Environmental Impact Assessment of Mining Subsidence by Using Spaceborne Radar Interferometry

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Key words: Mining Subsidence, InSAR, DInSAR, DEM.

SUMMARY

For underground mining, the extraction of coal or minerals can lead to the disturbance of the surface of the land. Surface structures may be damaged by tilting or lowering of the land surface as a result of ground subsidence. Mining subsidence therefore needs to be monitored throughout the operations, and perhaps beyond. Currently the majority of subsidence surveys are performed using total stations, digital levels and GPS with a height resolution of a few millimetres on a point-by-point basis. This paper demonstrates a cost-effective space technology, differential interferometric synthetic aperture radar (DInSAR), which is complementary to the conventional field surveying techniques for monitoring land subsidence due to underground mining.

Three underground coal mines located in eastern New South Wales, Australia, have been studied using DInSAR. Spaceborne SAR images acquired by ERS-1/2 and JERS-1 satellites were carefully selected to form interferometric pairs. DInSAR measures ground surface deformation by eliminating the topography from its interferogram. This can be done by introducing an external digital elevation model (DEM). The vertical accuracy of the DEM used reflects the minimum detectable phase signal of DInSAR. This paper assessed three DEMs derived from a range of remote sensing techniques for use in DInSAR processing.

The surface displacement maps derived from the DInSAR results had been analysed and validated against other information such as mine plan, schedule, and ground survey data with the aid of a geographic information system. One tandem DInSAR result indicated that a vertical resolution of +/- 2mm can be achieved. A L-band repeat-pass result showed a RMS error of 1.4cm against ground surveying data.

In the case of underground mining, the extraction of coal or minerals can disturb the surface of the land. Surface structures may be damaged by tilting or lowering of the land surface as a result of ground subsidence. This paper describes how the spaceborne differential interferometric synthetic aperture radar (DInSAR) technique was used to measure the ground surface deformation caused by underground mining activities. Both C- and L-band SAR images acquired by ERS-1/2 and JERS-1 satellites have been analysed. DInSAR results were cross-validated with the corresponding mine schedule and plans with the aid of a Geographic Information System. The C-band tandem DInSAR and L-band repeat-pass DInSAR results indicated that the vertical resolution was of the order of +/- 2mm and the RMS error was 1.4cm.

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1. INTRODUCTION

Australia is one of the leading mineral resource extraction nations in the world. It is one of the world's top producers of nickel, zinc, uranium, lithium, coal, gold, iron ore and silver. However, the complexity of the environmental issues and the potentially damaging consequences of mining have attracted public attention and political controversy. A range of environmental issues, such as ground subsidence monitoring, waste management, land rehabilitation, hazard and risk assessment, and socio-economic impacts on communities, have to be addressed before, during and after the mining operations.

The extraction of underground coal or minerals can disturb the surface of the land. The impact of mining subsidence, therefore, needs to be modelled before mining operations begin, and also has to be carefully monitored throughout operations. Currently the majority of subsidence surveys are performed using total stations, digital levels and GPS, with a height resolution of a few millimetres on a point-by-point basis. They are, however, time consuming and labour intensive. A new cost-effective space technology known as spaceborne differential interferometric synthetic aperture radar (DInSAR) can be used for monitoring mining subsidence.

2. METHODOLOGY

Synthetic Aperture Radar (SAR) is an active remote sensing system using the electromagnetic waves in the microwave region of the spectrum. Hence it is a 24 hour and all weather system. SAR systems measure the distance from the illuminated ground object to the transmitting radar antenna, and stores the amplitudes and phases of the reflected signals. The methodology for the measurement of mine-induced ground subsidence using spaceborne radar interferometry is described in the following sections.

