Mine Subsidence Monitoring Using Multi-source Satellite SAR Images

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Abstract

Ground subsidence due to underground mining has posed a constant threat to the safety of surface infrastructure such as motorways, railways, power lines, and telecommunications cables. Traditional monitoring techniques like using levels, total stations and GPS can only measure on a point-by-point basis and hence are costly and time-consuming. Differential interferometric synthetic aperture radar (DINSAR) together with GPS and GIS have been studied as a complementary alternative by exploiting multi-source satellite SAR images over a mining site southwest of Sydney.

Digital elevation models (DEMs) derived from ERS-1 and ERS-2 tandem images, photogrammetry, airborne laser scanning, and the Shuttle Radar Topography Mission were assessed based on ground survey data using levelling as well as GPS-RTK. The identified high quality DEM was then used in the DINSAR analysis. Repeat-pass acquisitions by the ERS-1, ERS-2, JERS-1, RADARSAT-1 and ENVISAT satellites were used to monitor mine subsidence in the region with seven active mine collieries. Sub-centimeter accuracy has been demonstrated by comparing DINSAR results against ground survey profiles. The ERS tandem DINSAR results revealed mm-level resolution.

Introduction

Mine subsidence is the lowering or collapse of the land surface, caused by underground mining activity. The rocks above mine workings may not have adequate support and can collapse from their own weight either during mining, or long after mining has ceased. Factors affecting subsidence include (Nesbitt, 2003):

- Depth of cover,
- Overlying strata properties,
- Seam thickness,
- Panel width,
- Chain pillar size, and
- Surface topography.

The need for subsidence monitoring of underground mining operations is multi-fold:

- Legislative requirement,
- Subsidence prediction,
- Maximize coal extraction,
- Structural design,
- Risk management, and
- Environmental monitoring.

For example, proposals to enhance coal recovery through the use of the longwall mining method will receive critical review and assessment as to the likely environmental impacts of subsidence. This assessment considers all impacts on infrastructure such as roads, houses, buildings, pipelines, bridges, as well as public utilities such as schools, water supply and sewage systems, and dams. In addition, the possible subsidence impact upon natural features such as streams, rivers, lakes, cliff lines, rock formations, and archeological sites are also considered. Recommendations for ongoing monitoring and review are included as approval conditions, with the results or reporting of such programs being included in the annual environmental management report.

In addition, in the established colliery fields of eastern Australia, it is becoming increasingly difficult to select underground mine sites which avoid major engineering structures, both on the surface and underground (highways, bridges, buildings, and abandoned underground workings). The Tower Colliery, an underground longwall mine southwest of Sydney, is a representative example where the surface topography overlying the mine consists of several steep-sided river gorges. The surface is traversed by a freeway which crosses one of the gorges. Consequently, a major surface subsidence monitoring program has been in place for several years, including intensive conventional line leveling, GPS and EDM surveying, plus real-time monitoring of critical components of the bridge structure.

Therefore, ground subsidence due to underground mining is of major concern to the coal mining industry, government regulators, and environmental groups, to name just a few. Subsidence is currently monitored by repeated ground survey using automatic/digital levels (in line leveling), total stations (in EDM height traversing) and GPS receivers (in static and real-time-kinematic (rtk) surveys) (Schofield, 1993). Both digital levels and total stations can deliver 0.1 mm height change resolution, while GPS can produce 5 mm in static and 2 to 3 cm in RTK height determination accuracy.

These current techniques monitor ground subsidence on a point-by-point basis and are, therefore, relatively time-consuming and costly. Hence, the monitoring is usually constrained to very localized areas, and it is very difficult to monitor any regional deformation induced by underground mining. In addition, even in the localized area, the monitoring points are not usually close enough to assist in understanding the mechanisms involved in ground subsidence.

