

Title:

**Interferometric Synthetic Aperture Radar (InSAR) and its potential to monitor subsidence over caving zones induced by underground mining**

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**Interferometric Synthetic Aperture Radar (InSAR) and its potential to monitor subsidence over caving zones induced by underground mining**

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## **ABSTRACT**

Utilisation of InSAR technique for monitoring of subsidence in mining areas, employing open pit and underground mining methods, has large potential due to sensitivity and the safety issues associated with usage of the classical surveying techniques. InSAR can also be very competitive concerning the cost of provided results. However, there are few issues that may significantly limit InSAR applicability for subsidence monitoring in mining areas. The altered terrain topography, involving steep slopes and deep pits, may lead to the layover of radar signal for specific satellite and pit geometry. Also, the highly dynamic character of subsidence induced by mining, especially using mass mining methods, may lead to issues such as apparent heave and ambiguous results.

In this paper the authors analyse the above-mentioned issues and demonstrate how InSAR technology was applied, as a supporting system, to monitor large scale and highly dynamic subsidence for a real case study in Western Australia.

**Key Words:** subsidence, mine deformation, InSAR, layover, phase ambiguity, topographic analysis, mine surveying, remote sensing, caving.

## INTRODUCTION

Mass mining techniques and the increased extraction intensity are clearly visible trends of future open pit and underground mining operations. The resultant mining impacts, including rock mass deformations and surface subsidence, will also have greater magnitude, extent and dynamics.

To better understand rock strata deformation mechanisms the accurate data of rock mass displacement, for the existing case studies, should be collected and analysed. The classical deformation surveying techniques have notable disadvantages that limit their reliability and sensitivity. They employ point-by-point data collection and therefore are relatively time-consuming and costly. Surveys usually cover only a small area and yield localised information. Furthermore, the classical techniques are not applicable for monitoring of inaccessible areas and since the monitoring points are not close enough; they are not able to provide reliable interpolation from collected data (Ge, Change and Rizos, 2004). Considering the above, there is increasing demand to design and utilise cost-efficient supplementary or alternative techniques with the capability to deliver continuous coverage and accuracies, comparable or exceeding that of classical surveys.

The attempts to utilise the results of photogrammetric surveys, particularly the aerial photogrammetry, rendered very promising results, however, they were limited in their sensitivity and accuracy. Only large magnitude deformations could be detected and analysed. The photogrammetric methods were not sensitive enough to monitor the early stages and far extensions of the deformation process.

By using the Interferometric Synthetic Aperture Radar (InSAR) the large scale, as well as, the localised surface subsidence can be monitored to the sub-centimetre accuracy. In addition the InSAR technique does not require any field instrumentation and consequently it allows for monitoring of hazardous and inaccessible areas. The Geographical Information Systems (GIS) software or any other spatial processing software can easily be used to further process the InSAR results. These results could be then utilised to provide a valuable calibration tool for the development of rock strata deformation models. Utilisation of InSAR technique significantly reduces the costs of subsidence monitoring and interpretation.

In spite of the wide application of InSAR techniques for monitoring large-scale deformations of the Earth crust, specific modifications are necessary to utilise of this technology in the mining context. Limitations, such as difficulty to resolve the deformation on a high gradient slope, or to retrieve the subsidence for localised, highly dynamic, ground movements and

unavailability of SAR images with the desired specifications, restrict the potential to monitor the high rate, localised mine subsidence on a day-to-day basis (Wegmüller *et al*, 2005). In this paper the authors analyse the above-mentioned issues and present how the photogrammetric and InSAR techniques can be applied to monitor large scale and highly dynamic subsidence. A real case study in Western Australia is used to present the results of analysis. Western Australia's climate of dry cloudless weather, with minimal rainfall, is conducive to obtaining very reliable SAR based interferograms. However, the vast mostly uninhabited area is not a primary target of satellite missions, hence the archived data is scarce and without any continuity. This issue has left authors with very small number of acquisition (10 ERS-2 SAR images between year 2000 and present) for the selected study area. The geometry of the archived ERS-2 data was also almost the worst for the InSAR application. The topography of a mine site may cause problems that can drastically reduce the amount of good measurements when using InSAR. In this paper, authors present an application of a new technique allowing for geometrical interpretation of mine site topography and for identification of poorly described areas. A comprehensive analysis of ground deformation dynamics, based on topographical surveys, has been carried out in order to determine which InSAR results may be affected by ambiguity issues. As a result, the authors were able to assemble a set of recommendations regarding the best geometry of SAR acquisitions, selection of SAR data, impacts of topography and processing techniques. These recommendations should lead to successful utilisation of InSAR method for monitoring of subsidence induced by the future mass mining.