2.1 Radar Interferometry

Interferometric Synthetic Aperture Radar (InSAR) is a well-established technique to reconstruct the Earth's topography by using different 'look' angles to compare the measurements to the same illuminated object. 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 one only receives reflected signals. This InSAR approach is known as 'single-pass interferometry', and is used for airborne and space shuttle SAR systems. 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, the approach is referred to as 'repeat-pass interferometry', and used in spaceborne SAR systems. This paper uses repeat-pass spaceborne DInSAR to monitor ground subsidence

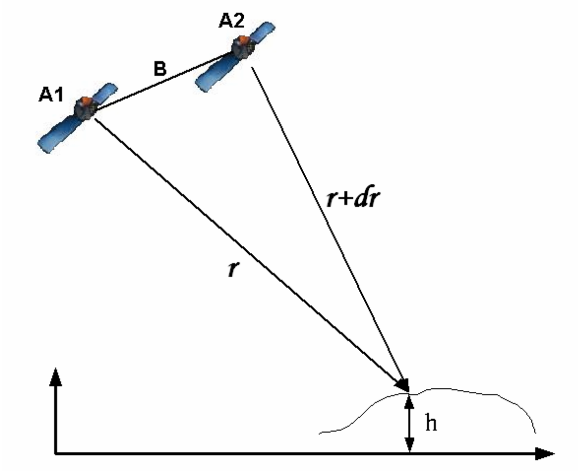

Figure 1. Geometry of InSAR.

When the SAR systems image an area on the ground, both amplitude and phase of the backscattered signal will depend on the scattering mechanism on the ground, as recorded by the receiving antenna. The degree of similarity in the scattering mechanism in the two images is indicated by the 'coherence'. Low coherence indicates the scattering mechanism is dissimilar between the two images, and typically results in increased phase noise. High coherence between the two images of an interferometric pair is preferred in order to minimise this phase noise. For interferometry, only the phase measurement is of interest. Hence the phase differences between the two images are used in order to reconstruct information about the terrain.

The phase difference data field, or the so-called 'interferogram', is generated by complex conjugate multiplication of the interferometric image pair data. In equation (1) below, the phase change ϕ in the interferogram is the composite of topographic information, surface displacement between the two image acquisitions, atmospheric delay, orbit errors, and noise:

$$\phi = \phi_{topo} + \phi_{disp} + \phi_{delay} + \phi_{orbital} + \phi_{noise} \tag{1}$$

where:

ϕ_{topo} = topographic component

ϕ_{disp} = ground surface deformation component

ϕ_{delay} = delay of the radar signal due to fluctuations in atmosphere delay

$\phi_{orbital}$ = orbital component relating to the relative position of the satellite tracks

ϕ_{noise} = phase noise due to the decorrelation of the interferometric signal

DInSAR is the process whereby the phase component caused by ground surface displacement is extracted by somehow eliminating or minimising the phase difference magnitudes attributable to other sources.

The atmospheric component arises due to fluctuations in the tropospheric water content for the raypath between the satellite and the ground target. The atmospheric delay component can be identified due to the fact that its fringe structure is independent over several interferograms (Massonnet and Feigl, 1995). It can also be modelled using GPS observations (Ge et al., 2003). In this study, the surface displacement induced by underground mining is expected to have higher spatial frequencies than the lower frequencies caused by the atmospheric delay, and therefore it is reasonable to assume that the differential atmospheric delay (across the image area) will be insignificant (Carnec et al., 1996).

The phases due to the orbital component can be modelled and removed using orbital data during data processing, and the phase noise can be minimised by carefully choosing the interferometric pairs so that they have minimum spatial and/or temporal baselines.

The surface deformation can be measured by removing the static topographic phase term in the interferogram using an external digital elevation model (DEM). This process is known as 'two-pass differential InSAR' (DInSAR). The detectable height resolution of DInSAR varies as a function of the quality of the DEM used as well as the magnitude of the spatial and temporal baselines of the interferometric pair. More details on DEM assessment are given in section 2.2. In DInSAR processing, the height ambiguity for the displacement phase is given by equation (2). A complete 2π phase change is therefore equivalent to a height displacement of $\lambda/2$ in the slant range direction ($\lambda / 2 = 2.8$ cm and 11.75 cm for C- and L-band microwave signals respectively). An example of a DInSAR interferogram is shown in Figure 2. The measured phases in the interferogram are 'wrapped' in modulo of 2π. The height displacement map can be derived by 'phase unwrapping' the interferogram.

