and production.

Taking this risk analysis into consideration, some areas were considered more critical than others. Hence, those areas of interest were chosen for monitoring by InSAR.

In this study, a total of 44 Sentinel-1 images acquired from January 2021 to December 2022 have been utilised to map the ground deformation over the areas of interest (Figure 3). It is important to highlight that due to satellite failure, a gap without acquisition exists between January and April 2022.

The Sentinel-1 satellite uses C-band (5.6 cm wavelength) SAR sensors, the interferometric wide swath image has a spatial resolution of 5 m by 20 m, and its swaths have a width of 250 km. Typically, the satellite acquires images over the same area every 12 days.

Since the acquisition of ALOS-2 has been irregular over the area of study, in this study only four ALOS-2 images from August 2021 to September 2022 have been used to map the ground deformation (Figure 3).

The ALOS-2 satellite uses L-band (23 cm wavelength) SAR sensors, and the interferometric Stripmap image has a spatial resolution of 10 m by 5 m. Swaths have a width of 50 km. Typically, the satellite acquires over the same area at least every 18 days.

The election of both sensors was based on the physiographic characteristics of the area of interest.

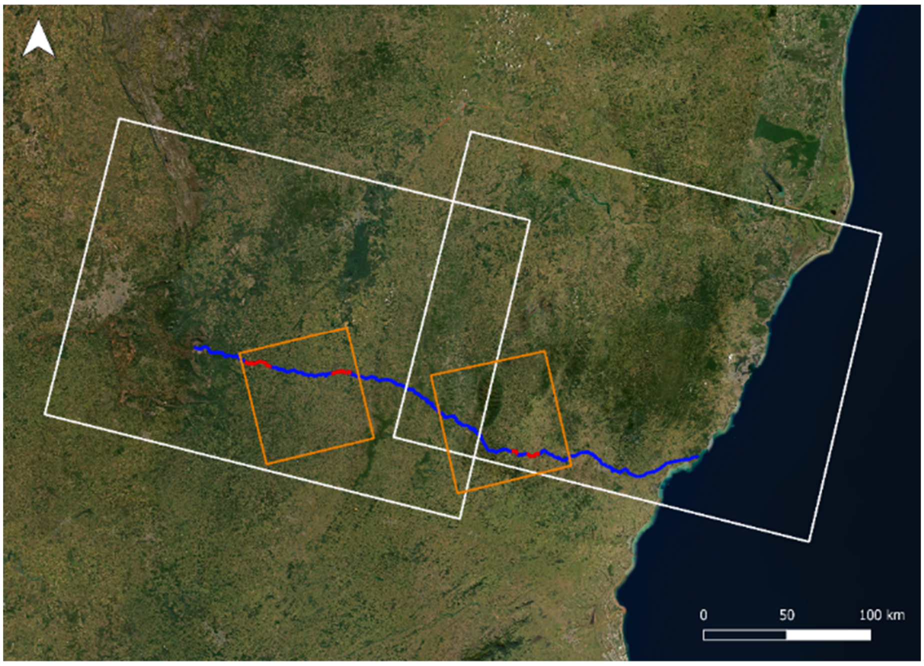


Figure 3 **Coverages of S1 images in descending orbit (white rectangles) and ALOS-2 images in ascending orbit (orange rectangles)**

3 Results and discussions

3.1 PSI study: Sentinel-1

ATLAS was successfully applied to the areas of interest using a set of Sentinel-1 (S1) images acquired from January 2021 to December 2022. Figure 4 demonstrates that ATLAS InSAR provided an updated inventory with the location, size and magnitude of ground displacements over Samarco's pipelines and its immediate surroundings. Based on these results, most of the areas of interest were considered stable during the period of study. Nevertheless, some local deformation areas relatively close to the pipeline alignment have been identified, and most of them correspond to movements away from the satellite. These motions are indicative of subsidence and are interpreted as settlements.