New techniques must be developed that both are accurate and give a fine spatial characterization of the ground deformation. Synthetic aperture radars look to the cross-track (or range) direction (direction perpendicular to the direction of motion) or along-track direction and use coded waveforms to
obtain fine resolution in the cross-track direction while using the along-track motion to synthesize a large antenna thereby obtaining fine resolution in the along-track direction. By taking multiple observations (subject to geometric constraints) that span the deformation signal of interest, differential radar interferometry can measure deformation to high degree of accuracy (better than 1 cm) over large spatial extents with high spatial resolution (Massonnet et al., 1993). Since radar beams scan in the range direction, the movement of the platform in azimuth direction completes the 2D imaging of the mining region (Stow and Wright, 1997; Perski and Krawczyn, 2000; Ge et al., 2001a, 2001b, and 2004c). The current geodetic technologies mentioned earlier, however, can only measure subsidence on a point-by-point basis. Therefore, DINSAR and geodetic technologies are complementary for the purpose of monitoring ground subsidence due to underground mining.

Like any other remote sensing technique, radar signals originating from the satellite-borne antenna pass through the atmosphere, strike the ground, are reflected by the surface, and pass back through the atmosphere before being received by the antenna. Although radar has the ability to penetrate cloud (and hence at the resolutions and wavelengths of interest in this study) the atmosphere rarely affects the imaging performance), it is one of the major errors sources in radar interferometry, i.e., where two radar images are combined to form the interferogram representing the difference of phase or electromagnetic wave path between the two radar image acquisitions. Ge et al. (2004b) explained how to use GPS observations to measure atmospheric disturbances so that the DINSAR results can be corrected.

It has been found that the GIS is an extremely useful tool to further analyze the GPS-corrected DINSAR results [i.e., mine subsidence maps]. Ge et al. (2004a) detailed how to use GIS to postprocess DINSAR results in order to deliver various high quality products that conform with the mining industry standards. Therefore, the optimal integration of the two geodetic techniques (Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (INSAR)) and the analysis and visualization techniques afforded by the Geographic Information System (GIS), makes it possible to measure, on a cost-effective basis, on a regular basis, the ground subsidence due to underground mining.

This paper, however, will focus on DINSAR only, and before evaluating the performance of multi-source SAR in monitoring mine subsidence, a brief description of DINSAR is given to provide background for discussion.

Consider two radar antennas, A1 and A2, separated by a baseline distance B, as shown in Figure 1. In the case of simultaneous imaging from two separate antennas, one both transmits and receives the radar signal, and the other only receives the reflected signal. This method is the so-called single-pass interferometry and is used for airborne and space shuttle SAR systems. Alternatively, single-pass interferometry could also take the so-called ping-pong mode, i.e., one antenna transmits and receives and then the other, which has been implemented in systems such as the TOPSAR, GEOE and STAR-3. In the case where a single-antenna SAR system is used to image the same area on the ground by revisiting after a period of time, such a method is referred to as the repeat-pass interferometry and is used more commonly in space borne SAR systems, although it has been done with airborne platforms.

When the SAR systems image the area on the ground, both amplitude and phase of the backscatters (dependent on the scattering mechanism on the ground) are recorded by the receiving antenna. The similarity in scattering mechanism in the two images is indicated by the coherence. Low coherence indicates the scattering mechanism is dissimilar between the two images and results in phase noise. For interferometry, the phase property is of most interest.

In a simplified geometry as shown in Figure 1, where the radar antennas are looking directly orthogonal to their orbit motion, the differential phase between the two repeat-pass SAR records is given by (Zebker and Goldstein, 1986):

\[ \Delta \phi = \frac{4\pi}{\lambda} B \sin(\theta - \alpha) + \frac{4\pi}{\lambda} \Delta r \]  

(1)

where \( \theta \) is the look angle to a given image point, \( B \) is the magnitude of the distance between the antenna locations, known as the spatial baseline, \( \alpha \) is the angle of the baseline vector measured from the orbital horizontal, \( \lambda \) is the radar wavelength, and \( \Delta r \) is the displacement of the image point along the radar line-of-sight from one observation time to the next.

