# Integration of InSAR and GIS for Monitoring of Subsidence Induced by Block Caving Mining

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**Key words:** subsidence, block caving, mine deformation, GIS, InSAR, DInSAR, mine surveying, remote sensing

## SUMMARY

Knowledge of surface subsidence, induced by underground mining, is an important factor that significantly helps to develop an accurate deformation model of rock strata. Such a model may allow prediction of future deformation and stress field in the rock mass above a mining extraction. The usual source of deformation data are classical surveys carried out on surface and along underground mining structures. In general, these classical techniques involve collection of accurate but sparse measurements in the form of levelling networks or GPS stations. The recent, extensive developments of remote sensing technologies suggest that a wide range of tools could be utilised to detect mining induced subsidence and provide valuable data for tuning rock strata deformation models. Of the available remote sensing technologies, the satellite borne Interferometric Synthetic Aperture Radar (InSAR) can deliver continues coverage and accuracies that are compatible or exceed capabilities of classical surveys.

The presented paper describes the author's experience with monitoring of mining subsidence over areas that are affected by mining utilising the block caving method. It demonstrates combined use of Radar Interferometry (InSAR) and Geographical Information System (GIS) as a powerful framework for determination, management and analysis of subsidence data. A block caving underground mining operation located in the Goldfields Region of Western Australia was used as a case study. The obtained results suggest that integrated InSAR and GIS technologies can provide significant advantages in relation to classical subsidence monitoring techniques. The method does not require field instrumentation, provides dense and continues coverage of otherwise inaccessible areas, delivers high accuracy of data and significantly lowers costs for the monitoring and interpretation process.

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## 1. INTRODUCTION

In general, the term of 'block caving' is used to refer all types of gravity caving underground mining methods that are based upon the utilization of gravity for flow of blasted and fragmented ore and the caved waste (Hartman, 1992). For many years block caving mining methods were widely used with respect to their critical advantages, in particular, the capability of delivering high level of production at significantly low cost. Today, these methods have become even more important. Many open pit mining operations of massive ore bodies are reaching their economic mining depth and for further production, consideration of underground operation is required. Caving methods offer practical solutions and usually are considered as first options. Referring that block caving mining generates progressive caving in overlying rock, the rock strata deformation is inevitable. Obviously, this can be a potential source of danger for people and infrastructures. It may also disrupt mine scheduling and increase the cost of mine safety and production (Lilly et al., 2000). Therefore surface deformation, and in particular subsidence monitoring and control, are of the major concerns to the any underground mining operation involving block caving methods.

Knowledge of surface deformation significantly helps to develop an accurate deformation model of rock strata over the extraction region. The usual sources of deformation data are usually classical surveys that generally involve collection of accurate but sparse measurements over mine surfaces and along underground mining structures. Classical techniques are carried out in the form of levelling networks or GPS stations. With respect to the point-by-point data collection, the classical techniques are relatively time-consuming and costly (Ge et al., 2004). Furthermore, inevitable disadvantages, for instance, localised character of data and difficulty to collect data from an inaccessible area, produce critical problems in mining-related applications of classical techniques. Taking the above into consideration, there is specific interest with development of cost-efficient supplementary or alternative techniques. Such techniques are expected to deliver high accuracy deformation data with continuous coverage, as well as, providing flexible tools to manage historical data that leads to a better understating of the mechanism involved in rock strata deformation.

The present paper aims to introduce a demonstration of an integrated solution, based on combined use of Remote Sensing (RS) and Geographical Information Systems (GIS) as a powerful framework for determination, management and analysis of mine deformation data. Of the available remote sensing technologies, the application of satellite borne Interferometric Synthetic Aperture Radar (InSAR) is introduced and briefly discussed. Furthermore, the paper demonstrates application of InSAR for subsidence monitoring in the vicinity of large underground mining operation located in Western Australian. InSAR has the ability to deliver continuous coverage and accuracies compatible or exceeding than that of classical surveys. Also, favourable climate conditions in Western Australia are conducive to provide reliable InSAR interferograms. GIS is used as a value-adding tool during and after the InSAR process to interpret and assimilate disparate InSAR results.

