Mine Closure 2022 - M Tibbett, AB Fourie & G Boggs (eds)
© 2022 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-4-1
doi:10.36487/ACG_repo/2215_56

InSAR monitoring of a challenging closed mine site with corner reflectors

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Abstract

Slope instability at mine sites is a hazard that may persist long after closure. Stewards of such assets can monitor and assess the associated risks by examining ground displacement over time. Mapping ground displacement through satellite Interferometric Synthetic Aperture Radar (InSAR) is an increasingly common tool for mine site monitoring. The satellite returns image acquisitions at regular time intervals, which are compared to each other to measure displacement.

InSAR is a remote sensing technique that can provide wide-area, high-precision data coverage, regardless of cloud cover. However, for InSAR to provide coverage, the radar reflectivity of the ground needs to stay consistent throughout the analysis period. This consistency is hindered by changes on the ground surface, such as construction, excavation, snow or water inundation, and the type, thickness, and seasonal variation of vegetation. These can be challenging variables across active sites, due to ongoing mining activities, and at closed sites, due to deconstruction of infrastructure, revegetation and any other process that alters the ground surface.

These challenges are present at one such site, which has been anonymised in this article, where closure activities make conventional InSAR workflows challenging. At this site, to be able to provide critical ground displacement data, more than 100 artificial radar corner reflectors (CRs) were deployed. These are metal structures carefully located and positioned to provide a strong, consistent radar response across desired assets.

The use of CRs for InSAR is not new, but they have not been widely adopted for mining applications, especially in large numbers. Our results demonstrate the benefits of using CRs for such applications, including improved precision and enhanced data coverage over key assets, such as the tailings storage facility. The success of the project highlights the importance of a collaborative approach in planning an InSAR monitoring program. Further, this study discusses challenges of InSAR and CR use for closed mine sites and provides alternative InSAR technologies to CRs that could be used for the application of mine closure.

Keywords: *monitoring, InSAR, coherence, corner reflectors, mine closure*

1 Introduction

In line with the Global Industry Standard on Tailings Management (International Council on Mining and Metals 2020), for all mine sites, active or closed, slope stability management and monitoring is important. In this paper, a mine operator wished to understand the feasibility of using satellite InSAR for wide-area ground movement monitoring of one of their mines, which is going through closure operations. The area of interest (AOI) the mine operator wanted to monitor was the entire mine site, including pits, waste piles, and the tailings storage facility (TSF) (Figure 1). It requested year-round InSAR monitoring with monthly reporting across the AOI.

Figure 1 Satellite optical image of the area of interest. Includes material © KARI 2020, Distribution (SI Imaging Services, Republic of Korea), all rights reserved

As part of the closure effort, the site is being revegetated, meaning vegetation density is increasing across all mine assets. Additionally, infrastructure is being decommissioned and removed and the site has an increasingly limited ground staff presence.

Interferometric Synthetic Aperture Radar (InSAR) is an active remote sensing technique for measuring ground displacement. The input data comprise imagery called Synthetic Aperture Radar (SAR), which can be acquired through clouds and at night. For further details of the technique, see Rosen et al. (2000).

For InSAR to be an effective mine monitoring tool, it needs to provide ground displacement measurements with suitable precision in meaningful time frames and with data coverage across mine assets. The precision of InSAR results is controlled by the resolution and wavelength of the SAR imagery and physical factors such as ground cover and atmospheric conditions. The latency for InSAR results is limited by the speed of SAR data availability from the satellite operators and the speed of processing by the InSAR provider.

To provide InSAR coverage, pixels must remain coherent through time (Woodhouse 2006). Coherence is a property that describes how much the ground surface changes between acquisitions and affects measurement quality. Variable surface characteristics through time result in low coherence and noisy results, and eventually in complete loss of measurement coverage.

2 Methodology

2.1 Synthetic aperture radar data

The European Space Agency (ESA) operates a constellation of satellites called Sentinels under the Copernicus programme. The Sentinel-1 satellites were operating together on identical orbits with a six-day separation. This meant that for many locations across the globe, a new SAR image was available every six days for InSAR processing workflows. This was the case across this mine starting from 2018.