## **SUBSIDENCE DERIVED FROM TOPOGRAPHICAL SURVEYS**

The large magnitude of subsidence that is developed over a long time period suggests that it should be detected by analysis of routine topographical surveys; particularly utilising the photogrammetry as a surveying technique. Such surveys are common practice at large mine sites. They provide up-to-date maps required for production purposes. The effective vertical accuracy of these surveys is in the range of  $\pm (0.1 - 0.2)$  m. Such accuracy is deficient for short-term subsidence analysis. However, the photogrammetric maps may be utilised when performing long term subsidence analysis and determining the trends and dynamics of this movement.

In this particular case study, the authors accessed and analysed six digital terrain models (DTM), based on the aerial photogrammetry surveys, created between 2001 and 2006. The DTM models were used to determine the vertical component of movement (subsidence) that

occurred between dates of topographical surveys. To remove the systematic error from individual DTMs, the common stable reference areas were selected and average elevations for each area were calculated. By comparing these average elevations, calculated for individual DTMs, the systematic component of elevation errors was determined and later removed from the calculated subsidence. The subsidence was calculated utilising the DTM from year 2001 as a base. The examples of subsidence maps, spanning years 2001-2003 and 2001-2006, are presented in Figure 1. The blue areas (south-west of the pit) represent subsidence induced by underground mining, when the red areas (north of the pit) represent the waste deposited inside the pit.

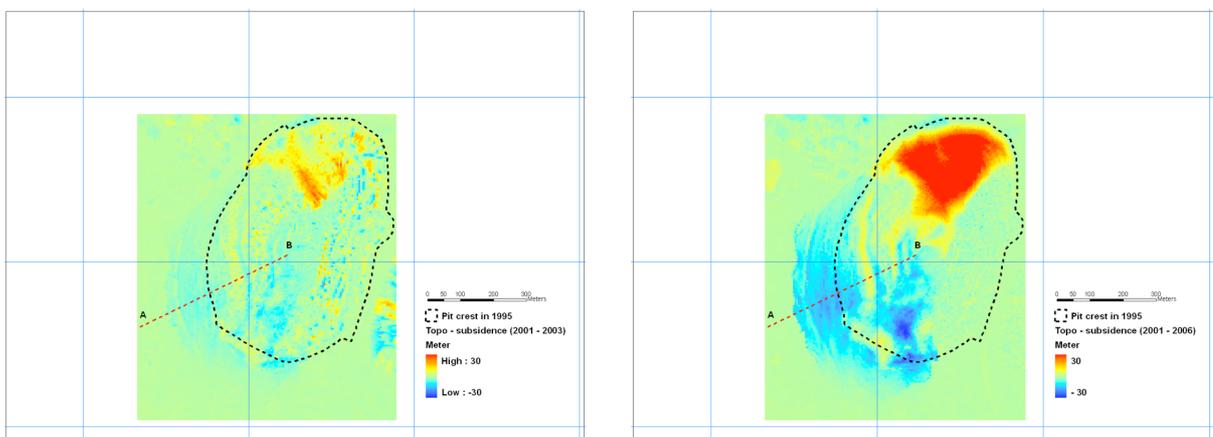


Figure 1: Subsidence between 2001-2003 and 2001-2006 derived from topo surveys

### **Subsidence magnitudes and rates**

The series of cross-sections, representing development of ground movement along the profile A-B (marked in Figure 1) is presented in Figure 2. It is clear that the area with greatest subsidence (south-west of the pit) experienced a total of -17 m of vertical movement between years 2001 and 2006, with the average yearly subsidence rate reaching -3.8 m/yr (in 2005).

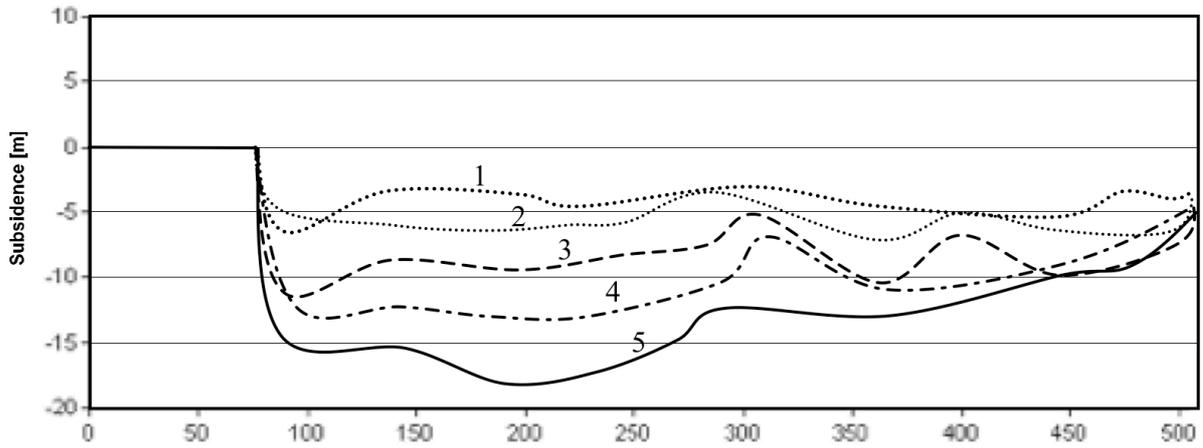


Figure 2: Subsidence referenced to DTM of 2001 along the cross-section A-B; (1) 2001>2002, (2)>2003, (3)>2004, (4)>2005, (5)>2006