## 2. INSAR AND DINSAR BACKGROUND

A space borne Synthetic Aperture Radar (SAR) system generates a radar map by scanning the Earth's surface (Jarosz and Wanke, 2004a). The sensor (antenna), as it moves along its orbital path, transmits microwave pulses and receives the echoes (Fig. 1). The SAR systems leads to provide Single Look Complex (SLC) images that represents SAR data after pre-processing and in complex format. Phase continuity information is also preserved within the image. The amplitudes of the corresponding pixels are averaged and the difference of phase values is calculated for each point of the image (Oliver and Quegan, 1998).

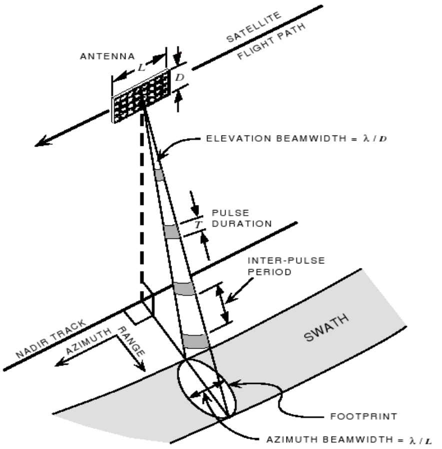

**Figure 1**- Imaging geometry of a space-borne SAR system (Alaska SAR Facility website, 2003)

The Interferometric Synthetic Aperture Radar (InSAR) is defined as the product of a SLC slave image with the complex conjugate of a master image. By subtracting the phase of two registered SLC SAR data images, pixel by pixel, an interferogram can be produced (Fig. 2) (Fitch, 1988; Franceschetti and Lanari, 1999). The size of pixel may vary from 8 m to 40 m depending on satellite and antenna specification. The phase difference is given in the range from -π to π, called module 2π, and is colour encoded as fringes (Kampes and Usai, 1999).

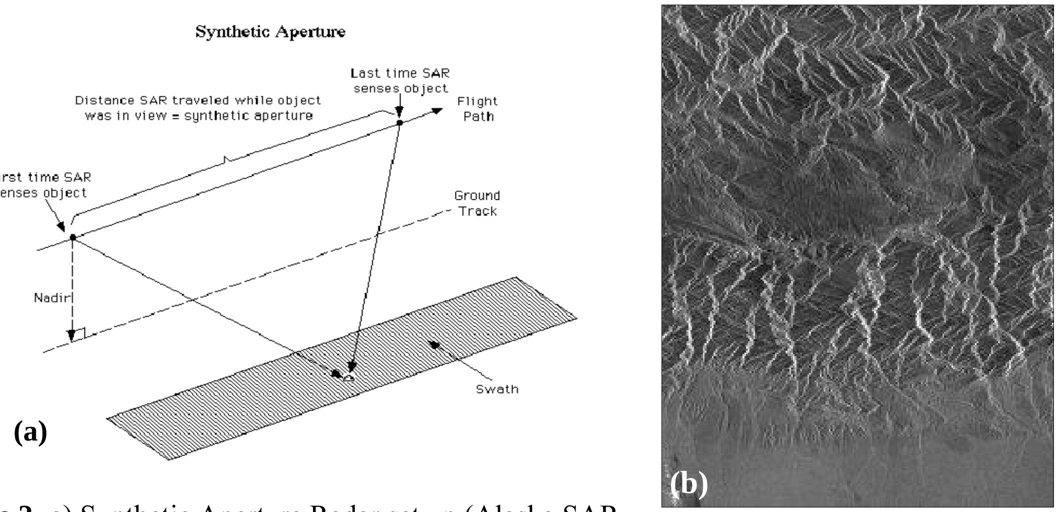

**Figure 2**- a) Synthetic Aperture Radar set up (Alaska SAR Facility website, 2003), b) sample of SAR image

Differential Interferometry (DInSAR) exploits the coherent nature of SAR echoes to measure the difference in phase of the backscattered signal. If the positions of the antennas are known accurately and if the same object can be scanned from the same location at two different times, then the difference in the backscattered signal's phase infer object movement. Similarly, if the phase difference is obtained when the same object is scanned from two locations, the height of the object can be established. The in-path length differences are a function of the topography of the surface, changes in the position of targets on the Earth and the differences in atmospheric or ionospheric conditions. The differential interferometry techniques use two or more observations, made from approximately the same location in space (distance between two positions of the sensor, called a baseline, this should be minimum) at different times. After removing certain topographic and orbital effects, the ground movement along the line of sight between the radar and the target is obtained. Any surface displacement appears as a phase shift with the radar measuring the scalar change in the satellite ground distance (Hanssen, 2001; Kampes and Usai, 1999).

