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# Operational mine monitoring with InSAR

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## Abstract

*Imagery acquired from spaceborne Synthetic Aperture Radar (SAR) sensors can be used to monitor ground motion over man-made targets and natural terrain. SAR Interferometry (InSAR) has been demonstrated as an effective tool for characterising slope creep and subsidence at operating mine sites. Conventional InSAR approaches are limited in their ability to monitor areas of active dumping/excavation and measure fast motion. Furthermore, there is typically a latency of weeks to months between occurrence of movement and delivery of monitoring products to mine engineers. Operational improvements to InSAR processing and onsite product usage have shifted InSAR from a nice-to-have to a need-to-have service at many mines.*

*This paper examines three case studies of InSAR use for operational mining. In the first, motion detected over 12 months at an open pit mine is reviewed. In this pit, the ground-based monitoring is extensive and can be used to verify areas of motion that are at the high end of InSAR's detectable range of motion. Other in situ instrumentation can detect sub-millimetre deformation; however, they are single point measurements rather than the wide coverage offered by InSAR. InSAR's wide coverage is shown to detect previously unknown areas of movement.*

*The second case study is from an underground mine using the block-caving mining method. The InSAR images cover the entire area of surface subsidence. InSAR measurements are used to determine the limits of deformation as a result of caving, to a level of 1 mm over one year. In the field, this measurement of small deformation extends beyond the visible crack limit. By comparing InSAR deformation over several years, the changing limits of the block caving strain front can be mapped and compared to crack limit predictions, existing cracks that have been mapped in the field, and historic production limits to improve the predictions of deformation and caving advance into the future.*

*The third case study is from a run-of-mine stockpile located at an open pit mining facility. InSAR measurements are used to measure deformation over the entire surface of the stockpile. In this case, the deformation is caused by settlement, rather than instability. The data is evaluated to distinguish settlement from instability. Unfortunately, there are few available cases of instability monitored with InSAR with which to compare to normal settlement. Distinctions are suggested, to be validated with future work.*

*Evaluating the results of InSAR monitoring allows for improved risk management of geotechnical hazards because previously unknown areas of motion, or unrealised extent of existing areas, can be identified when the rate of motion is very small. The additional time provided by this early warning can give a mine operator valuable time to re-assess the hazards, and undertake more thorough analysis or install more focused monitoring in order to mitigate the risk, if necessary. Additionally, the improved knowledge of the state of stability of the geotechnical structure allows for improved analysis and design, which can result in more optimised design and operation of the mine.*

## 1 Introduction

Satellite-based interferometric synthetic aperture radar (InSAR) has the ability to detect small deformations over large areas with high precision. Deformation monitoring can detect motion as low as 5 mm between two images, and at the millimetre scale when multiple images are combined for improved error processing.

InSAR's promise has long been the ability to detect risks across an entire mine site, including pits, stockpiles, leach pad, tailings etc. The capacity to map the extent of deformation areas and to identify potential hazards in areas where no other monitoring exists are the key benefits associated with InSAR for mining applications.

Several limitations have hindered a wider adoption of InSAR for operational monitoring of slope creep and subsidence at mining facilities. Firstly, the processing time required to deliver measurement results after a new image has been acquired by satellite has traditionally been days, weeks or even months. This lag has meant that it is often too late to implement mitigation measures for a given risk. Secondly, active mine sites have dynamic, constantly changing surfaces, making it difficult for successful InSAR measurements between image acquisitions. Thirdly, the rate of slope of deformation and subsidence at a mine site can be extreme and limits conventional InSAR monitoring methods to monitoring only the slower movement areas.

This paper provides an overview of improved InSAR techniques that overcome previous limitations and presents three case studies to demonstrate the operational value of InSAR for mining.

# 2 InSAR overview

Over the last five years, the adoption of interferometric synthetic aperture radar (InSAR) techniques for monitoring displacement has increased in the mining sector. Operational users have integrated InSAR into best practices and are pushing service providers to improve InSAR product reliability and quality.

InSAR techniques have been used to monitor slope stability, tailings dams and infrastructure at mine sites around the world (Rabus et al. 2009; Herrera et al. 2010). Mine operators have benefitted from InSAR by improving safety, production and environmental monitoring but they have also identified limitations to the techniques. For fully operational InSAR monitoring, mine operators require reliability, quality and timeliness. Decision makers require rapid delivery of 24 to 48 hours to act on potential risks, but existing methods had significant limitations in meeting this requirement. Open pit mine sites also have extremely dynamic, constantly changing surfaces that impact InSAR monitoring in two key areas:

- Quality (coherence) is impacted due to changing ground cover.
- Fast motion exceeding the wavelength over short distances causes aliasing.

This section discusses InSAR improvements realised to address these three issues of dynamic landcover, fast motion and product timeliness.