However, in late 2021, Sentinel-1B suffered a technical problem (European Space Agency [ESA] 2022a), and it is uncertain whether it will resume operations. Data acquisitions across the mine now occur every 12 days but may improve with the launch of Sentinel-1C, expected in 2023 (ESA 2022b).

SAR imagery from the Copernicus programme has the added benefit of being open source. With a global land and coastal archive from 2014, Copernicus data are an attractive imagery source for academic and commercial applications.

2.2 InSAR feasibility

InSAR is not a technique that works the same everywhere. As detailed in Hanssen (2003), there are several factors that dictate whether InSAR is a successful ground monitoring solution. For example, the ground conditions of the AOI must be analysed to confirm coherence is of an acceptable level over the area measurements are required. The location, spatial extent and magnitude of movement is used to decide how large the processing window should be and what SAR data should be used. Also, the availability, accessibility and consistency of the appropriate SAR data, and its cost, needs to be considered.

Certain factors pose challenges for consistent InSAR provision across the whole mine site. First, coherence is limited due to vegetation that covers this tropical landscape, and mine site revegetation means vegetation density will change over time and seasonally. Mine closure also involves the removal of buildings that would have been stable radar reflectors. Mine assets such as the TSF will be resurfaced with additional topsoil to mitigate flooding as compaction occurs. All these changes cause a loss of InSAR coverage and increase uncertainties in the measurements where data coverage is preserved.

2.3 Interferometric synthetic aperture radar

Ground displacement measurements from InSAR are attainable by stacking SAR images through time, with pixel-to-pixel alignment across an area. The spatial resolution of the results is limited by the spatial resolution of the imagery, typically on the order of a few metres to tens of metres and depending on processing techniques. The displacement of each pixel, however, can be measured with millimetric precision as this is constrained by measuring small shifts in the radar wavelength.

The imagery typically covers many kilometres, meaning InSAR can provide high-precision measurements over wide areas, potentially with millions of individual data points. After processing, each of those data points provides a time series of movement.

InSAR is a relative measurement technique, not absolute. A reference point is selected that is assumed to be stable and all other displacement measurements are relative to that point. For this mine site, the reference point chosen is on natural ground and close to the AOI.

InSAR processing across this site was trialled using the Differential Interferometric Synthetic Aperture Radar (DifSAR) workflow. DifSAR considers the total radar responses in each pixel and can perform well even with data that does not have consistently high coherence. This generally results in wide data coverage across the AOI, but at the expense of including more unwanted contributions to the signal (i.e. noise), which increases uncertainties.

The challenge is this mine site is not consistently coherent throughout the year; therefore, the InSAR coverage does not cover all the mine assets in that period. For example, Figure 2a shows coherence is quite strong in February, notably so across the TSF wall on the left side of the mine in Figure 2. However, later in May (Figure 2b), coherence is reduced and InSAR coverage is lost over large areas, including the TSF. This corresponds to the seasonal vegetation change. For this mine site, the DifSAR technique is not an optimal InSAR solution for year-round monitoring.