In general, the characteristic of InSAR technique can be summarised as following (Jarosz and Wanke, 2004b):

- InSAR does not require any field instrumentation and consequently results in significantly reduced costs of monitoring and interpretation process,
- Allows the monitoring of hazardous and inaccessible areas, as the method requires little ground-based monitoring to calibrate the results,
- Provides data with high vertical accuracy,
- Works under different atmospheric condition and
- Links easily to the GIS environment.

In spite of the wide application of InSAR and DInSAR, there are some critical limitations and sources of error that invoke special consideration in applications of InSAR. The general techniques limitations can be listed as following:

- Poor temporal resolution (limited satellite coverage)
- Decorrelation of images
- Orbital, atmospheric and topographic errors
- Coherence problem caused by vegetation effect
- Phase errors due to the processing (eg. unwrapping related errors)
- The InSAR processing software has a high level of complexity and requires a relatively long time to be understood and mastered. The support from the software developers is limited.

However, it is proven that DInSAR technology is able to detect relatively small vertical movements (of sub-centimetre magnitude) occurring on the earth's surface due to geomorphological or geotectonic processes (Crosetto et al., 2003). The capabilities of this technology to map catastrophic ground movements, such as earthquakes and volcanic deformation, are also well established. Information from InSAR can be used to generate digital elevation models (DEM's) of an observed surface of the earth. InSAR and DInSAR are became a widely used operational technology. It also should be considered that several radar satellite missions especially for InSAR are scheduled for the next few years and therefore, in the near future, weekly or daily InSAR data will be available with global coverage (ERS Mission Homepage, 2001).

## 3. DATA PROCESSING AND RESULTS

According to Franceschetti (1999), the InSAR process can be outlined in four main steps:

1. Processing and transformation of raw data (radar and orbital) into, a Single Look Complex image format,
2. Data registration and re-sampling,
3. Computation of the interferometric phase image and the coherence maps and
4. Creation of deformation maps including phase unwrapping and slant to height conversion processes.

This first step of the InSAR processing is performed by satellite data collection and processing agency before distribution of SLC images. In registration step, the slave image is aligned with the master image, and the computation of the reference phase of the ellipsoid is performed. Because the slave image is acquired from a different viewing point than the master (reference) image, the data must be re-sampled before the slave image can be projected onto the first master image (Kampes and Usai, 1999; ERS Mission Homepage, 2001). In this step, the offset vectors of alignment of the slave image to the master image are estimated by computing the correlation of the magnitude images for shifts at the pixel levels. Based on the estimated vectors, the 2d-polynomial model of the required degree of correlation is computed. The least square method is used to determine the final solution (Kampes, 2001). The next step is to generate the interferogram and coherence maps. After this step the process can vary depending on the planned purpose of analysis involving different scenarios. Various configurations can be used including: generating Digital Elevation Models (DEM) using DInSAR with a single image pair, generating deformation maps using existing DEM for removing topographical effects and obtaining surface deformation using DInSAR technique with multiple images.

In order to find out the best possible configuration for the mining subsidence study located in Western Australia, different sets of SAR images were selected and analysed. As the result, the initial investigation was planned based on acquired data sets from ERS missions (ERS 1 and 2) over the period 1995 and 2003. Two tandem SAR images acquired on the 14th and 15th of December 1995 with a baseline value of 515 m used to remove topography effects (topo pair). It was assumed that it does not include any mining-induced effects as the underground mining had just started. The processing of available data for the selected period of time resulted in only one pair of SAR images, acquired on the 22nd of January and 2nd of March 2003, with suitable baseline (378 m) to be used to retrieve surface deformation (‘defo’ pair). All other combinations provide baselines larger than 400 m. The long temporal baseline between ‘topo’ and ‘defo’ pairs was a result of ERS-2 satellite technical problems (stability and navigation) which occurred during the selected period of time. However, it was expected that ideal climate conditions in Western Australia can limit these adverse effects. The DORIS InSAR Processor (Kampes and Usai, 1999) was used for DInSAR processing.