If the natural variation in \( \Delta \phi \) due to a reference surface at zero elevation is removed from Equation 1, then

\[ \Delta \phi_{\text{mag}} = \frac{4\pi}{\lambda} B \cos(\theta_0 - \alpha) \frac{h}{r_0 \sin \theta_0} + \frac{4\pi}{\lambda} \Delta r \]  

(2)

where \( \theta_0 \) is the look angle, not to the image point but to the reference surface, \( r_0 \) is the range to the reference surface, and \( h \) is the height of the image point above the reference surface.

Equation 2 indicates that the first term is proportional to topography and the second term is proportional to the topographic change. Because the wavelengths for X-, C-, and L-band radar are 3 cm, 5.6 cm, and 23.5 cm, respectively, C-band radar is about four times as sensitive as L-band, while X-band radar will be twice as sensitive as C-band for mine subsidence detection.
If the two images are acquired at the same time but at different sensor locations, then the phase difference is related to the topography. If the scene is imaged from the same location but at different times, then the phase difference is a record of topographic change. If the scene is imaged from different locations and at different times, then the phase difference is a record of both topography and topographic change. Because \( B/r_0 \) is much smaller than one (e.g., \( B = 800 \text{ m}, \ r_0 = 800 \text{ km} \), then \( B/r_0 = 10^{-3} \)), the phase difference is much more sensitive to ground displacement than to terrain variation.

Note that Equation 2 is based purely on geometric relationships. When contributions from the atmosphere, orbit error, and radar noise are considered, the interferometric phase, \( \phi \), in the interferogram, consists of several different components:

\[
\Delta \phi = \phi_{\text{topo}} + \phi_{\text{disp}} + \phi_{\text{delay}} + \phi_{\text{orbital}} + \phi_{\text{noise}} \tag{3}
\]

where \( \phi_{\text{topo}} \) is the topographic component, \( \phi_{\text{disp}} \) is the ground surface deformation component, \( \phi_{\text{delay}} \) is the delay of the radar signal due to the fluctuations due to the atmosphere, in particular the changes of water content, \( \phi_{\text{orbital}} \) is the orbital component related to the relative position of the satellite tracks (it can be modeled and removed using orbital data during the processes), and \( \phi_{\text{noise}} \) is the phase noise due to the decorrelation of the interferometric signal caused by either long baseline distance or temporal separation between the two image acquisitions.

In two-pass DINSAR analysis, the topographic contribution to the phase difference in Equation 3 is carefully removed using an external digital elevation model. Atmospheric disturbances can be either accounted for using GPS observations, or neglected if the atmosphere is homogeneous at the time of radar acquisition. Orbit contribution can be corrected during DINSAR analysis. Various filtering techniques can be used to suppress radar noise. Therefore, ground movement has been singled out from Equation 3 in this process. Since the first description of the DINSAR technique, it has been demonstrated as a very useful method of mapping the ground deformation due to volcanic activity, glacier movement, seismic events, and underground mining activities. DINSAR for mine subsidence monitoring has been reviewed in detail in Ge et al. (2004a).

In order to determine what is the minimum detectable mine subsidence using a DEM of given accuracy we assume that a signal-to-noise ratio of 0 dB is the minimum required to ensure valid interpretations, then equating \( \phi_{\text{topo}} \) to \( \phi_{\text{disp}} \) in Equation 3 yields an equation for detectable subsidence versus DEM height error that can be parameterized by baseline as shown graphically in Figure 2. Note that the units of the horizontal axis are mm. Therefore, if the baseline of the radar pair is 250 m, mine subsidence as small as 2.5 mm can be detected using a DEM accurate to 5 m.

**Selection of a Digital Elevation Model**

When the two-pass differential INSAR is adopted for mine subsidence monitoring, a high horizontal resolution and high vertical accuracy digital elevation model should be used in order to ensure the quality of DINSAR result. Simulated SAR images, when (a) the three arc-second SRTM DEM and (b) a one arc-second photogrammetric DEM are used in the DINSAR analysis, were compared with the master image. The simulated image from 1" DEM reveals a lot of ground surface details and hence is much easier to be co-registered precisely with the master image than the simulated image from 3" DEM. Therefore, the residual topographic signal in the DINSAR result is expected to be much smaller when high horizontal resolution DEM is used because of higher co-registration accuracy between the master and DEM simulated images, or neglected if the atmosphere is homogeneous.