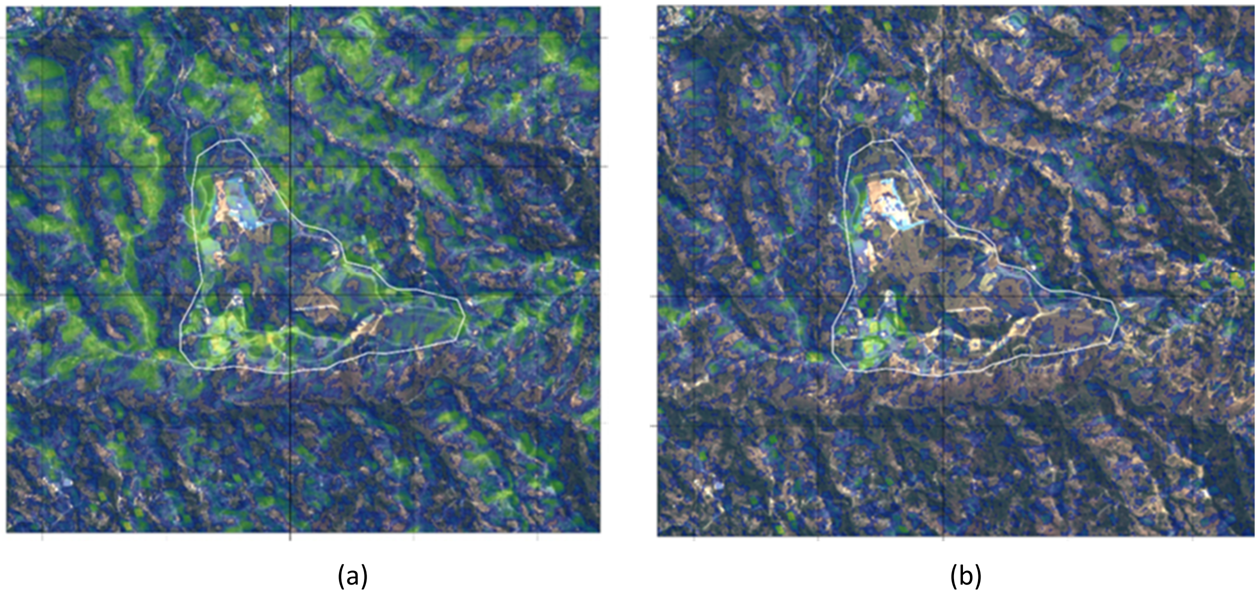

(a) (b)

Figure 2 A comparison of coherence maps across this mine (bounded by a white line). Yellow is high coherence, blue is low coherence, and, where the optical image can be seen underneath, coherence has fallen below a threshold of 0.25. Where this has occurred, InSAR measurements would contain a large proportion of noise and extracting ground motions would incur large uncertainties. (a) Coherence between 07 February 2019 and 19 February 2019; (b) Coherence between 2 May 2019 and 14 May 2019. Contains modified Copernicus Sentinel data 2019–2021

In contrast, persistent scatterer interferometry (PSI) limits data coverage to only the most coherent points in the image. This means data coverage is generally sparser than that of DifSAR; however, measurements are less noisy, allowing for greater precision and lower uncertainties. Given the lack of built infrastructure and rocky outcrops, PSI would certainly yield fewer data points and be even more unsuitable. However, this conclusion can be reversed if the number of highly coherent reflectors across the mine was increased, making PSI a more viable option.

2.4 Corner reflectors

2.4.1 Introduction to corner reflectors

Where coherence is low, artificial radar reflectors can be deployed to provide bright and consistent radar responses (e.g. Garthwaite 2017). Artificial radar reflectors are called corner reflectors (CRs) and consist of three sides of radar reflective material, such as aluminium, arranged into a 90° × 90° × 90° corner (Figure 3). The CR is deployed with an alignment to reflect a large proportion of an incoming radar beam back in the direction from which it came – that is, in the direction of the receiver on the satellite.