During the process, GIS packages, ArcGIS Desktop 9.1 and GRASS, were used for SAR image recognition and post-processing InSAR results. SAR images usually cover large areas on earth (100km×100km), therefore it is recommended to use small areas, focusing on designed extent for analysis. It may significantly decrease the complexity and time of the interferometric process. Before starting image processing, the master and slave images were imported to GIS environment for detecting favourable extent of studies. The selected coordinates were then used to run image-cropping process. For each step, the generated images were transferred to GIS environment in raster format where sets of spatial and statistical tools allow for pixel by pixel data analysis. At this stage of the studies, GIS functionalities are mainly used for raster files creation, mapping of field data, including reference coordinate points, validation of surveying stations, data georeferencing and results projection. The main steps involved in the DInSAR processing are illustrated in Figure 3 and 4. Significant surface subsidence was detected over the area above the active underground mining operation. The Figures 5 shows the 3D views of detected subsidence over the area of study.

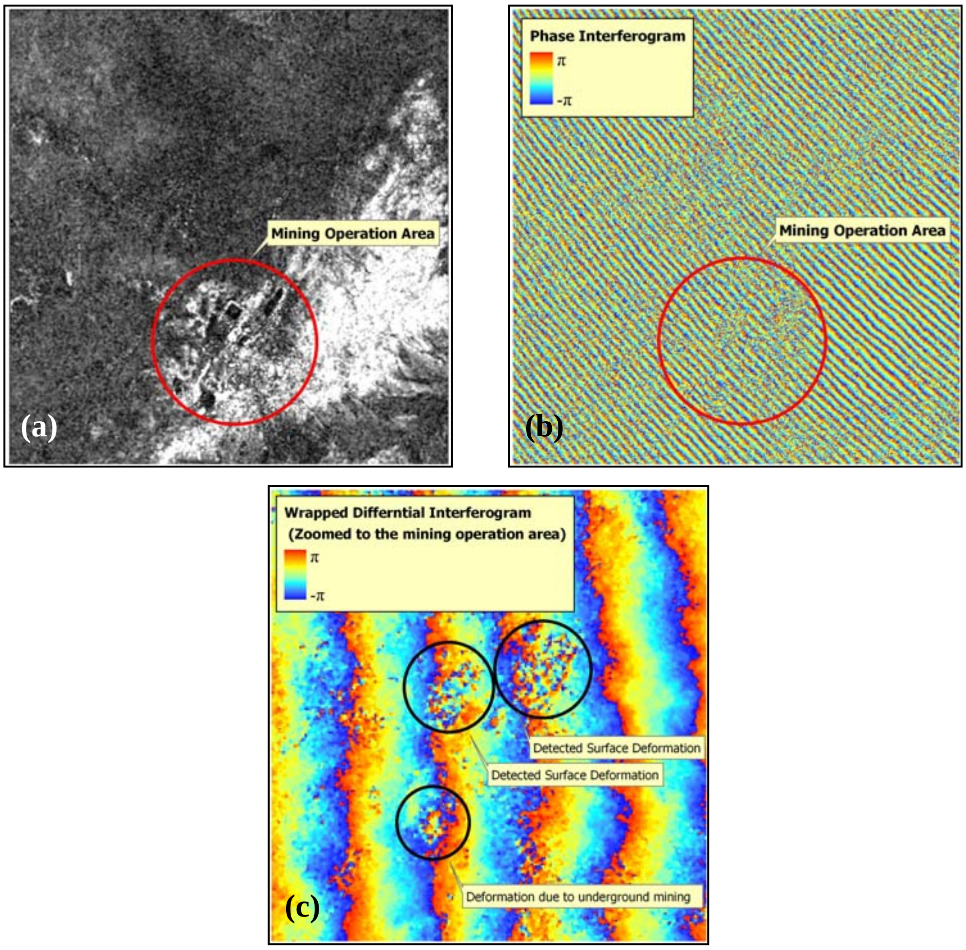

**Figure 3**- Main steps of DInSAR processing: a) Master SAR image, the red circle shows the location of selected case study, b) Phase interferogram resulted from subtracting the phase of two registered master and slave images, c) Differential interferogram before phase unwrapping

**Figures 4-** Detected subsidence over the underground mining operation. Final result after phase unwrapping and slant to height conversion processes.