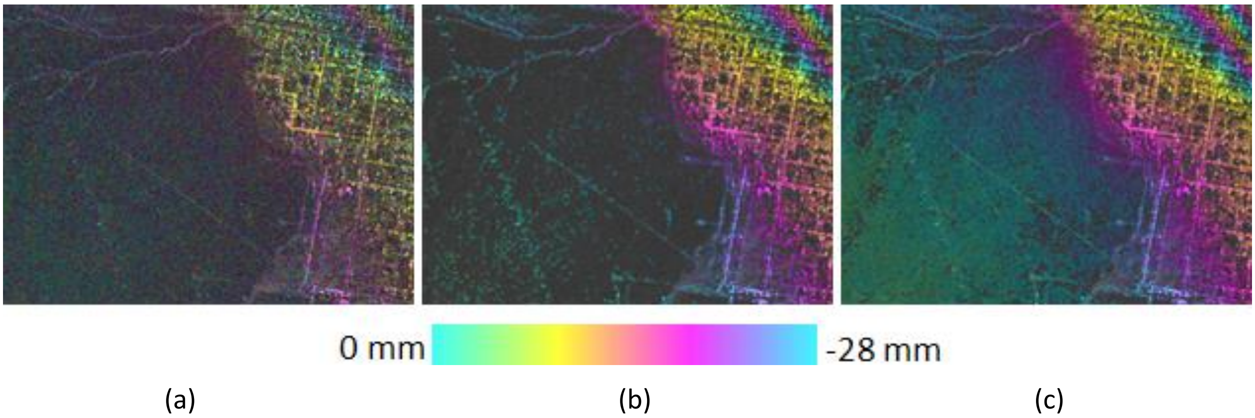
## 2.1 Temporary targets

InSAR can exploit a series of overlapping radar images (known as a 'stack') to measure ground surface movement. Each image is a grid of pixels, only some of which are information-bearing. In order to monitor a given target on the ground, it must reflect a stable echo to the radar satellite over a minimum of two images acquired from near-identical viewing geometry. Hence, InSAR is predicated upon identifying targets with a temporally stable signal; such targets can be classified as Permanent (or Persistent) Targets or Temporary Targets.

A Permanent Target (PT) is a SAR image pixel that reflects a stable signal to the satellite over multiple successive passes. PT's are ideal for temporally continuous monitoring of ground displacement with millimetre accuracy. PT's can be further divided into Point and Distributed Targets/Scatterers. A Point Target is a SAR image pixel dominated by a single object that individually determines the return signal. A Distributed Target is a SAR image pixel that contains many sub-objects that collectively contribute to the radar echo; its signal degrades due to realignment of sub-objects over time, and due to changes in look angle over multiple satellite passes. Point Targets are ubiquitous in urban/man-made environments, whereas Distributed Targets are much denser over natural terrain such as bare ground, parks, or dykes. Distributed Targets can also be used for temporally continuous measurements of ground displacement, but with a higher error than Point Targets.

A Temporary Target (TT) is a SAR image pixel that returns a stable signal to the satellite over discrete periods of time. For instance, a rock may be exposed during the summer months, but obscured by snow during the winter. The displacement of TTs can be characterised for each time period during which they are stable. Because TT's exhibit fewer phase-stable temporal samples, their measurement accuracy is lower than PT's. Most InSAR methods overlook TT's because they are not continuously stable over time. However, TT's are important for monitoring areas with dynamic landcover as targets can appear due to excavation, disappear due to deposition, or cycle due to weather phenomena.

Figures 1 and 2 illustrate the reduction in noise and improvement in coverage and measurement density that is possible by integrating both PT's and TT's for InSAR displacement mapping.



(a) (b) (c)

**Figure 1** (a) The phase of two SAR images can be differenced to measure displacement, albeit with high error and noise. PT's (b) provide an accurate displacement history, with appreciable noise reduction. Furthermore, TT's (c) extend the spatial coverage, while preserving low noise and providing a complete or piecewise displacement history. Note that the edges of the displacement area are clearly revealed only with TT InSAR

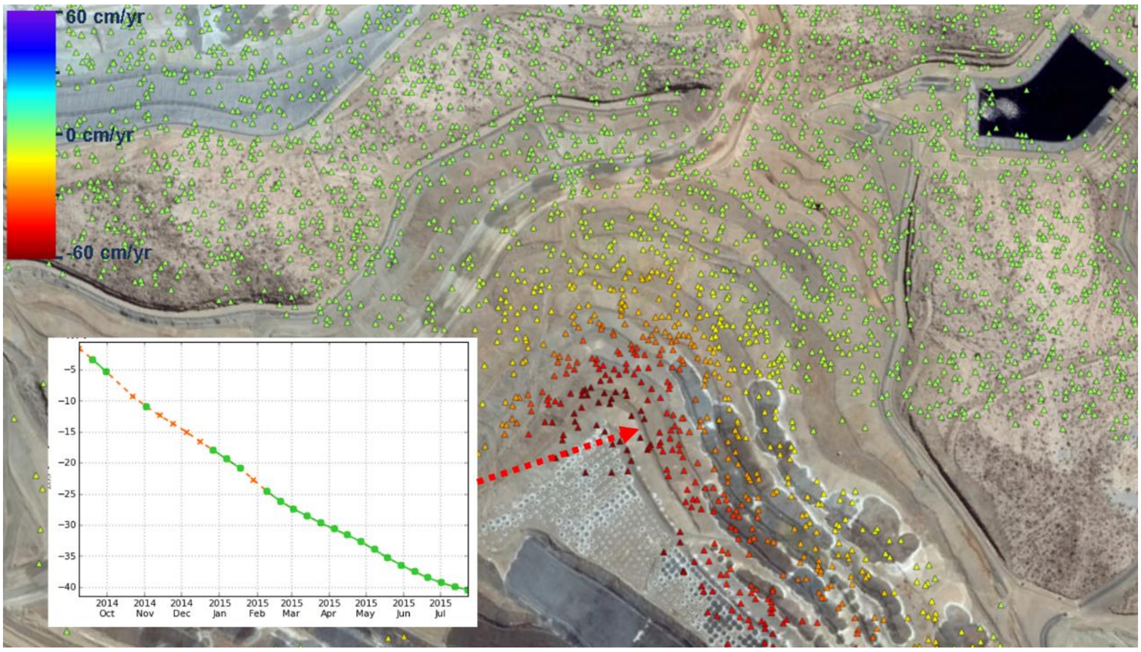


**Figure 2** The spatial and temporal evolution of displacement can be mapped for tens of millions of targets (triangles) throughout an active mine site. The graph shown in this figure is velocity for one year, of a temporary target exhibiting original measurements (solid circles) during time periods of inactivity interspersed with interpolated measurements (dashed crosses) during periods of high mining activity. Such TT's are ubiquitous at active mines; relying exclusively on PT's significantly reduces the coverage and density of measurements