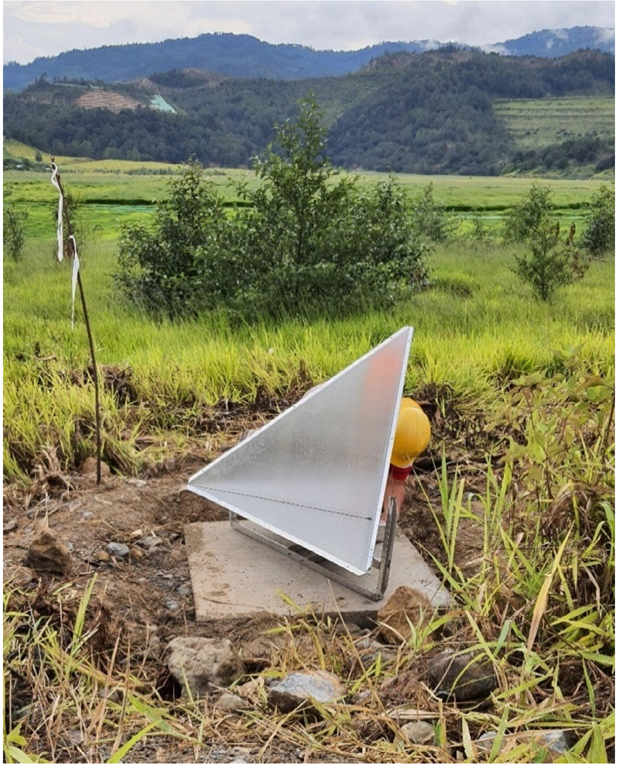


Figure 3 An installed corner reflector

The CRs installed onsite have three triangular faces allowing a cover to be fitted (not pictured). The cover prevents water, leaf litter or other materials from collecting in the CR, which would reduce its proficiency at reflecting the radar beam. The corner sits on a base that can be oriented towards the satellite as required and that is mounted on a concrete base, which anchors the CR to the ground.

2.4.2 Corner reflector deployment planning for use with InSAR

CRs require careful planning before deployment. To optimally reflect the radar back to the satellite, a CR should be carefully aligned to face the chosen satellite's viewing geometry, known as its line of sight (LOS). For this mine site, the CRs are optimally oriented to be used with Sentinel-1. This LOS is the axis along which displacement is measured.

A CR should be located where it will be the dominant signal in an area. Some pixels may naturally be dark in SAR imagery if they do not already contain good radar reflectors. For a CR to be visible, it needs to provide a significantly stronger response than the background.

CRs must be fixed to the target structure for which displacement is measured, referred to as anchoring. It is important to consider if the target ground motion will be present at the surface of if the CR would benefit from being anchored at depth. However, the anchoring structure should be constructed so that it does not subside under its own weight or cause slope instability.

Ideally, the anchoring structure will not exhibit strong thermal expansion and/or contraction with changes in the weather, as this can cause noise that makes seasonal trends harder to isolate. To mitigate this, local temperature measurements can be used to make a thermal correction during processing. Any movement of the CR, additional to the target ground motion, will produce noise in the measurements.

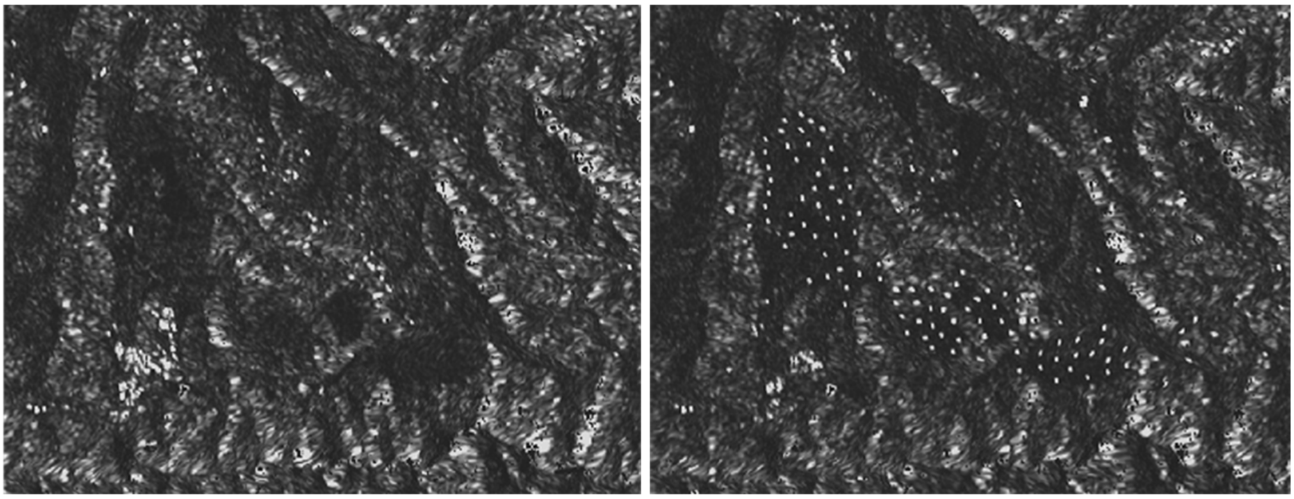
Logistically, CR locations need to be accessible to ensure they can be easily and safely installed and maintained. However, if they are accessible to the public, they are at risk of being disturbed or damaged.