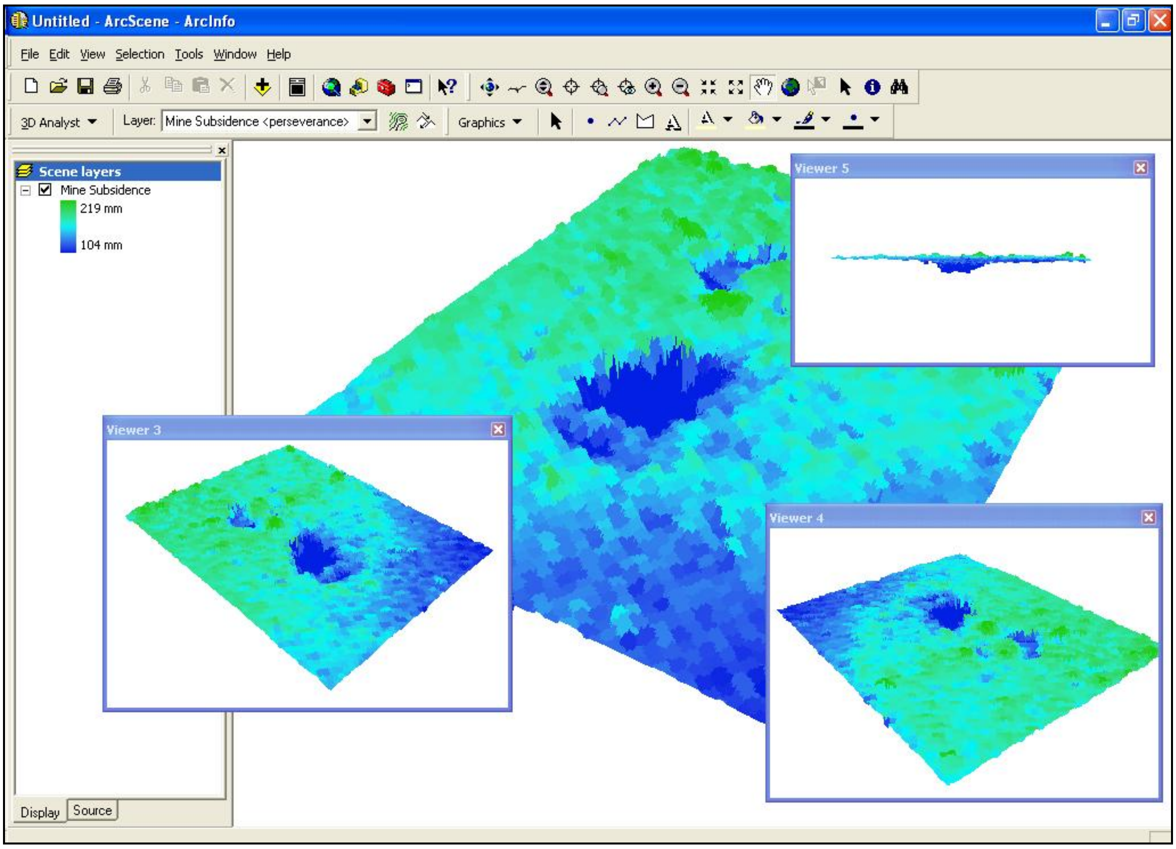

**Figure 5-** 3D views of mining subsidence

In order to assess the reliability of DInSAR data, results need to be compared with collected data from the field. Data acquired from slope stability monitoring system (running in the mine site for several years), were used to validate obtained results. The graph shown in Figure 6 represents the cross-section of the subsidence trough above the mining area over the period of 26 February 2003 to 2 April 2004, with classical survey method and detected deformation using DInSAR technique. As shown, both methods represent relatively good correlation of results. The classical survey does not cover the whole area of subsidence, as a significant portion of it was not accessible or reflectors were lost over the extended period of the monitoring time.