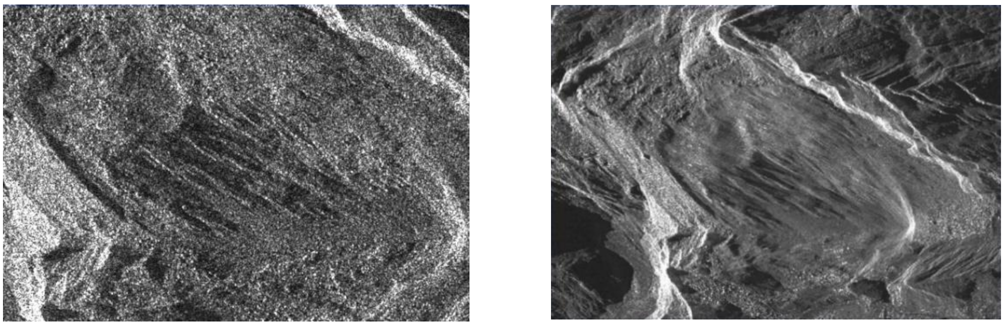
## 2.2 Fast motion

Certain mining areas such as slopes overlying block caving operations exhibit motion exceeding several centimetres per day. For the purposes of InSAR monitoring, fast motion is defined as motion exceeding half a wavelength along the satellite line-of-sight (LOS) over a distance of two resolution cells during one satellite revisit. For instance, for the TerraSAR-X (TSX) Stripmap beam, LOS motion exceeding 15 mm over a distance of 6 m per 11 days introduces aliasing. This means that the motion is spatially undersampled, and a higher resolution SAR image can sample it adequately. Aliasing will limit typical InSAR methods in fast motion areas; a complementary technique known as speckle tracking sacrifices some accuracy to reduce the impact of aliasing. Basically, this technique is equivalent to doing a very accurate local fine registration on the coherent speckle present in both images. The correlation algorithms used for this task are related to corresponding methods in radargrammetry. The resulting shift map can be converted to a motion map in the same manner as an interferogram.

The sensitivity of InSAR is linked to the half-wavelength, whereas the sensitivity of speckle tracking is linked to image resolution; for TSX or Cosmo Skymed Stripmap, these numbers are 15 mm and 3 m respectively. Speckle tracking can recover fast motion when it causes entire image pixels to shift to an extent that can be detected by correlation techniques. The sensitivity of speckle tracking lies between 1/20th and 1/10th of a resolution cell, i.e. 150–300 mm for TSX Stripmap. Thus, a motion field with an increasing spatial gradient can be measured by InSAR up to the point where it gets aliased; speckle tracking starts detecting this motion field where it integrates to the aforementioned minimum sensitivity. Due to the varying sensitivities of the two techniques, there may be a spatial gap in measurements. In practice, such gaps are readily interpreted by the user due to the presence of fast motion flanking either side of the gap, measured by InSAR and speckle tracking respectively.

For completeness, it is useful to describe SAR speckle and its characteristics. Speckle is a noise-like appearance common to all coherent imaging systems such as SAR, sonar, and laser. The true speckle pattern of SAR amplitude is a result of coherent addition of distributed scattering centres that exist within a resolution cell. The similarity of the speckle pattern between two SAR images is directly linked to coherence. The temporal coherence is reduced by changes of sub-pixel location and strength of distributed scatterers, whereas the spatial coherence is reduced by different incidence angles to the distributed scatterers within a pixel. As the speckle tracking applied for measuring fast motion uses correlation over image patches, it is a combination of true speckle tracking and feature tracking. In other words, the correlation techniques track spatial shifts in: a) true speckle over featureless ground, and b) ground features with correlated or uncorrelated speckle.

Figures 3 and 4 illustrate some nuances of speckle and coherence over a block cave mining area exhibiting fast motion.

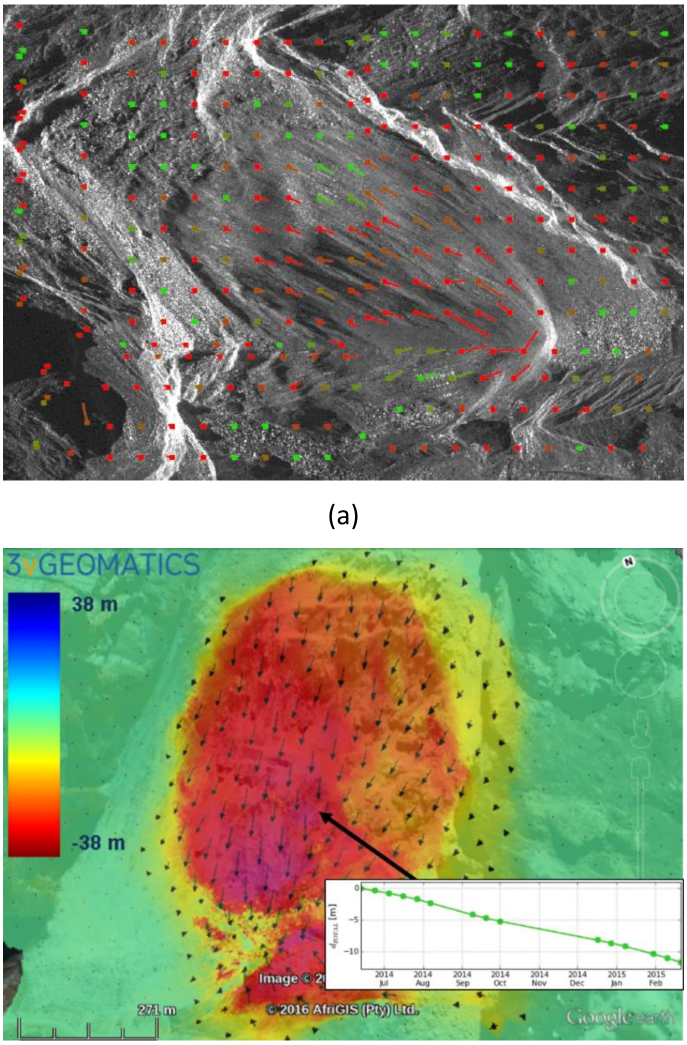


(a) (b)

**Figure 3 (a) SAR speckle is evident as salt and pepper noise in a single amplitude image over a complex block caving operation. (b) Multiple time-separated images have been incoherently averaged to derive a mean amplitude image. Such incoherent averaging reduces speckle, but also reveals signs of fast motion in the blurry area at the centre of the image. The blurriness is caused by temporally averaging pixels that are misaligned due to the fast motion**

**Figure 4** A zoomed-in coherence image shows relatively high coherence in white surrounding the fast motion zone in black; in this case, the low coherence in the centre is caused by misalignment of pixels over time, rather than decorrelation of the speckle

Figure 5 shows an example of speckle tracking applied for displacement mapping of this large block caving zone.