The accuracy of the external DEM is equally important. In order to ensure the quality of DINSAR result and form the base of operational mine subsidence monitoring, DEMs derived from repeat-pass INSAR as well as other techniques such as photogrammetry, airborne laser scanning (ALS), and the Shuttle Radar Topography Mission are compared based on ground survey data using levelling as well as GPS-RTK (Chang et al., 2004; Lee et al., 2005) as summarized in Table 1.

Although the ALS DEM has much higher vertical accuracy, the coverage is very limited and the unnecessary high horizontal resolution also significantly slows down the DINSAR analysis. On the other hand, the SRTM DEM delivers about the same vertical accuracy as photogrammetric DEM, but the available horizontal resolution is much lower. Therefore, the 1" photogrammetric DEM with a horizontal resolution equivalent to most of the SAR image resolution has been identified as the best DEM for DINSAR analysis presented in the following section. Using the RMS accuracy of 3 m from Table 1, the minimum detectable mine subsidence is better than 2 mm according to Figure 2 if the baseline is 250 m.

**Mine Subsidence Monitoring Using Multi-source Satellite SAR Images**

**JERS-1**

There are 13 JERS-1 image acquisitions available from August 1993 to January 1996. The critical baseline for L-band INSAR is about 1,400 meters. Based on this theoretical limitation, twenty-eight interferometric pairs were formed and tested for their strength of coherence over a site southwest of Sydney covering seven active coal mines. The results show that only 11 pairs have sufficient coherence to distinguish...
the phase caused by subsidence from the noise. Some of these DINSAR results can be viewed at http://www.gmat.unsw.edu.au/LinlinGe/MineSubsidence.gif.

One overlap has been found between the DINSAR result and ground survey data at one of the collieries between September and November 1993. The DINSAR result was postprocessed and overlaid with the mine plan as shown in Figure 3. The maximum subsidence detected was at Longwall 12 during the period. This location has been confirmed by comparing with the actual mine schedule.

To validate the result, the subsidence profile derived from DINSAR was compared against the ground survey data. Considering uncertainties introduced by datum conversion during the georeferencing, two more lines were drawn parallel to the original leveling line 900, as shown in Figure 3. The original leveling line 900 is in the solid dark line, while other slightly displaced lines are in triangles (900 Line 2) and dots (900 Line 3). The DINSAR subsidence profiles drawn from the three lines are compared with the ground survey data measured in August, September, and November 1993, and the best fit of the three (900 Line 3) is shown in Figure 4.

Figure 4 shows that the maximum subsidence occurred within the first 400 meters from the first leveling point along the line. The subsidence detected by DINSAR is for the period of 26 September to 09 November 1993. However, unlike the data measured in August and November, the record in September is only up to the 19th leveling mark (about 390 m from the first ground mark). The ground survey data beyond the 400 m mark is therefore added to

the September to November data from August to November 1993 in order to validate the whole line. The discrepancies have been measured by calculating the RMS values (standard deviation of the errors) of the subsidence profiles against the ground truth data. The result shows the subsidence profile along 900 Line 3 has a RMS error of 1.4 cm.

From Figure 4 it can be seen that the DINSAR result agrees better with the whole survey line than with only the maximum subsidence region. In fact, the "sinkhole" between the 2nd and 6th marks introduces most of the error. Away from the sinkhole, the DINSAR result follows the ground truth very well. Also obvious from the figure is that there is as much as 2 cm difference at the sinkhole between the two ground survey results. Therefore, it is crucial to ensure there is spatial and temporal overlap between the DINSAR result and the ground survey in order to assess the remote sensing result. Although this overlap is still not the ideal spatial and temporal overlap we have been looking for (since the ground survey beyond the 400 m mark was not done in the epoch of September 1993), the RMS is now as low as 1.4 cm. Furthermore, the exact dates of the ground survey are not available. The difference between these dates and those of satellite image acquisitions would also inflate the RMS error.
images, there are three tandem pairs in which the ERS-2 image is acquired 24 hours after the ERS-1. A total 153 possible combinations of INSAR pairs were formed, and 48 of them have the baseline distance less than the critical baseline of 800 m for C-band INSAR. In general, the ERS repeat-pass INSAR pairs exhibit very low coherence even within a single cycle of 35 days because of vegetation over the mine site. It is therefore difficult to phase-unwrap the interferogram due to the high phase noise.