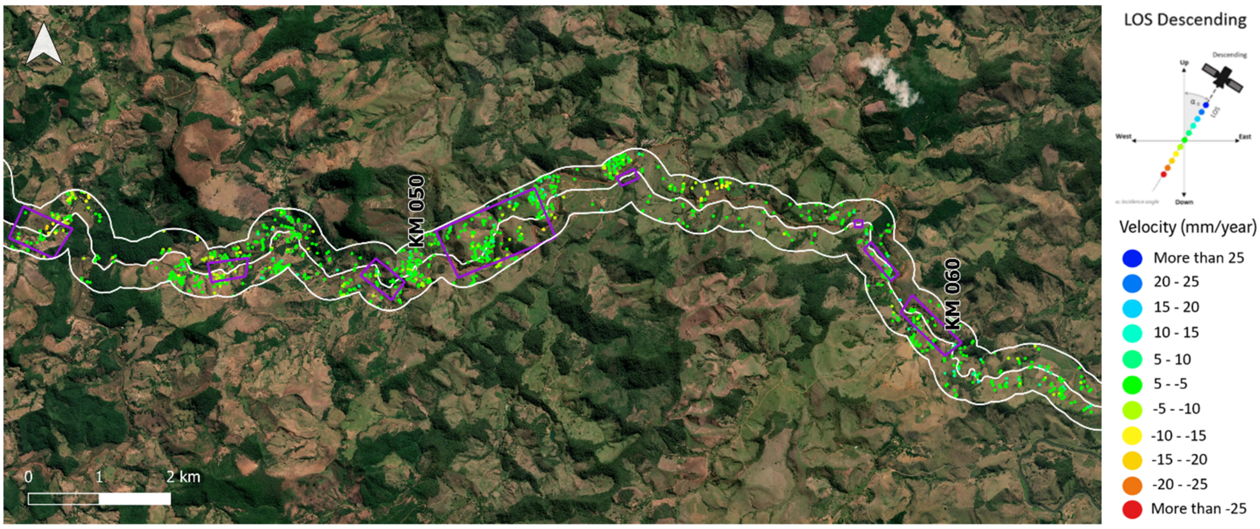


Figure 4 **Velocity map measured in line of sight descending with S1 between January 2021 and December 2022 over some of the areas of interest**

An example of the pipeline's monitoring is shown in this section. Figure 5 shows the velocity of the displacement map over one of the areas of special interest. Maximum accumulated deformation values of more than -20 mm were identified inside the area around Point A, which also showed a non-linear deformation pattern, starting with stability, followed by a subsidence period, which ended in a stable scenario, with the last acquisition showing a potential reactivation of the movement (Figure 6).