(a)

(b)

**Figure 5** (a) An individual speckle tracking map shows vectors indicating local shifts between two images; the longer vectors at the centre measure fast motion at the block caving site. (b) All pairings of speckle tracking maps can be integrated into a refined displacement map that shows the spatial and temporal evolution of fast motion. The arrow size indicates magnitude of deformation

## 2.3 Rapid delivery

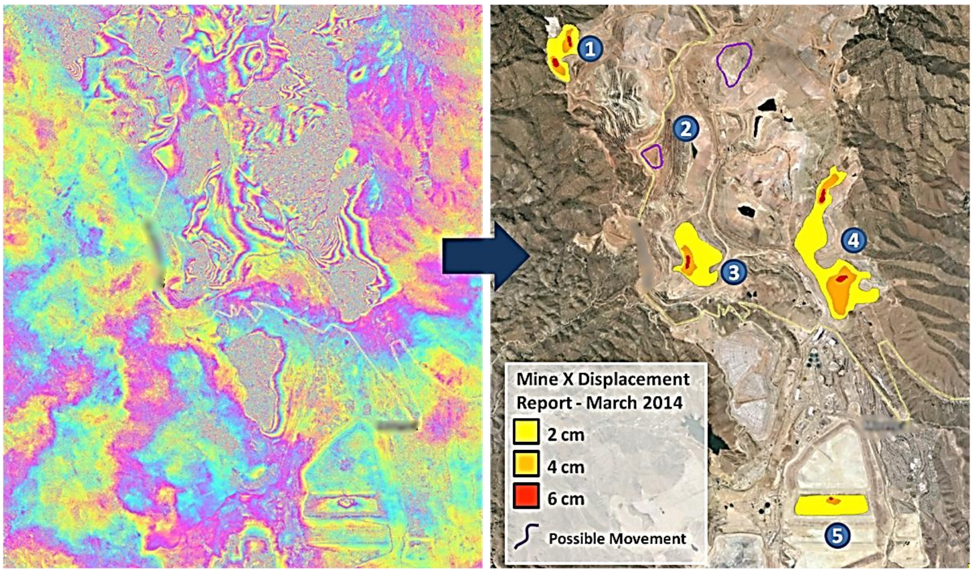
To better integrate InSAR data into ongoing mine operations, improved delivery times are necessary. For operational mine monitoring, two pieces of information were critical:

- Identification of new areas of displacement.
- Changing rates of displacement in known movement areas.

Recent operational monitoring programs have shown that delivery of accurate, reliable deformation results within hours of satellite acquisition is possible. Faster processing and improved information extraction can meet operational needs with minimal impact to data precision. Rapid delivery allows operators to make informed decisions and improve environmental monitoring, safety and production.

SAR images cover large areas of thousands of square kilometres with high resolution of a few metres. This results in several hundred million pixels that need to be analysed spatially and temporally to generate measurements and deliver displacement maps. Rapid reporting requires acceleration of all bottleneck InSAR algorithms. In many cases the algorithm can be easily separated into parallel tasks and/or leverage multiple Central Processing Units or Graphics Processing Units. Most image processing algorithms are amenable to parallel processing because each pixel or groups of pixels is subject to the same computation, and can therefore be assigned its own processor, followed by aggregation of computed results. For example, a commonly used InSAR algorithm, known as the Goldstein-Werner (Goldstein & Werner 1998) filter achieved a speedup ranging between 3x and 16x depending on the workload. Other algorithms were sped up 1–3 orders of magnitude to enable rapid delivery of displacement products for mining.

Extracting critical information from often complex InSAR images is vital to improve the speed and effectiveness of monitoring. Figure 6(a) shows an interferogram and Figure 6(b) shows a sample rapid report for a mine site. Only the relevant data from the interferogram is shown, and presented as an easy to use map. To use the InSAR generated information effectively, mining staff must be able to extract the relevant information quickly, efficiently and with minimal training. Areas of displacement are highlighted across the mine site, providing mine managers actionable information. An accompanying displacement summary provides additional interpretation for each area of displacement identified.



(a) (b)

**Figure 6** (a) An interferogram and (b) a sample rapid report for a period of 33 days. The objective is to quickly provide only relevant information to mine operators for decision making. Areas of displacement are highlighted; two areas show only 'possible movement', because of some ambiguity with height error. Each rapid response map is accompanied by concise analysis including magnitude of deformation, temporal context. New motion areas are highlighted