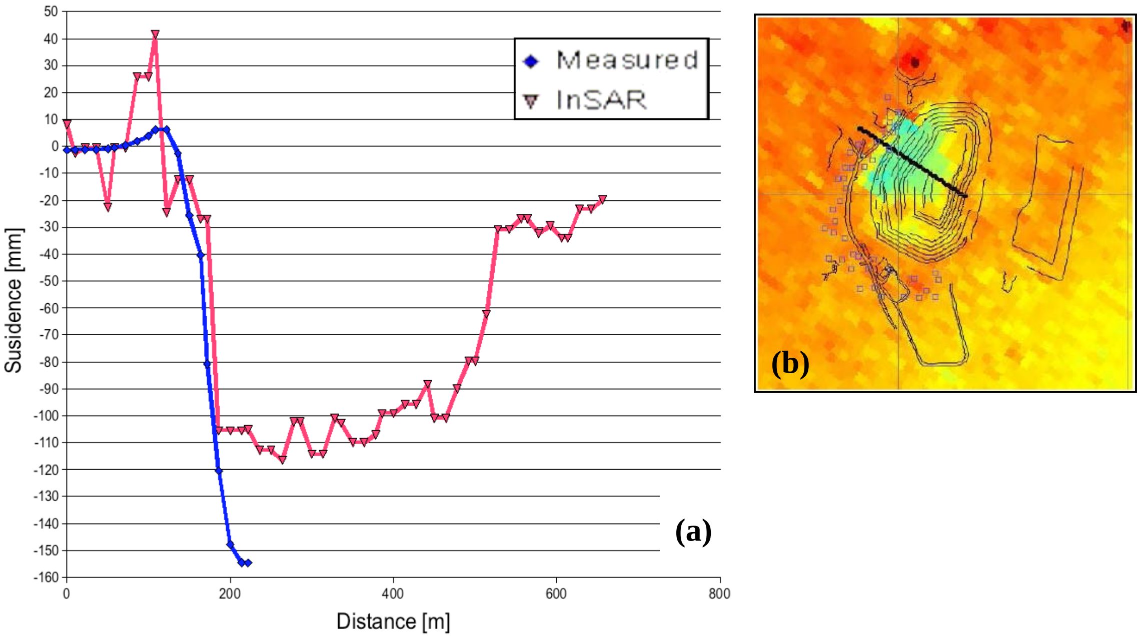

**Figure 6-** a) Comparison of subsidence "Measured vs. InSAR", b) Position of subsidence cross-section

## 4. CONCLUSION

The combination of InSAR capability of making many thousand accurate measurements over small areas, and GIS ability to handle, analyse and model spatial data, offers detailed analysis of the deformation mechanism. The initial results, presented in this paper, confirm the applicability of the InSAR technology for monitoring mine subsidence at a significantly low cost, high accuracy and extended coverage that includes inaccessible areas. With respect to the availability of weekly or daily InSAR data with global coverage in the near future, the technique could play an important role in development of a supplementary or alternative mine subsidence monitoring method. However, specific modifications are necessary for utilising the technique in the mining context. Limitations such as 1) difficulty to resolve deformation with high gradient changes, 2) difficulty to retrieve the high deformation rates for localised deformation and 3) the lack of SAR images with required specifications, are restricting the potential of this technology to monitor a high rate, localised, day-to-day deformation such as mine subsidence.

The future aim of our research will be to improve current InSAR capabilities, with respect to characteristics of mining-induced deformation. At the current stage of study, the lack of data did not allow application of comprehensive GIS-based data analysis. However, using new sets of data acquired from new satellite missions and additional field data collected from mine sites, it should be possible to create a highly responsive and accurate mine subsidence monitoring system. An addition of GIS-based solutions, in specific, allowing for analysis of deformation trends and spatial modelling will be the aim of next phases of this research. The other will be to produce and supply training datasets for numerical models of surface deformation.

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