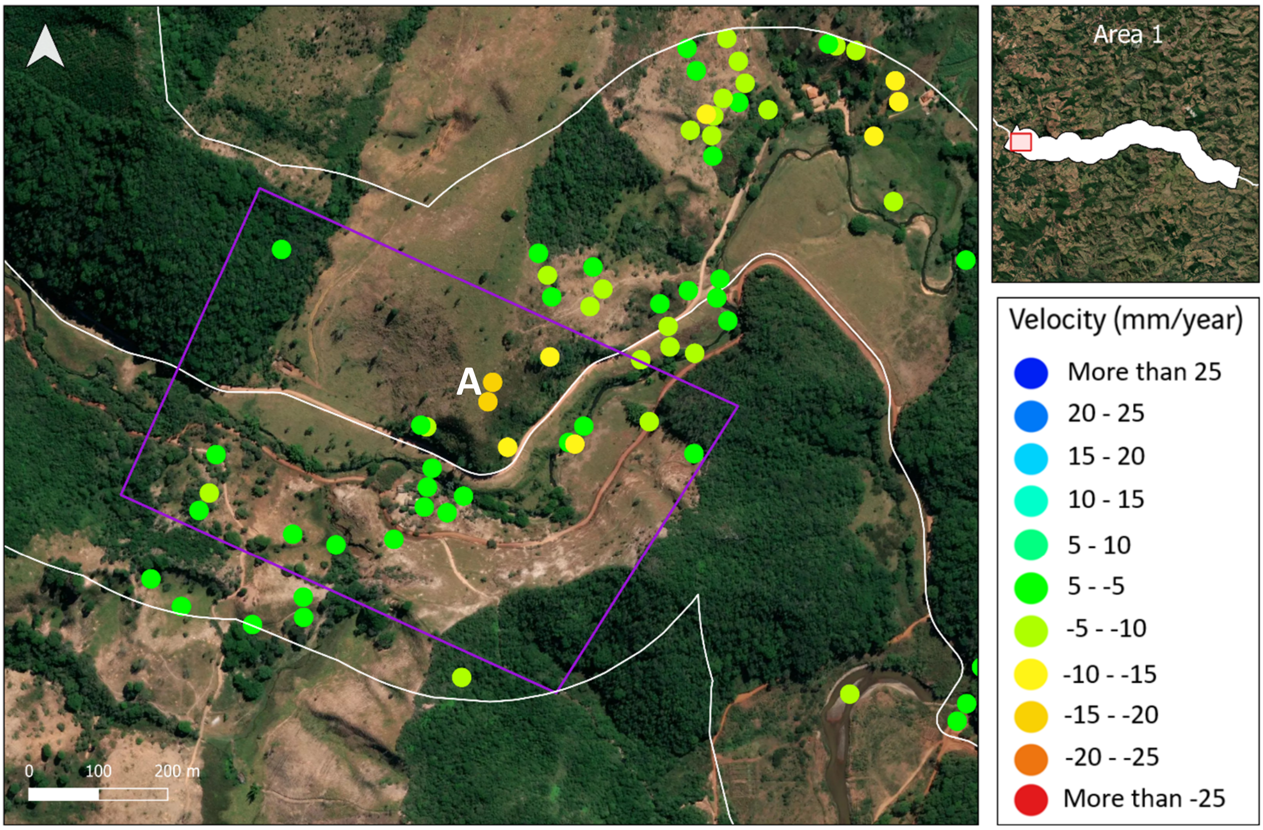


Figure 5 Detailed S1 PSI results where the values of accumulated deformation of -20 mm in LOS descending were detected

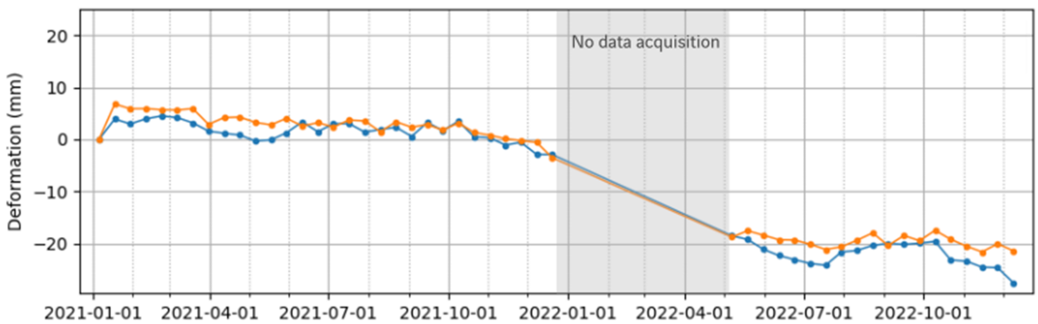


Figure 6 Deformation time series for the two points referred to by the letter A in Figure 5

3.2 InSAR combined with field inspections to increase safety

Combining InSAR with other monitoring techniques offers plenty of advantages in the monitoring of pipelines. InSAR provides a broad perspective, detecting movements across the entire pipeline alignment and indicating areas where additional monitoring methods may be required. It complements traditional geotechnical instrumentation and field inspections by helping determine where to install more instruments, increase inspections or implement early-stage mitigation interventions.

The results observed in the PSI study are consistent with those detected through a visual field inspection during the first 2022 semester by Samarco´s geotechnical team. The area where an accumulated deformation of more than -20 mm was detected (Figure 5) shows clear visual signs of movement on the field (Figure 7).