The subsidence dynamics over the period 2001 and 2006 are presented in Figure 3. This assessment was performed for the region of maximum subsidence. To eliminate inconsistency of detected local subsidence values represented by the individual pixels, the maximum rate was determined by averaging subsidence over an area of sixteen pixels (~ 20 m\*20 m). According to the values presented in Figure 3(b), the subsidence rate reached the level of 6.0 m/yr or 16.4 mm/day. Changes of the subsidence rate were observed over relatively short horizontal distances; particularly the greatest change of ~6 m/yr was observed over the distance of 22.3 m. In this particular case the local geological fault was responsible for such great variation of subsidence rate.

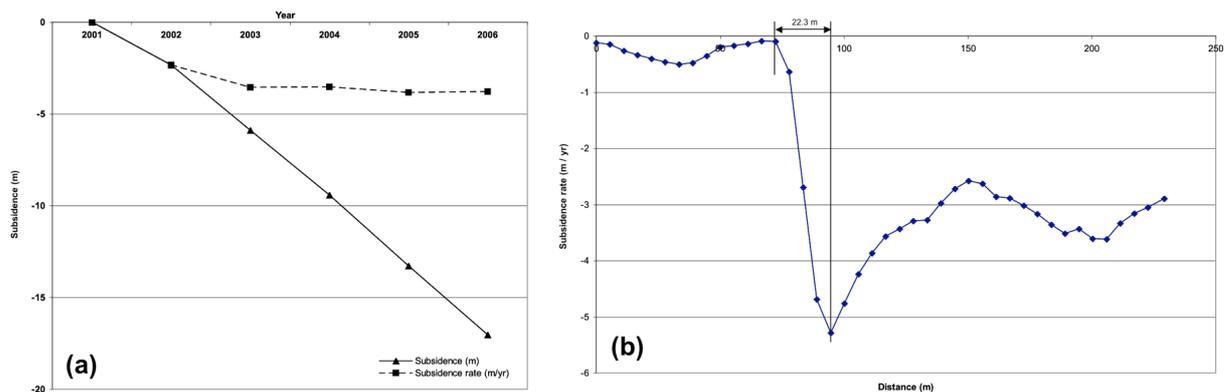


Figure 3: a) Development of subsidence between 2001 and 2006, b) Subsidence rate in the period 2003-2004 along the profile A-B (from the point A to the edge of pit's crest)

### Apparent heave

The subsidence results obtained from the analysis of topographical surveys suggested that some portions of the open pit slopes had experienced uplift (heave) not subsidence. Detailed

analysis of the slope movement explained this phenomenon as not real, but apparent uplift. It became clear that the change of elevation at any location is a result of two components: the vertical movement (subsidence) and the horizontal shift of the ground. If these two movements act on a slope or a mining bench, and the horizontal movement is directed towards the centre of a pit, the result can be an apparent heave of the ground (as shown in Figure 4). When creating graphs representing the subsidence troughs the “apparent heave” should be accounted for and removed from the final results.

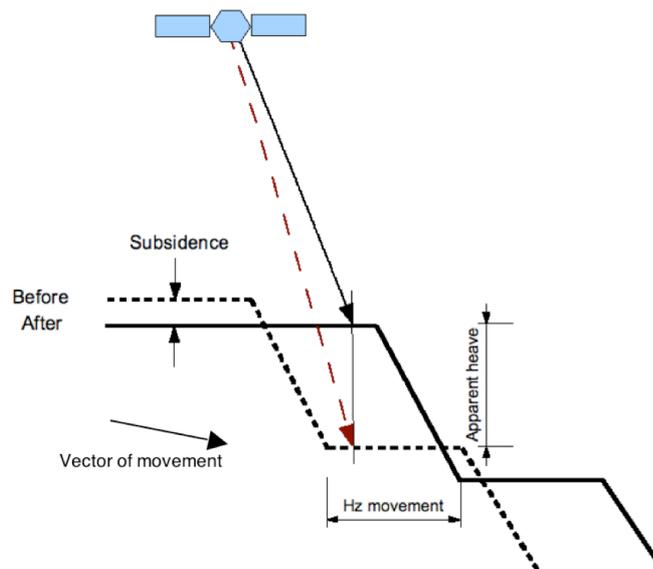


Figure 4: Apparent heave of the ground

As presented above, the analysis of DTMs, derived from topographical surveys, can provide valuable information regarding development of subsidence over underground mining. However, obtained results lack the sensitivity and accuracy that is required for more detailed analysis of rock strata movements. For this reason, the InSAR technique was tested to determine if it could fulfil these requirements.