For this mine, CRs were deployed at reference point locations. This provides all measurement points with strong radar responses, which helps maintain the precision in the results. Multiple reference point CRs provided redundancy in the case that one became damaged. It also provided an opportunity for cross-examination of reference points to identify any movement.

2.4.3 Corner reflector deployment

A CR deployment schedule was produced with the highest priority mine assets, identified by the mine operator, receiving CRs first. Once deployed, the CR's health was verified as Sentinel-1 imagery was acquired.

Shown in Figure 4a, the mine before CR deployment did not provide many bright radar responses. However, in Figure 4b, the mine is spotted with bright radar responses, indicating the presence of CRs at those locations.



(a) (b)

Figure 4 SAR intensity image across the mine. (a) Before corner reflector (CR) deployment; (b) After CR deployment. Contains modified Copernicus Sentinel data 2019–2021

3 Results

Over 100 CRs were deployed across this mine, providing consistent, high-precision measurement points for as long as they aren't disturbed. Natural coherent points were included during InSAR processing across the area to provide additional measurement coverage.

A cumulative displacement map between November 2020 and June 2021 is shown in Figure 5. The colour scale highlights the magnitude of displacement in the LOS of the satellite. In this example, much of the mine and the surrounding area is stable, but red data points are seen in the centre of the tailings indicating movement away from the satellite. Maps at other deformation scales and over different time periods were provided to the mine operator to highlight displacement in other key areas. The displacement maps highlight the spatial distribution and magnitudes of ground movement. This is useful for wide-area screening and for developing better spatial awareness of ground stability and potential hazards across a site as well as disclosure.

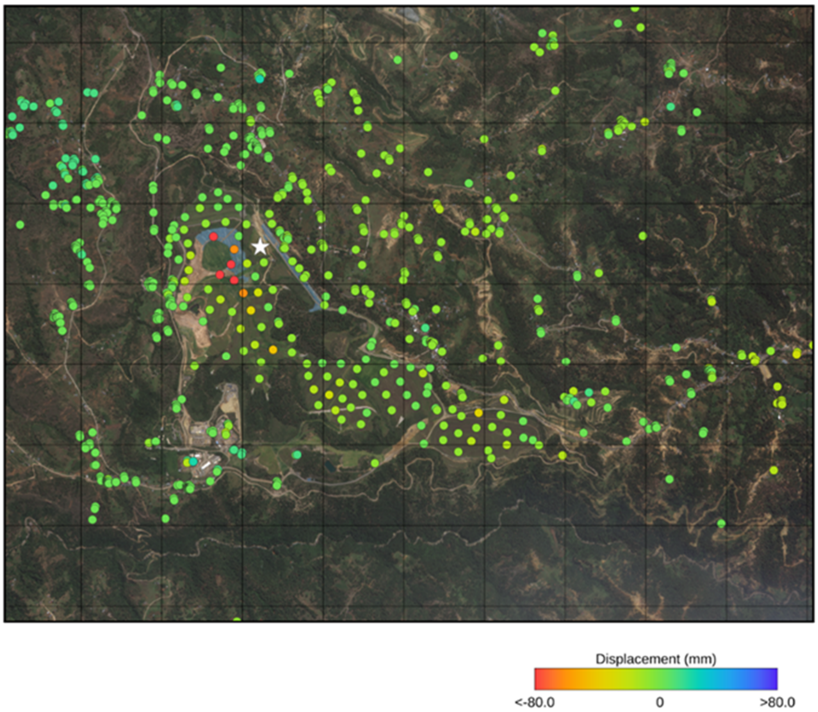


Figure 5 InSAR cumulative displacement map across the mine. Stability is green, while displacement towards and away from the satellite is coloured blue and red, respectively. SAR data included spanned between November 2020 and June 2021. The white star indicates the location of the reference point. Contains modified Copernicus Sentinel data 2019–2021. Includes material © KARI 2020, Distribution (SI Imaging Services, Republic of Korea), all rights reserved

Each data point in Figure 5 has an associated time series of displacement, which can be viewed in graphs, such as the example shown in Figure 6. This time series from a CR on the TSF shows 70 ± 12 mm of displacement away from the satellite at that location on the tailings between November 2020 and June 2021. Time series graphs, such as Figure 6, allow the user to quantitatively interrogate the evolution of ground movement at specific locations.