# 3 Case studies

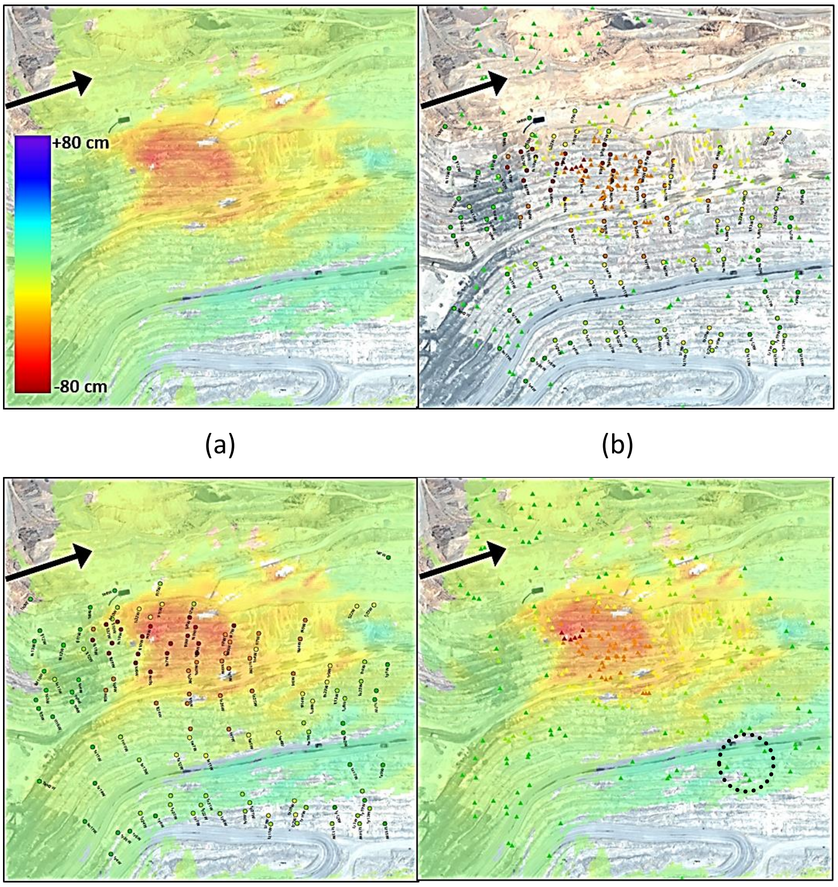
This section provides three case studies from operational use of InSAR products for mining.

## 3.1 Open pit

This case study is from an open pit, hard rock mine. The mine is a porphyry copper deposit, with lithology consisting of intrusive and volcanic igneous units. The study area consists of medium to fine grained quartz monzonite porphyry. The dominant structures are long, continuous faults with little to no gouge. They strike east-northeast and dip 55 to 65 degrees to the south. The other significant structures are joints sets that generally strike to the north and dip 70 to 75 degrees to the east. At the time of the study the active working slope was 365 m high. The pit slope had an inter-ramp angle of 40 degrees and dipped to the south. The study area had been in operation for five years with production ranging from 50 to 100 ktons per day. At the time of the case study, production was 50 ktons per day.

The InSAR coverage for this mine property is primarily intended for areas with little to no ground-based monitoring. All areas of the active pit, including the study area, are monitored with some combination of ground based monitoring technology, so the pit is not a primary monitoring target for InSAR. However, due to the wide coverage area and favourable monitoring geometry, many areas of the pit do have useable InSAR data. The purpose of this case study is to review the InSAR data in the pit study area and compare it to the ground based monitoring in order to assess the utility of the results in areas without ground-based monitoring.

Figure 7 shows a comparison of measurements from InSAR over the pit with prism for an 11 month period.



(a) (b)

(c) (d)

**Figure 7 An overview of the pit area. (a) Cumulative InSAR results for an 11 month period are shown; (b) plots the coincident prism data; (c) shows a strong correlation between the two data sources; (d) shows selected points and the location of the point used for comparison in the following figure. The black arrow indicates the satellite LOS**

The study area was monitored for deformation using ground-based instrumentation. The entire study area was monitored with IDS IBIS-FM radar. Two Leica TM-50 total stations measure approximately 100 prisms once per hour. Several CNI Slideminder wireline extensometers and permanent GPS units continuously monitored known movement areas. An on-going InSAR monitoring program using TSX Stripmap imagery with 3 m spatial resolution was implemented in 2014. InSAR displacement reports were delivered every 11 days, within a few hours of image acquisition and comprehensive InSAR reports including a time series of deformation measurements was delivered every six months.

The time series data from a stack of interferograms is directly compared to the time series data from reflective prisms. Specifically, InSAR points that are co-located with reflective prisms are identified, then the time series data from each is plotted together. The reflective prism data is three-dimensional in the direction of movement while the InSAR data is one-dimensional in the look direction of the sensor, or LOS. To compare the time series data more directly, the prism data is re-processed to also show the expected measured motion in the direction of the InSAR sensor.

The stack of InSAR images used spans 11 months, with a total of 30 images; however, for this study only six months of prism data was available for the study area. The six months of prism data is compared with the corresponding six months of InSAR data in Figure 8. When the 3D displacement was converted to match the InSAR LOS geometry, it shows that the data correlate strongly.