## **SUBSIDENCE DERIVED FROM INSAR**

### **Short background of InSAR**

Satellite radar interferometry (InSAR) is a remote sensing technique. It makes use of Synthetic Aperture Radar (SAR) observations of the Earth's surface to acquire topographic information. By combining two SAR images of the same area, information about the

topography can be attained. This is achieved by subtracting the phase information of one image from the other, forming what is called the phase interferogram. The phase is related to the geometry of the satellites as shown in Figure 5 below. The difference in path length  $\Delta R$  is related to the phase via the equation:  $\frac{4\pi}{\lambda}(\Delta R)$ .

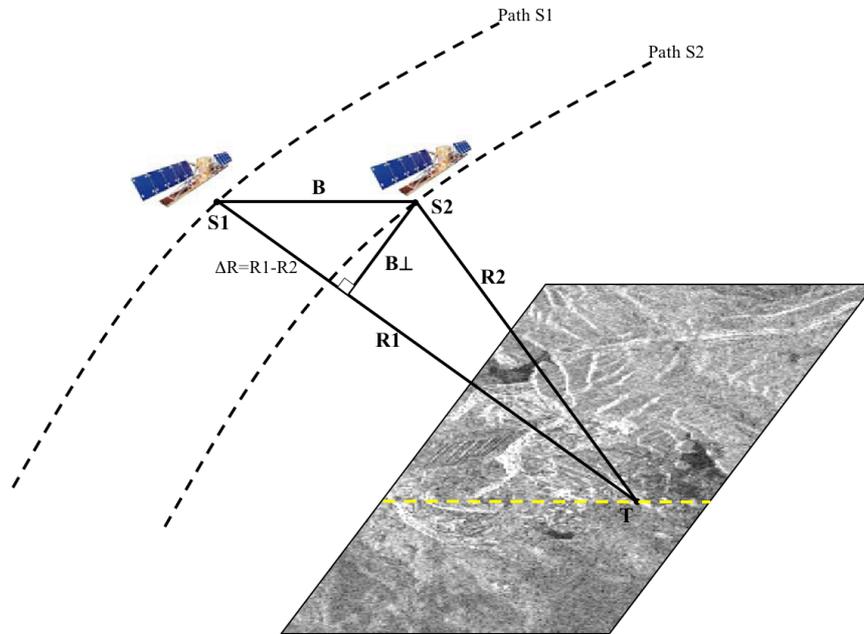


Figure 5: Geometry of acquisitions for InSAR processing. S1 and S2 are the 2 satellite positions, B the baseline, R1 and R2 the ranges to target T and  $B \perp$  the perpendicular baseline.

Synthetic Aperture Radar is an active sensor and can operate day and night. The wavelengths employed allow penetrating cloud cover. In the initial SAR missions (ERS1-2, RADARSAT, ENVISAT, etc.) each image covered an area of approximately 100 km\*100 km at a spatial resolution of approximately 25 m\*25 m. Newest missions are able to deliver a significantly higher scanning resolution that in case of the TerraSAR-X reaches the pixel size of 1 m\*1 m. For every SAR pixel we have an observation, which is made up from all the scatterers within that cell. A SAR image contains both the phase and amplitude information of the radar signal. The SAR based surveying technique provides much more dense coverage of observations than usually can be achieved by using the classical surveying techniques. It also allows surveying areas that are traditionally difficult to access (for example the caving zones). If two interferograms or an interferogram and a Digital Elevation Model (DEM) are available, then it is possible to apply techniques that give information about the change of radar path occurred during the time span of the interferogram (Gabriel, Goldstein and Zebker, 1989).

These techniques are known as differential interferometric techniques (DInSAR). The simplest and most popular differential technique, based on two passes of satellite (called 2-Pass technique), requires a single interferogram and corresponding DEM to determine deformation. If two interferograms are available with a common image then a 3-Pass technique can be used. In 2-Pass, the DEM is used to generate a simulated interferogram containing topographic information only, which is then subtracted from the real interferogram to remove the topographic component of the phase. This leaves the differential phase, which contains information about the surface deformations only. The differential phase may contain phase noise due to atmospheric differences between the two SAR images. The change in radar path length can be measured to within centimetric, or even millimetric, accuracy due to the wavelength of the radar radiation (5.6 cm for C band radar). However, if a sheer deformation step greater than half the wavelength (i.e.  $>2.8$  cm) occurs, between two adjacent cells, it will be lost due to the wrapped nature of the phase. Such an event introduces ambiguities into the deformation estimates. If the deformation is moderate (less than half of wavelength between adjacent cells), the total deformation magnitude greater than half the wavelength can be measured by unwrapping the phase. Because the interferometric phase gives a measure of change in path length, it is only possible to get a one-dimensional line-of-sight deformation measurement.