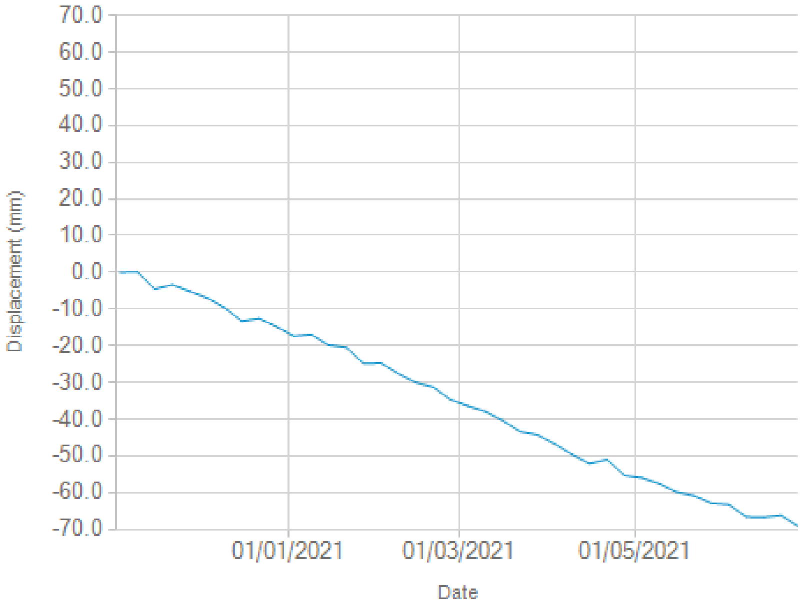


Figure 6 An example time series from within the mine's tailings storage facility, showing tailings displacement away from the satellite of roughly 70 ± 12 mm between November 2020 and June 2021

4 Discussion

4.1 Discussion of results

InSAR is best used to identify motion from large stacks of SAR imagery. Over short periods, InSAR is susceptible to greater proportions of noise that, over time, can be minimised. This noise comes from several sources, but most prominently from changes in atmospheric humidity. The magnitude of this effect varies with the local environment and climate.

Longer period, cumulative InSAR maps like Figure 5 do a good job of smoothing these short-term noise signals out. However, the short-term signals are still apparent when the time series is interrogated. Attempts are made to reduce or correct for noise during the InSAR workflow.

4.2 Successes of the project

4.2.1 InSAR monitoring over a challenging closed mine site

InSAR results are now being provided across the site year round, a key objective for this work. The high-precision measurements provided by the CRs and the addition of naturally coherent points in and around the site have provided a network of measurement points with wide coverage. The CRs have provided discrete point measurements that can be correlated with other ground-based monitoring solutions like GPS, levelling, piezometers and accelerometers, providing additional insight.

4.2.2 Collaboration between data provider and end user

To ensure a fit for purpose product that answers the key requirements of the end user, a good relationship between the data provider and the end user is hugely beneficial. An optimised InSAR application for mine closure requires an InSAR provider, with experience in assessing a site's feasibility for InSAR, accessing suitable SAR data, and successfully implementing InSAR techniques. A fully optimised approach also requires the mine's operator to strongly collaborate with the InSAR provider. A mine operator's detailed knowledge of the mine site allows an InSAR provider to tailor the technique and maximise the value of the data. The InSAR provider should provide technical training, consultation, and tools to aid the mine operator to see the value in the data.

It is especially important for collaboration with the use of CRs. With physical assets deployed on the ground, CRs add a new dimension of project complexity to InSAR. They add cost of manufacture, deployment, and maintenance, HSE exposure and logistics. These challenges do not exist within a typical InSAR project but had to be overcome at this site for InSAR to succeed.

The collaboration on this project also allowed for specific impactful benefits, including:

- Refining CR locations by identifying where they were/were not suitable (both in terms of InSAR monitoring and in terms of ground conditions/hazards).
- CR design evolution. The mine operator's closure team identified ways of improving the CR design in terms of practicality for this site.
- CR asset monitoring. This is completed both onsite and remotely. For example, when it is identified remotely that CR brightness is decreasing, site personnel can inspect the specific CR and complete maintenance.