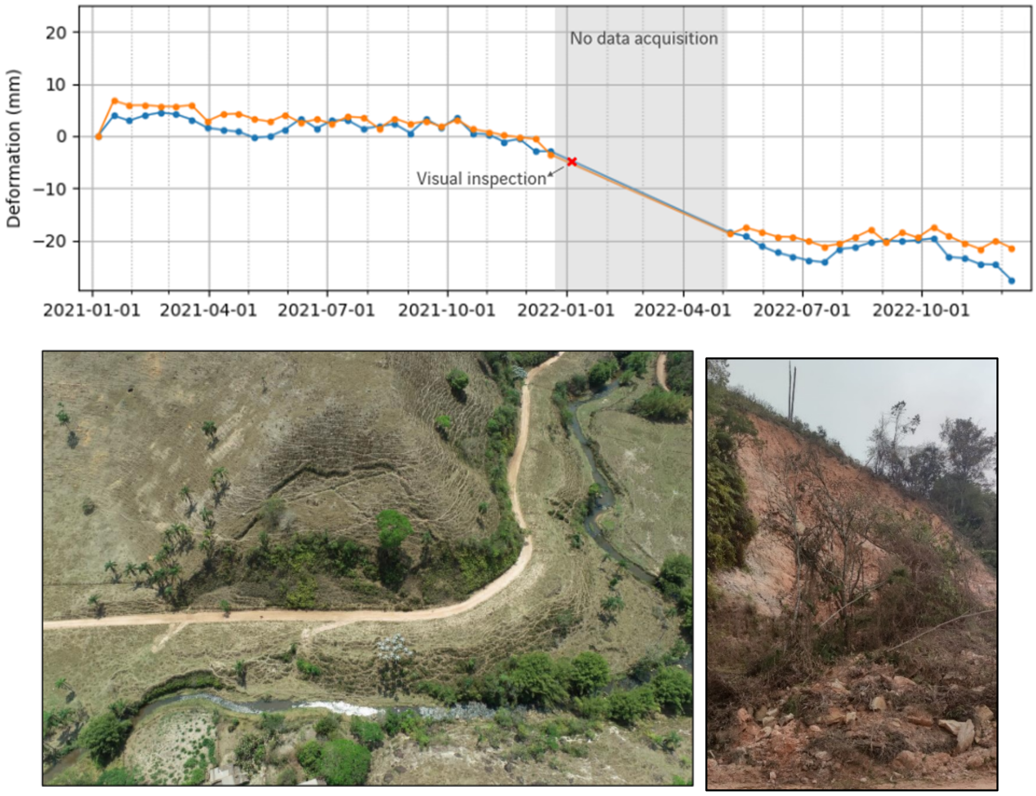


Figure 7 Slope failure on Area A identified during a visual inspection carried out during rainy season, January 2022

The InSAR results and the time series graphs associated with these areas corroborate the deformation patterns and trends identified on the ground through field inspections. Therefore, InSAR has been proven a suitable monitoring technique for pipeline monitoring in the area, providing valuable information for safety and risk management.

3.3 DInSAR study: ALOS-2

A DInSAR study was successfully applied to the areas of interest using a set of ALOS-2 images acquired from August 2021 to September 2022. Figure 8 demonstrates that DInSAR analysis provided an additional inventory of ground displacements over Samarco's pipelines and its immediate surroundings using L-band imagery, which allows for deeper penetration into vegetated areas. Figure 8 shows the same pattern of deformation in the area observed in the Sentinel-1 PSI results, with maximum accumulated deformation values of around -4.5 cm during the period of study.

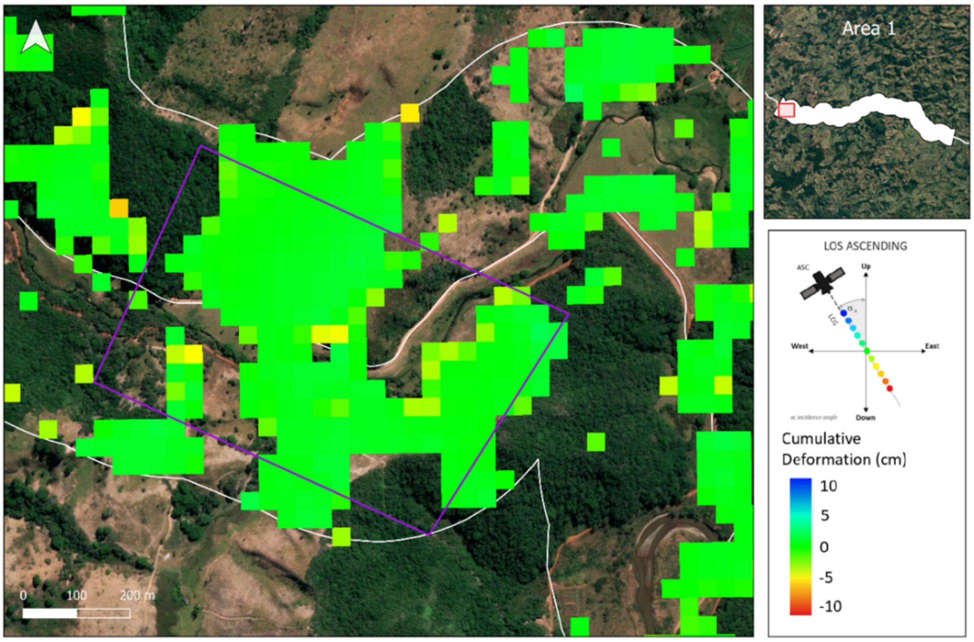
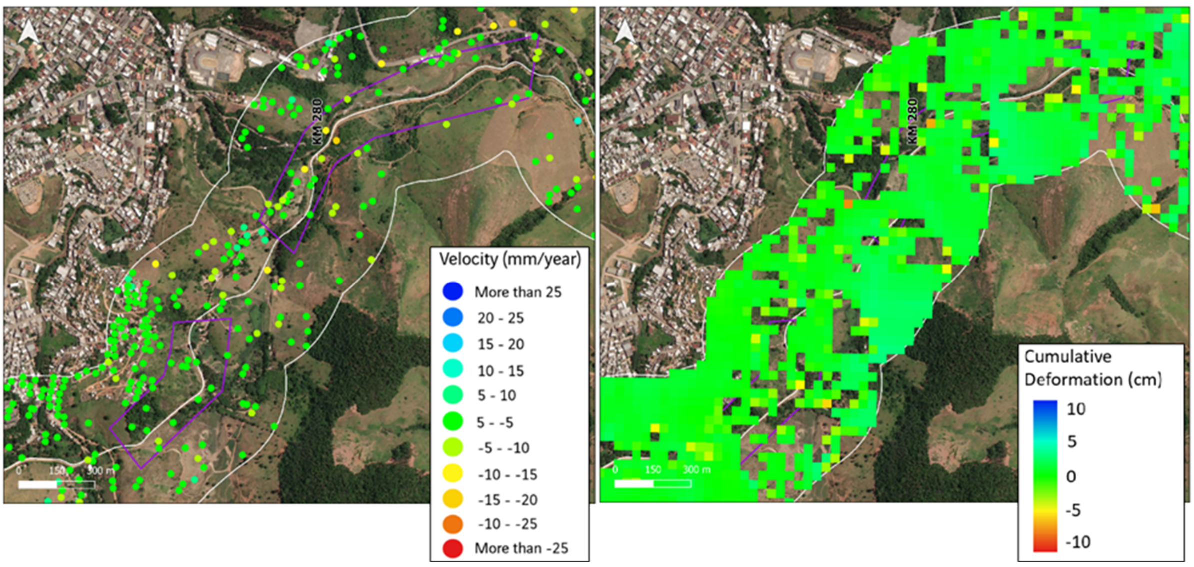