The Synthetic Aperture Radars are side-looking radars and they are affected by certain terrain distortions. One such distortion is called layover. The layover is present when multiple targets at the same range from the radar, in the same radar pulse, are combined into the same response signal (pixel on a SAR image). Figure 6 helps to describe this phenomenon.

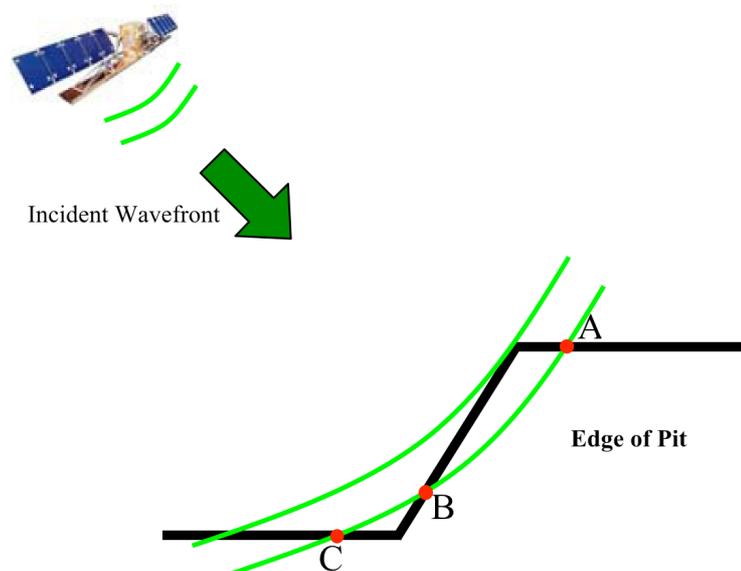


Figure 6: Layover points (A, B and C) will fall into the same cell of the SAR image

The satellite sends out short, high energy pulses and listens for the echo; ideally, the oblique incidence angle of the satellite means that only one echo from each target on the ground will be received. Therefore, echoes from adjacent targets will not be confused. This is not the case on the steep side of a pit where the radar wavefronts are striking few points simultaneously: on the surface (A), on the wall (B) and on the floor (C) of the pit (see Figure 6). This means that, in the SAR image, all these three points will be superimposed, forming a very thin but bright area in the image (layover area). The superposition of targets means that an interferometric signal cannot be discriminated, making it a useless area for the interferometric analysis. The steep slopes of open pits and waste dumps are highly conducive for this layover distortion. By masking out these areas we can ensure that these errors would not propagate to the later stages of InSAR processing.

### **Test site and available SAR data**

To test capabilities of InSAR technique, a typical WA mine site was selected for analysis. The site was characterised by existing, non-active, open pit that was affected by extensive subsidence induced by the underground mining utilising the sub-level caving (SLC) extraction method. The subsidence area was characterised by relatively large horizontal and vertical movements covering the crest and Western slopes of the open pit. The deformation area was out-of-access for any surveying personnel. To determine the existing deformation a remote sensing method was required.

Due to time limits the undertaken research activities were based only on the available historical SAR data. The available data set covering the mine site was very limited; the ESA archives listed only ten (10) ERS-2 SAR images collected after year 2000. All of the ERS-2 data was acquired from the same path of a descending orbit, meaning that the radar was viewing in the (near) east to west direction. From available SAR images only 3 pairs could be used for further interferometric processing. These pairs are summarised in Table 1.

Table 1: SAR scenes selected for processing

Pair (orbits)	Time Separation	Baseline
41554-40552	70 Days	79 m
42556-41053	105 Days	68 m
46564-42055	315 Days	115 m

Since there were no common images between these three pairs, a DEM was required to derive the differential phase. These three pairs of images have been processed to identify possible ground deformation.

### Layover analysis

The selected site was characterised by significant slopes left from previous open pit activities. The layover analysis had to be carried out to determine and eliminate layover areas from further InSAR processing. Figure 7 illustrates the geometry of the descending satellite for the case study. The ERS satellite was viewing the pit from the East at an incidence angle of  $23^\circ$ . The special algorithm and software was developed and used to determine the extent of layover area.