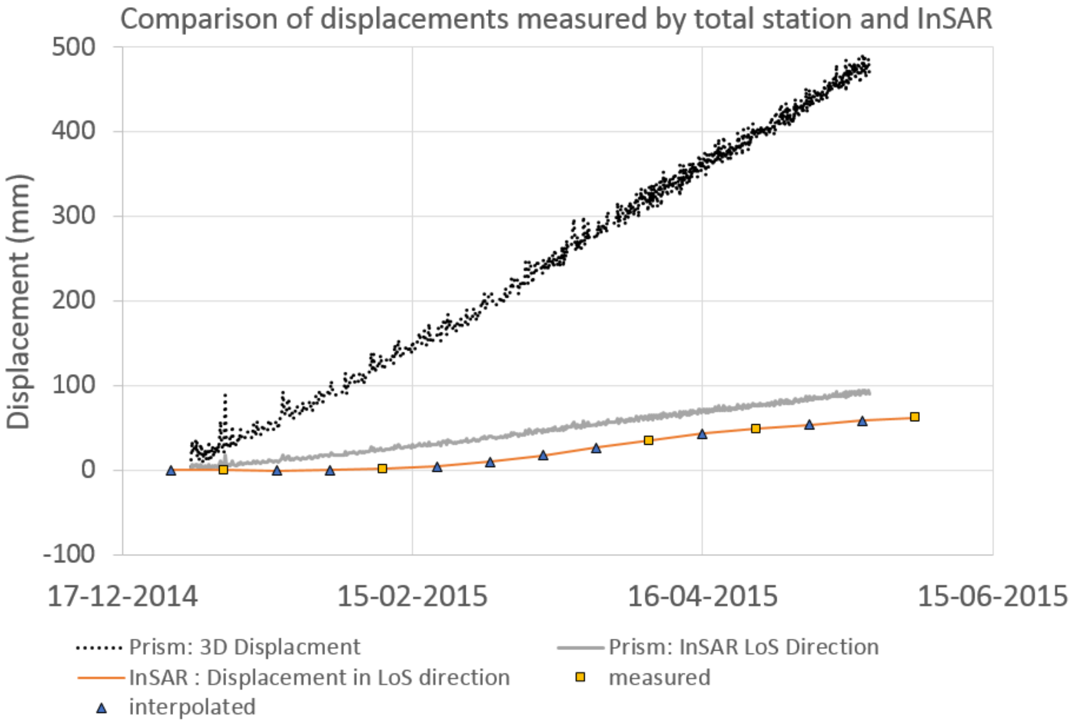


**Figure 8 Time series data for co-located prism and InSAR data points spanning a six month period. Both measured prism movement data and the calculated prism movement data in the LOS direction of the InSAR radar are shown. The displacement history from InSAR agrees well with the prism measurements projected along the LOS**

The ground radar monitoring from IBIS was also able to validate the quality of InSAR data. InSAR measurements were able to identify the same areas of movement on the pit wall with similar rates of deformation. Figure 9 shows that pit monitoring results from both sources are comparable; however, there are key differences that demonstrate that the two data sources are complementary. The frequency of ground radar measurements is approximately every 15 minutes while InSAR data is provided every 11 days. The high frequency allows mine operators to assess changing risks in the pit. InSAR can increase the monitoring coverage and provide monitoring beyond the pit crest to give geomechanical staff a better understanding of deformation.

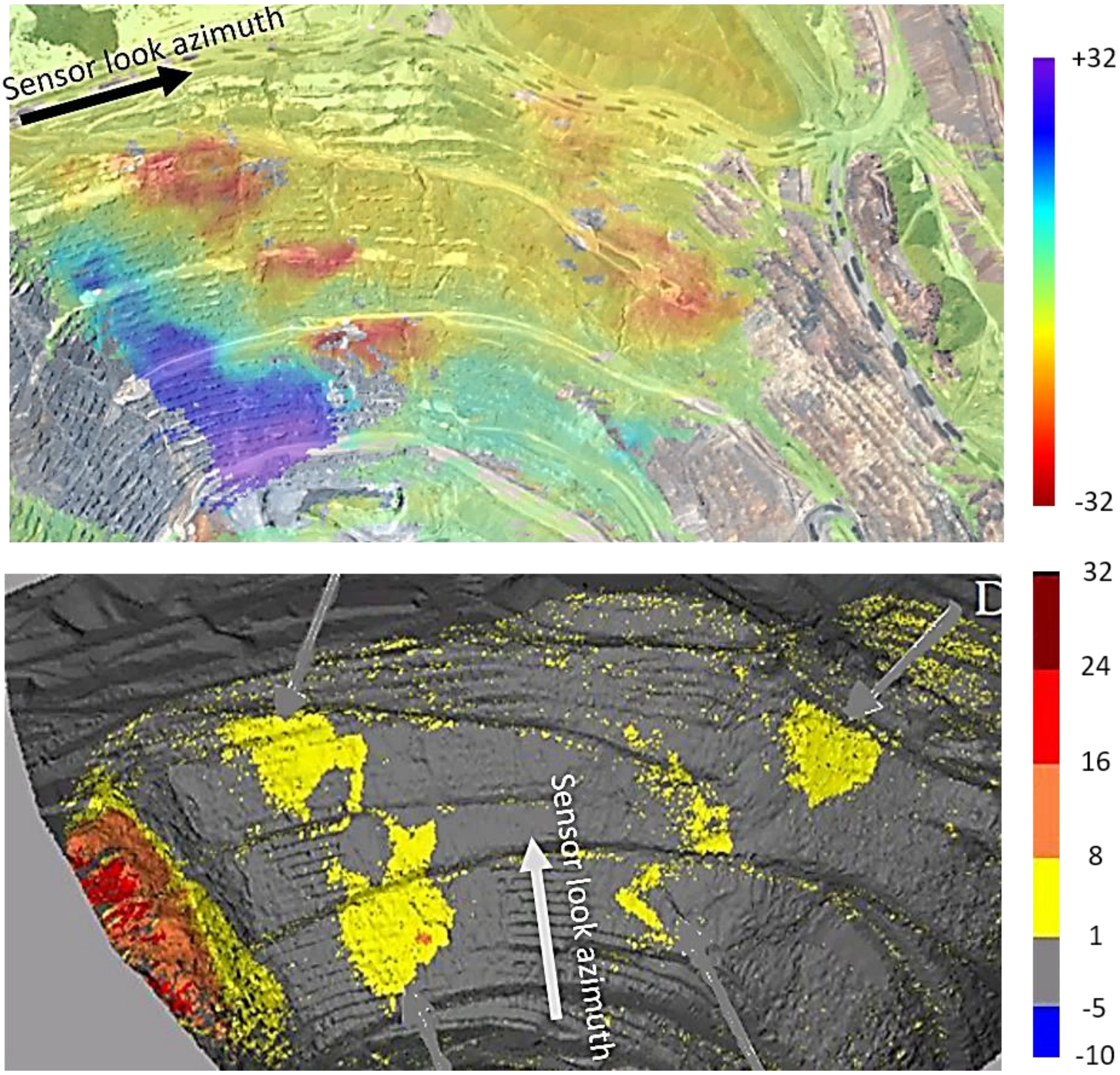


**Figure 9** **InSAR pit deformation observed from June 2014 to June 2015 in the top image. Ground based radar results from May to June 2015. The look directions of the LOS for both measurements are shown**

## 3.2 Block caving

The second case study is from an underground mine using the block cave method. It is a skarn deposit with bedding and major structure oriented east-west and dipping vertically. The daily production is 80 ktons. The cave zone is well developed on the surface. Several GPS units monitor the perimeter of the cave zone, but the data was not available for this case study. The goal for InSAR monitoring in this case are the areas beyond the visible crack limit, especially in the vicinity of important infrastructure. The concern is that subsidence induced by the block cave may cause damage to the infrastructure.