However, Figure 5 is the differential interferogram of an ERS tandem pair acquired on 29 and 30 October 1995 and a perpendicular baseline distance of 49 m with mine plan overlaid. Mine subsidence within 24 hours has been revealed with confidence and been confirmed with the record of mine progress from underground survey. Further analysis was made for this ERS tandem pair. The subsidence that occurred during the 24-hour period is extracted and color-coded as shown in Figure 6a. It shows both the location and amplitude of the subsidence, and it is overlaid with the mine structure and date of the mine schedule. In Figure 6b two subsidence profiles are drawn along and across the longwall. It shows that the subsidence has the maximum 1 cm amplitude occurred during the 24 hours, and the phase noise introduces a background of about ±2 mm, which agrees with earlier prediction based on DEM accuracy.

In order to compare the C- and L-band INSAR, the coherence test results for the C- and L-band interferometric pairs are summarized in Figure 7. The triangles are the interferometric pairs having high phase noise in their interferograms. The circles are the pairs having good coherence so that subsidence fringes can be identified. It has been shown clearly that the coherence degrades (or the phase noise increases) when the temporal and/or perpendicular baseline distances increase. Figure 7 shows that the L-band (i.e., the longer wavelength) is more tolerant to the physical and temporal separations between the radar image acquisitions, and preserve higher coherence, than C-band (i.e., the shorter wavelength) due to the fact that longer wavelengths are less sensitive to changes caused by vegetation than shorter ones. From the figure it can also be seen that, in general, the maximum usable temporal separation and baseline distance are 105 days and 200 m for ERS (C-band) and 132 days and 900 m for JERS-1 (L-band) respectively in climatic and vegetative conditions similar to our study site. Therefore, long wavelength radar systems such as the L-band JERS-1 SAR are more suitable for monitoring mine subsidence in vegetated regions.

RADARSAT-1
In order to explore the challenges in using DINSAR on an operational basis, the authors scheduled nine successive SAR acquisitions over the mine sites using the Canadian commercial satellite RADARSAT-1. A RADARSAT-1 DINSAR result in Figure 8 shows the mine subsidence was about 5 cm and at the location of overburden stockpile the surface elevation increased about approximately 2 to 3 cm. Analysis of RADARSAT-1 data acquired in fine-beam mode has demonstrated the advantages of shorter re-visit time and reduced volumetric decorrelation over the vegetated area compared to ERS-1 and ERS-2 DINSAR results.

ENVISAT
Seven ENVISAT images have been acquired over the same site during 29 March 2003 and 10 May 2003. It has been found very challenging to derive a meaningful result because the images were acquired from both descending and ascending passes with four different imaging modes. More ENVISAT acquisitions have been requested.

Discussion
The potential of DINSAR as an operational tool for ground surface displacement monitoring is discussed in the context of future constellations of INSAR satellites.