$$\phi_{disp} = -\frac{4\pi}{\lambda}\delta R \qquad (2)$$

where
ϕ_{disp} = ground surface deformation component
δR = height displacement in slant range direction

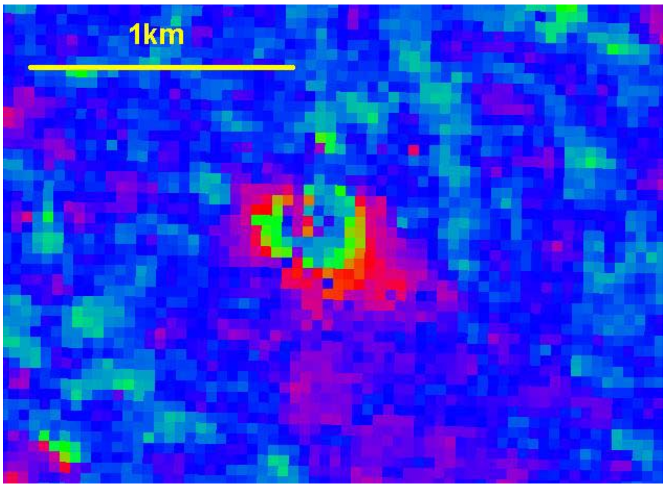

Figure 2. DInSAR interferogram of mine subsidence over a period of 44 days, eastern NSW, Australia.

2.2 Digital Elevation Model

The quality of the DEM used to remove the static topography during DInSAR processing influences the minimum detectable phase signal as indicated in Figure 3 (Nolan and Fatland, 2003). There are several remote sensing techniques for DEM generation, such as aerial photogrammetry, airborne or spaceborne InSAR, and airborne laser scanning (ALS). For the underground mining sites discussed in this paper, three DEMs generated by photogrammetry, spaceborne InSAR and ALS are available.

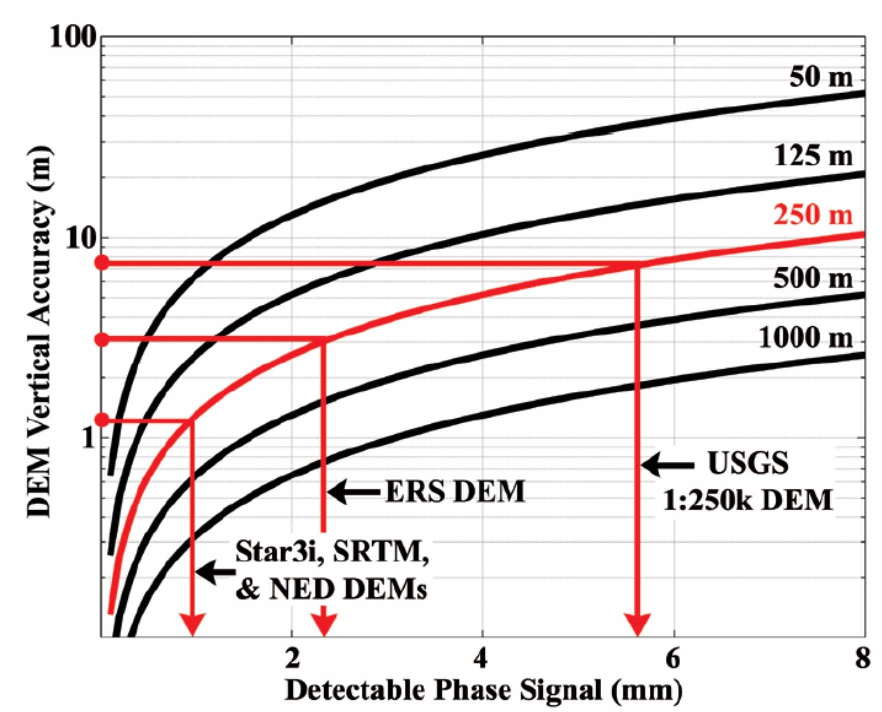

Figure 3. Relationship between DEM vertical accuracy and phase signal strength, as a function of baseline length (Nolan and Fatland, 2003).