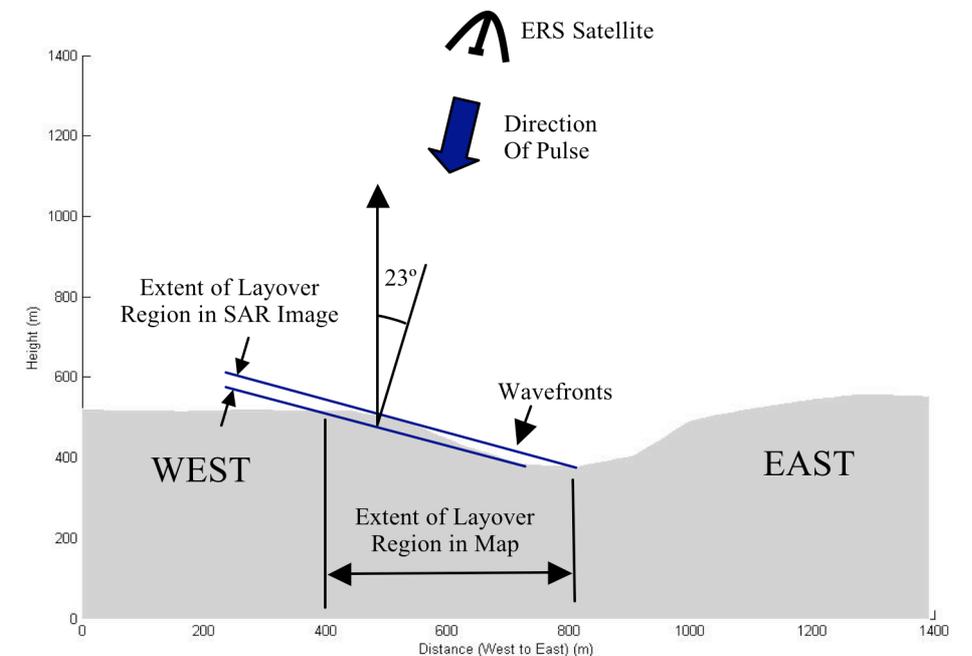


Figure 7: Height profile across the pit indicating the layover scenario

To generate the layover mask for the case study, the Shuttle Radar Topography Mission (SRTM) DEM (USGS, 2007) was used. Although the difference in date between the SAR images and the SRTM DEM was some three years, the results of the layover analysis seemed to agree very well with the image analysis. The original SAR image for the case study is shown in Figure 8, alongside the same image with the layover mask superimposed. This figure is presented such that the ERS satellite was viewing the terrain from the right hand side of the page. In the slant-range image, the layover region is small and clearly in a crescent-

shaped area on the left side of the pit. The shape and position of the layover mask confirms that the SRTM DEM is sufficient to describe it.

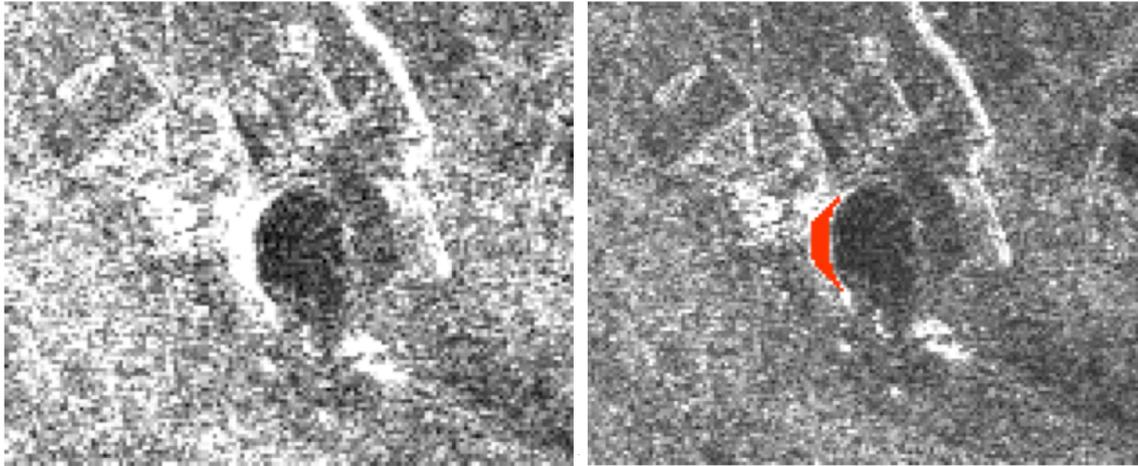


Figure 8: A slant range SAR image of the pit (left); with layover area highlighted (right)

The terrain-corrected images are shown in Figure 9 where the input SAR image and the layover mask, have been rectified to their proper shape and relative positions as would be seen on a normal map. It is clear that the rectification process has had a huge effect, considerably increasing the size of the layover area and decreasing the size of the Eastern wall of the pit. Unfortunately much of the pit is obscured from view and the drastic effect of layover clearly limits the available interferometric signal on the Western side of the feature.