Although it is possible to map mine subsidence using radar systems installed on aircraft (e.g., AIRSAR; http://airsar.jpl.nasa.gov/) or the space shuttle (e.g., SRTM; http://www.jpl.nasa.gov/srtm/), it is much more cost-effective to do so using spaceborne radar systems. Figure 9 summarizes the radar satellites collecting data which can be used for DINSAR analysis, in the past, currently, and in the near future. The upper part of the figure illustrates the lifetime of the satellites and the bottom part is a histogram showing the total number of available satellites. From the figure it can be seen that after the first radar mission of SEASAT in 1978, spaceborne radar missions have been dominated by the NASA space shuttles (http://www.jpl.nasa.gov/radar/sircxsar/) until the launch of ENVISAT-1 by the European Space Agency (ESA) on 17 July 1991. As a result of the race among the European, Japanese, and Canadian space agencies, ERS-1, ERS-2, and RADARSAT-1 have been launched. A golden period for INSAR was the years 1993 to 1998, especially between 1995 and 1998, when spaceborne radars were available at two different bands (C- and L-bands, 5.6 cm and 23.5 cm, respectively in wavelength) and the maximum number of satellites reached four. The climax of this period was the ERS tandem mission in which the ERS-1 and ERS-2 satellites imaged the same area only 24 hours apart. In a new round of interest among the European, Japanese, Canadian, American, and Chinese space agencies, ENVISAT has been put into orbit in 2002; ALOS has been launched on 24 January 2006; TERRASAR-X and RADARSAT-2 will be launched in 2006 and 2007, respectively; a small S-band radar satellite will be launched in 2007 by China; constellations of INSAR satellites have also been planned for the next 5 to 10 years by the NASA and other space agencies (Solomon et al., 2003). Therefore, the new golden period will be defined by several radar (including some INSAR dedicated) satellites collecting data in the X-, C-, S-, and L-bands.

Figure 5. ERS tandem DINSAR interferogram overlaid with mine plan. A color version of this figure is available on the ASPRS website: www.asprs.org.
With such promising availability of SAR satellites in the next few years, DINSAR will be able to monitor mine subsidence and ground deformation in general, on a cost-effective and operational basis and complement other high quality ground-based geodetic techniques in terms of coverage, precision, accuracy and reliability.

Conclusion
Mine subsidence monitoring using the DINSAR technique as a cost-effective and complementary method to conventional geodetic techniques has been demonstrated in this paper. The series of ERS-1, ERS-2, and JERS-1 radar images used for interferometric processing demonstrate the ability of DINSAR to locate the affected areas caused by mine subsidence in a vegetated region in New South Wales. For mine subsidence monitoring the JERS-1 (longer wavelength) DINSAR is more robust in the presence of vegetated or agricultural ground cover, and also more suitable for areas experiencing high rate ground deformation, compared to ERS-1 and ERS-2 (shorter wavelength) DINSAR. However, DINSAR of short wavelength is much more sensitive to mine subsidence. For example, subsidence with a maximum amplitude of 1 cm over 24 hours has been detected using a Tandem ERS pair with a resolution of ±2 mm. C-band radar is four times as sensitive as L-band, while X-band radar will be twice as
Acknowledgments
This research work has been supported by the Cooperative Research Centre for Spatial Information (CRC-SI) Project 4.2 (CRC-SI 2005), whose activities are funded by the Australian Commonwealth’s Cooperative Research Centres Programme. The Australian Research Council (ARC) has been supporting sensitive as the C-band ERS radar for mine-induced ground subsidence detection.

One temporal and spatial match between the ground truth and a JERS-1 DINSAR result is found at a colliery during September to November 1993. The quantitative validation by comparing the DINSAR-derived subsidence profile against the ground truth shows a best RMS error of 1.4 cm. Considering the georeferencing uncertainties and contribution of the sinkhole, there is no doubt that this DINSAR result has demonstrated sub-centimeter accuracy.

An operational trial with RADARSAT-1 was very successful, but DINSAR with ENVISAT imagery has been complicated by acquisitions from different passes and imaging modes.

Several radar satellite missions, some especially designed for INSAR, are scheduled for the next few years. Therefore, in the near future, radar data of global coverage with weekly or even daily revisit will be made available at multiple bands, for example, X-, C-, S-, and L-bands. With atmospheric disturbances properly accounted for, DINSAR will be a cost-effective, reliable, and operational complement to traditional ground survey methods.
DINSAR research at UNSW over a number of years. The Australian Coal Association Research Program (ACARP) has also supported research into ground subsidence monitoring using DINSAR.

References