Where such collaboration does not occur, there is a risk that end-users may not receive data that is fit for purpose, or adequately address the challenges of the site. A one-size-fits-all approach can be an attractive prospect but can quickly run into limitations posed by site conditions such as variable vegetation cover, non-favourable slope angles, or site activity such as construction work. Likewise, without appropriate expert support and training, the onus to interrogate a complex dataset and evaluate the impacts of any limitations rests on the non-specialist end user.

4.3 Practical challenges and limitations of corner reflector use

Using CRs for InSAR does add additional challenges, a short summary of which is provided in Table 1.

Table 1 Short summary of corner reflector capabilities and limitations

Capabilities	Limitations
Measurements obtained exactly where they are needed	Measurements from only where highly coherent points are located
Measurements possible across otherwise incoherent areas	Additional project cost and complexity
Greater precision than would be achievable with only natural scatterers	The InSAR technique becomes reliant on the CRs being present and not being disturbed
Provides a bright radar reflector reducing the risk that vegetation could limit InSAR coverage in the future	CRs are optimised for a certain satellite at a certain wavelength

The CR deployment at this mine was more challenging due to the COVID-19 pandemic and travel restrictions. A site visit would normally aid in the design of a CR network and its deployment, but without a site visit, some local factors were not immediately apparent. For example, over the course of the two-year project, a few of the 100+ CRs that were deployed were not usable for the full period. In the wet season, some CRs were partially flooded, reducing their ability to efficiently reflect the radar beam. Similarly, some CRs close to tall vegetation filled with leaf litter. To prevent the accumulation of debris in the CRs, covers were installed over the impacted CRs. A human challenge has been theft and vandalism of CRs that are close to roads.

4.4 Corner reflector alternatives

For AOIs with poor coherence, there are alternatives to CRs. While CRs are passive radar backscatterers, an active radar source or Compact Active Transponder (CAT) can be deployed in a similar way, as shown by Hole et al. (2011). The benefit of a CAT is its markedly smaller size, and that it does not need to be specially aligned towards the LOS of a certain satellite. However, they do require power, are more expensive and can be a more tempting target for vandalism.

To increase coherence without deploying infrastructure, more frequent SAR images can be used in the data stack. Shorter time spans between images leave less time for the ground surface to change, which typically improves coherence. However, this is limited by the maximum revisit time of a satellite. There are, however, modern constellations of SAR satellites providing revisit times down to daily acquisitions, such as Capella Space (2022) and ICEYE (2022). These new generations of SAR satellite are not yet proven for InSAR use.

A third alternative to improve coherence, especially in vegetated areas, is to use longer radar wavelengths such as L-band, which can penetrate through vegetation better than shorter wavelengths. All L-band data available at the time of writing are from commercial SAR providers. However, there are future SAR missions planned for more regular, open-source L-band such as NASA and ISRO’s joint NISAR mission (Valev 2022) and ESA’s Rose-L missions (ESA 2020).

The InSAR processing workflow can also be adapted to improve coverage. A technique called Temporary Scatterers can be used to enhance InSAR coverage and span gaps both spatially and through time. This increase in coverage can result in increased uncertainties.

5 Conclusion

InSAR is a ground motion detection technique that can be successfully utilised in a mining setting for mine closure. Closure can add challenges to the application of InSAR, so collaboration with a bespoke InSAR provider will enable the end user to provide input into the application of the technique, which in turn aids in gaining the most from the data.

The InSAR results provided here are not a comprehensive description of the InSAR data over this mine site. However, to comment generally, the important addition of CRs has improved InSAR coverage across the AOI, including where InSAR would otherwise not provide measurements. They have allowed the mine operator to monitor this site all year and with millimetric precision using InSAR. A close collaboration between the site operators and the data providers is key to the success of such projects.

Acknowledgement

This paper has been written with special thanks to the mine operator's closure team. Without their input, this project would not have been possible. Thanks also to the mine operator who has approved this collaborative paper. We thank the reviewers for their considered review and constructive comments. Finally, thank you to the collaborators at CGG from within the InSAR, Satellite Mapping and Minerals and Mining teams.

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