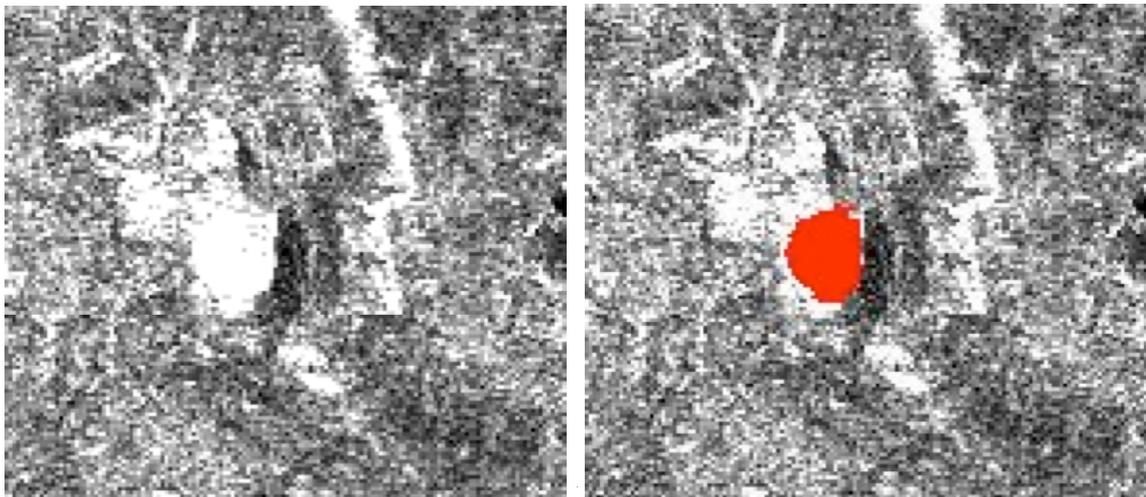


Figure 9: A geocoded SAR image of the pit (left); with layover area highlighted (right)

### **Data processing and results**

The data processing procedure that was used can be split up into the following main steps:

- Generation of real and simulated interferograms

- Generation of the mask encompassing layover and pit
- Generation of the differential phase and removal of any baseline trend
- Derivation of the line-of-sight deformation
- Georeferencing of the results into a suitable map projection.

The interferometric processing has been performed using the Doris interferometric processing software (Kampes and Usai, 1999) together with precise orbits (Scharroo, Visser and Mets, 1998) from the Delft Technical University. Phase unwrapping has been performed using the SNAPHU software from Stanford University (Chen and Zebker, 2001). The georeferencing and layover mask generation has been performed using the in-house developed software utilising MATLAB® environment.

From three pairs of SAR images (see Table 1) and due to quality of the obtained interferograms, the results from one pair were acceptable only. The masked line-of-sight deformation map, based on 41554-40552 pair, was generated and georeferenced into latitude and longitude. The temporal baseline of the interferogram was 70 days. The available data was acquired from the satellite descending orbits, meaning that the radar was viewing in the (near) east to west direction. This caused the west wall of the pit to be in an area of layover (see Figure 7). The east wall of the pit was in a good view of the radar.

A relatively large deformation can be seen in the 70-day interferogram. The analysis of changes, based on the historical topographical data, suggests a high rate of subsidence in 2003 at the level of 6.0 m/yr or 16.4 mm/day in the southwest area of the pit. Over 70 days, between the SAR acquisitions, the vertical component of movement reached 1144 mm. Such change happened over a horizontal distance of 22.3 m, meaning that the change between neighbouring SAR pixels reached a similar value. High rate of subsidence leads to ambiguity issues that cannot be resolved by current processing procedures and techniques. A new processing technique, taking into account the dynamics of deformation field, must be developed to resolve movement of such high intensity. However, the InSAR processing provided highly valuable information regarding the deformation in the large area surrounding the footprint of underground extraction. The 70-day subsidence detected by InSAR, north of the pit is shown in Figure 10 (left). In order to eliminate impact of local distortions on the far-reaching subsidence trough, a global polynomial was best fitted to the masked layer containing subsidence detected by InSAR. The applied mask eliminated the layover areas and the areas of known man-made terrain disturbance. The best fit of a polynomial was characterised by: power = 3, mean error =  $3.98e^{-5}$  m and RMS = 0.002451. Figure 10 (right)

represents the interpolated subsidence results in a contour form around and to the north of the pit.