Extensive InSAR monitoring was undertaken using regular ascending and descending TSX Stripmap acquisitions of the block caving area. Ascending and descending satellite passes are more suitable for viewing east and west facing slopes respectively. Hence, combined measurements from the dual passes can improve the coverage of displacement measurements at mine sites with appreciable slopes.

Aliasing from fast motion has been a concern for InSAR monitoring. Some areas showed motion rates of 15 mm per day. To overcome this issue, speckle tracking techniques were applied in the fast moving areas overlying the block cave. Figure 10 shows the resulting deformation map that outlines the extent of the fastest moving areas, and reveals the shape of the motion field.

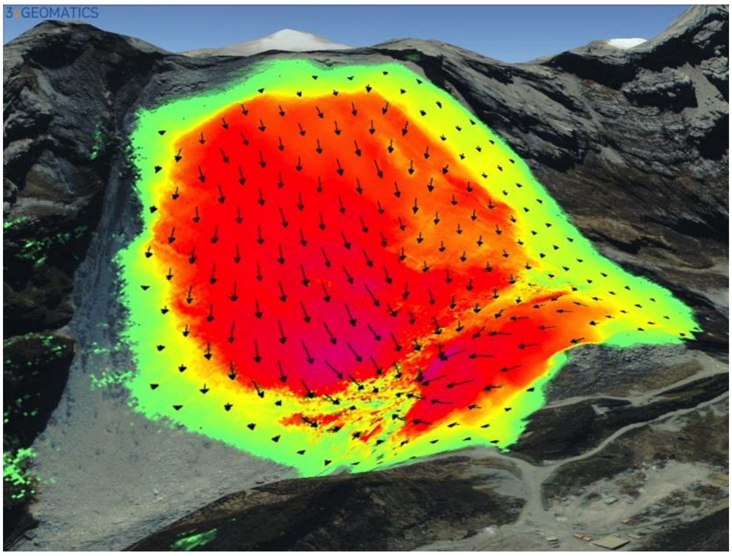
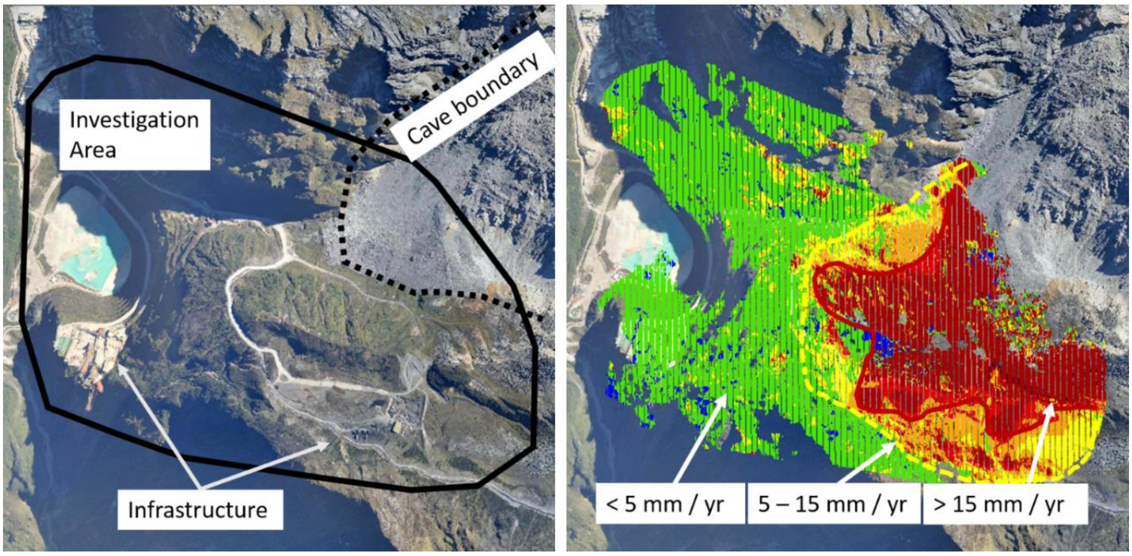


**Figure 10** Speckle tracking techniques were applied to measure fast motion caused by block cave mining. The larger red area at the top and the smaller red area at the bottom are the two main lobes of the motion field. The arrow size shows the motion magnitude and the local fall line

In addition to the fast motion area, InSAR measurements over the rest of the mine site were used to detect previously unknown hazards. Aliasing was not an issue beyond the edge of the cave, and InSAR was used to map subtle motion that could pose a risk to adjacent infrastructure. Figure 11 shows infrastructure proximal to the edge of the cave, and the utility of the InSAR results in mapping the zone of influence of the motion resulting from the block cave. Approximately 20 mm/year of deformation was measured.



(a) (b)

**Figure 11** (a) Infrastructure close to the edge of the cave boundary could potentially be affected by deformation resulting from the block caving. (b) InSAR results outside of the block cave map the zone of influence of the block caving. The infrastructure that is closer to the cave is within the zone of influence, and requires further monitoring and asset management

The infrastructure in that area should be reviewed to understand how much deformation can be tolerated. Projections of potential deformation assuming increasing, decreasing, and steady state movement rates should be made and compared to the infrastructure's tolerance for deformation and required lifespan. InSAR monitoring should continue to verify projections and detect changes. Additional monitoring with GPS should be considered to provide more frequent updates and to determine the movement direction.