Figure 8 Detailed ALOS-2 DInSAR results where the values of velocity around -4.5 cm in line of sight ascending were detected (from August 2021 to September 2022)

3.4 Comparison Sentinel-1 versus ALOS-2

The combination of Sentinel-1 (C-band) and ALOS-2 (L-band) data allows for a deeper understanding of the terrain's behaviour. The wavelength used in InSAR studies determines how the radar signal interacts with the surface. The larger the wavelength is, the greater the penetration into the vegetation will be, but the resolution and sensitivity with respect to terrain deformation will be lower. L-band works with larger wavelengths (15–30 cm) compared with C-band (3.8–7.5 cm). L-Band therefore penetrates more deeply on vegetated areas and is less affected by temporal decorrelation than C-band but is slightly less sensitive to deformation (Seppi et al. 2022).

Figure 9 presents a comparison of the measurements retrieved over the same area. On the left are the results obtained using the PSI technique on a set of C-band Sentinel-1 images, and on the right are the results obtained applying the DInSAR technique to a pair of L-band ALOS-2 images.



(a) (b)

Figure 9 Comparison of InSAR results with (a) Sentinel-1 C-band and (b) ALOS-2 L-band data

The results presented in this work show that a combination of L-band and C-band appears to be suitable for pipeline monitoring in the area. By using a combination of both bands, the L-band signals can provide better coherence and penetration over vegetated areas, while the C-band signals can capture higher resolution- surface details. Furthermore, the Sentinel-1 data used for this study is far more extensive than the ALOS-2 data, which has not only allowed the study of the area to be conducted over a longer period but has also complemented the information acquired with only ALOS-2.

The combination of both satellites enables a more comprehensive understanding of the areas of interest for Samarco. It allows follow-up on ground displacement previously mapped, detects new precursor movements along the pipelines and enables the implementation of early-stage mitigation interventions.

4 Conclusion

The study demonstrates that ATLAS InSAR, a remote sensing technique utilising satellite-acquired images, proves to be a suitable monitoring method for mining pipelines. This research focuses on the monitoring of Samarco's mining pipelines, monitored using Sentinel-1 and ALOS-2 images, covering the two periods January 2021 to December 2022 and August 2021 to September 2022, respectively. The analysis involved two interferometric approaches: conventional DInSAR with L-band images and PSI analysis with C-band images. The combination of L-band and C-band in InSAR applications offered notable advantages, such as enhanced penetration through vegetation and reduced decorrelation effects as well as a longer study over time, which contributed to better monitoring and analysis of the areas of interest for Samarco.

After the first historical analysis, Samarco has adopted ATLAS InSAR as a long-term monitoring program. The InSAR data enables the periodic follow-up of ground displacements previously mapped as well as the detection of new precursor movements to landslides and slope failures around the pipelines. Non-linear motion or motion acceleration can also be identified, enabling the implementation of early-stage mitigation interventions. Ultimately, the technology helps guarantee the integrity of the pipelines and can be a tool for reducing risks associated with its operations. The results allowed Samarco's team to effectively plan the monitoring instrumentation network and the visual field inspections oriented to the critical sectors, leading to less uncertainty in the area and minimising onsite intervention by focusing it where it is needed.

Acknowledgement

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