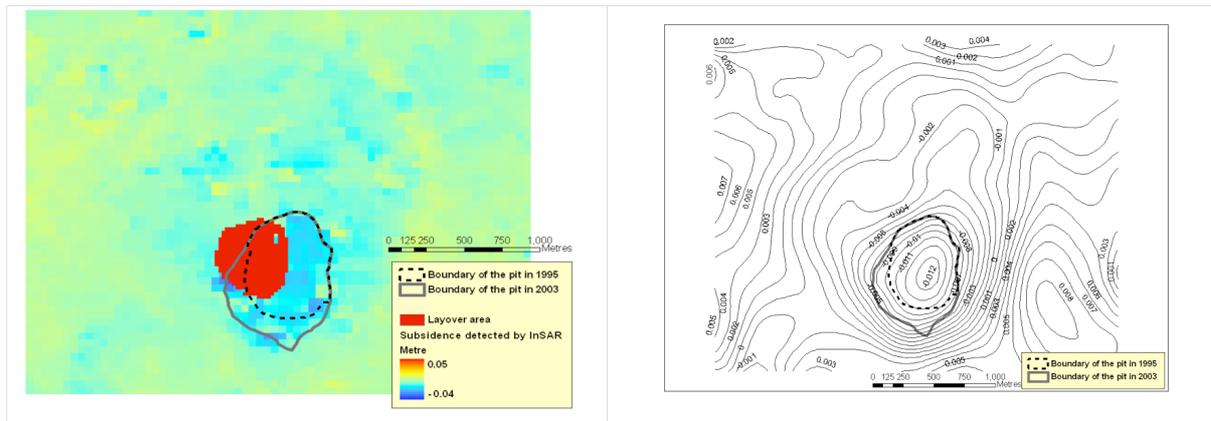


Figure 10: Subsidence detected by InSAR over the period of 70 days (left); Interpolated subsidence trough (right)

## CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

The analysis of historical DTMs, derived from the periodic topographical surveys utilising aerial photogrammetry, allowed extraction of information related to subsidence induced by underground mining. These results, however, suffered from low vertical resolution and their accuracy was typical for topo surveys ( $\pm 0.2$  m).

A rock strata deformation analysis requires much higher accuracy of input data. The new remote sensing technologies may resolve this dilemma. The InSAR method of subsidence monitoring uses a rapidly developing satellite and radar technologies that offers many potential advantages. As a remote sensing method, it allows for monitoring of surface movement in the mining areas that are inaccessible due to their instability, and cannot be monitored safely using the conventional monitoring techniques. InSAR can provide accuracies with centimetric or even millimetric standard errors. These accuracies are in the order of one or even two magnitudes better than provided by topographical surveys. However, the numerous parameters that impact on the accuracy and effectiveness of InSAR indicate that this method should be considered as experimental if applied for monitoring of high rate surface subsidence.

The authors performed initial tests regarding application of InSAR to WA mining conditions. The very small number of archived SAR acquisitions, available for the selected case study, has left authors with limited choices regarding data selection. The geometry of the available data was also far from ideal for the application. However, even with such constraints the InSAR provided valuable results. In addition to the subsidence results the research delivered

important insight about InSAR methodology itself. This is especially true if applied for monitoring of mining induced, localised, highly dynamic surface subsidence in the area of an existing deep open pit mine with steep slopes. The analysis showed that layover is almost a certain occurrence in SAR images of open pits. With the improvement of the data selection strategies it would be possible to optimise acquisition of SAR images, minimise the layover and maximise the samples in the area of interest. Taking the previous into the account, the development of a methodology to simulate SAR scenes would be very helpful. Such methodology should allow generating SAR scenes based on available Digital Terrain Model (DTM) using selective parameters such as satellite position or incident angle. The simulated SAR scenes could then be used to detect potential areas for layover and to provide better estimation of data suitability prior to ordering.

The initial SAR missions (ERS1-2, RADARSAT-1, ENVISAT, etc.) provided a spatial resolution of approximately 25 m\*25 m. The newest missions, such as TerraSAR-X and RADARSAT-2, are able to deliver significantly higher scanning resolutions reaching the pixel size of 1 m\*1 m for TerraSAR-X and 8 m\*8 m for RADARSAT-2. Using the new satellite missions, it should be possible to accurately detect small-scale, highly dynamic deformations and provide better estimation for phase unwrapping, which significantly decreases the impact of ambiguity issue.

In some cases, SAR interferometry technique suffers from the problem that suitable targets are not visible to allow the accurate processing. If the natural targets are not available the artificial targets (transponders) could be introduced. Such approach should allow for accurate georeferencing of SAR scenes and consequently increase the accuracy of subsidence monitoring. It is suggested to implement an array of transponders, with some in a stable zone, not subject to deformation, and some in an active zone affected by mining subsidence. Stability and movement of transponders should be monitored using GPS and/or classical surveying methods. This approach should help identifying any problems due to ambiguity and phase unwrapping, as well as, validating the InSAR results.

## **ACKNOWLEDGEMENTS**

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