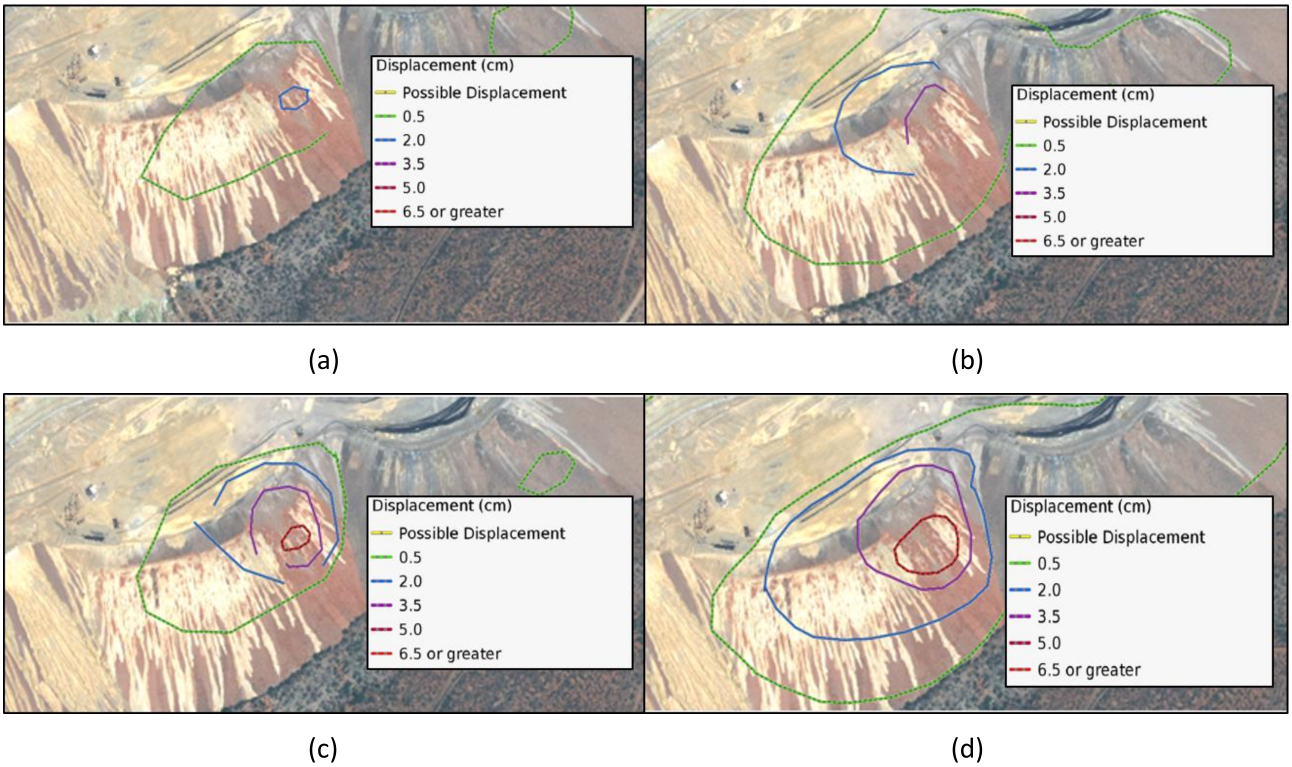
## 3.3 Mine stock pile

The third case study is an over burden stockpile at an open pit copper mine. The stockpile has been in use for over 20 years. The majority of the stockpile is active with recent material placement and routine circulation of process water and low pH solution for metal extraction. The stockpile varies in height from 15 to 150 m above natural ground level and covers approximately 1 km² of area. The rock used in this stockpile is primarily igneous intrusive such as quartz monzonite porphyry and diorite.

The specific location used for the case study is on the perimeter of the stockpile. In this location, there has been no active material placement or circulation of process solutions for over ten years. The nearest active area of the stockpile is 275 m away. The study location at the perimeter of the stockpile is 120 m high. There is no major infrastructure at the crest of the stockpile. There is a major process solution collection facility at the toe of the stockpile here.

There is no geotechnical monitoring instrumentation at this location. Inspections are conducted several times per year. The primary operational concern in the study area is the flow direction of surface water run-off resulting from seasonal rain. Tension cracks have occasionally been observed at or near the crest, but no significant deformation has been noted.

The stockpile was covered as part of an on-going InSAR monitoring program using TSX Stripmap imagery with 3 m spatial resolution. InSAR displacement reports were delivered every 11 days, within a few hours of image acquisition. Motion was first detected by InSAR between 15 and 26 August 2015 and continued to grow in the subsequent three images as shown in Figure 12. Storm water had accumulated in the area due to improper drainage and had stayed for a week or more before draining into the dump but no movement was identified prior to the InSAR report. The maximum LOS movement observed with InSAR was approximately 168 mm over an 11 day period.



(a) (b)

(c) (d)

**Figure 12** Motion was detected at the stockpile using InSAR. These consecutive rapid reports show a growing rate and extent of motion from 15 August to 28 September. The images show motion from (a) 15 to 26 August; (b) 26 August to 6 September; (c) 6 September to 17 September; and, (d) 17 to 28 September

Early movement detection allowed mine operators to implement a simple mitigation plan that included an additional storm water release drain and hauling material to the area for releveling. Subsequent InSAR reports did not show any additional motion.

# 4 Conclusion

Improvements in InSAR technology and deployment have a unique role to play in operational monitoring of slopes, subsidence and other mine risks. Space-based InSAR cannot match the monitoring frequency of prisms, ground-based radar or other in situ sources but it can provide complementary information in areas where other data collection is not feasible. Validation from other established techniques shows that the precision is suitable and coverage is unmatched.

Aliasing from rapid motion, incoherence from active mine sites, and lack of timeliness are no longer limiting factors in a well-executed operational InSAR program. Temporary Target processing algorithms allow for motion detection in areas of recent dumping or excavation. Rapid motion can be monitored and provide insight into the rate and extent of deformation from mining techniques such as block caving. It is also possible to provide deformation data from InSAR within hours of acquisition rather than days.

The greatest benefit of InSAR is the ability to detect and measure previously unknown deformation; InSAR is highly effective in combination with a terrestrial monitoring system. The case studies show that risks can be reduced by early detection, and an improved understanding of mine deformation is possible.

# Acknowledgement

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