The quality of the DEMs have been assessed using the field data collected by a real-time kinematic Global Positioning System (RTK GPS) survey. The DEMs have been cross-validated with the RTK GPS survey results along 8 different paths, in which some paths (roads) have been surveyed twice in both directions. The assessment results are summarised in Table 1.

		ALS	Photogrammetry	InSAR
Part 1	**Path 1 forward**	0.30 m	2.43 m	11.74 m
	Path 1 backward	0.30 m	2.43 m	11.70 m
	Path 2	0.09 m	1.35 m	4.26 m
	Path 3 forward	0.10 m	2.26 m	18.57 m
	Path 3 backward	0.11 m	2.30 m	18.45 m
	Path 4 forward	0.14 m	1.90 m	19.38 m
	Path 4 backward	0.15 m	1.85 m	19.39 m
	Mean	**0.17 m**	**2.08 m**	**14.79 m**
Part 2	**Path 5**	not available	1.03 m	7.89 m
	Path 6		3.10 m	14.87 m
	Path 7		1.22 m	27.81 m
	Path 8		3.75 m	26.39 m
	Mean		**2.28 m**	**19.24 m**

Table 1: RMS errors of the profiles extracted from the three DEMs compared with RTK GPS ground survey data.

Table 1 shows that the DEM generated by ALS has the best vertical accuracy, being between 0.09 ~ 0.3m. The second best vertical accuracy is that given by the photogrammetric DEM, with the accuracy from 1.03 ~ 3.75m. InSAR-tandem generated DEM in this case has an accuracy of the order of 10 ~ 20m. The ALS DEM, however, has only a very limited coverage over the test sites hence the photogrammetrically-derived DEM was used to remove the static topography during DInSAR processing. With a vertical resolution of 2 ~ 3m, the theoretical detectable phase signal based on Figure 3 would be up to < 3mm for an interferometric pair with a baseline of 250m.

3. DINSAR RESULT ANALYSIS USING GIS

DInSAR results generate a map of ground surface displacement values at pixels with geographic coordinates. The comparison of DInSAR results against other information, such as mine plan, schedule and ground survey, is essential for a quantitative analysis. The data collected from various sources are then interpreted and cross-validated on the same geodetic coordinate system by exploiting the power of a Geographic Information System (GIS). With the aid of GIS, information can be analysed systematically and then visualised in various ways.

Three underground collieries located in eastern New South Wales, Australia, were chosen as test sites. The historical radar images acquired by ERS-1/2 and JERS-1 satellites have been processed using repeat-pass DInSAR. Generally, temporal decorrelation degrades the capability of DInSAR for differentiating the signals caused by surface displacement from the noise. Furthermore, the test sites have a mixture of farmland, vegetation and forest cover so that the coherence in C-band ERS-1/2 interferometric pairs is barely conserved for a revisit period of more than 35 days (which is the repeat cycle of the ERS-1/2 satellites). In contrast, the temporal decorrelation due to changes of vegetation has less of an impact on L-band (or signals with longer wavelengths) JERS-1 interferometric pairs.

However, the radar images acquired by the ERS 'tandem' mission have a short time interval (24 hours) between the two ERS-1/2 image acquisitions. The interferometric pairs formed by using tandem image pairs therefore result in high coherence. Two tandem images were acquired on 29 and 30 October 1995 by ERS-1 and ERS-2. The differential interferogram derived from this tandem pair is shown in Figure 4. The location of the detected displacement has been confirmed with the corresponding mine schedule. Due to the lack of field survey data over the same period, cross-validation was not possible. Nevertheless, further profile analyses in Figure 5 indicate that the resolution of the technique is about ± 2 mm for tandem-based DInSAR. This corresponds to the expected phase signal, as mentioned in the previous section.

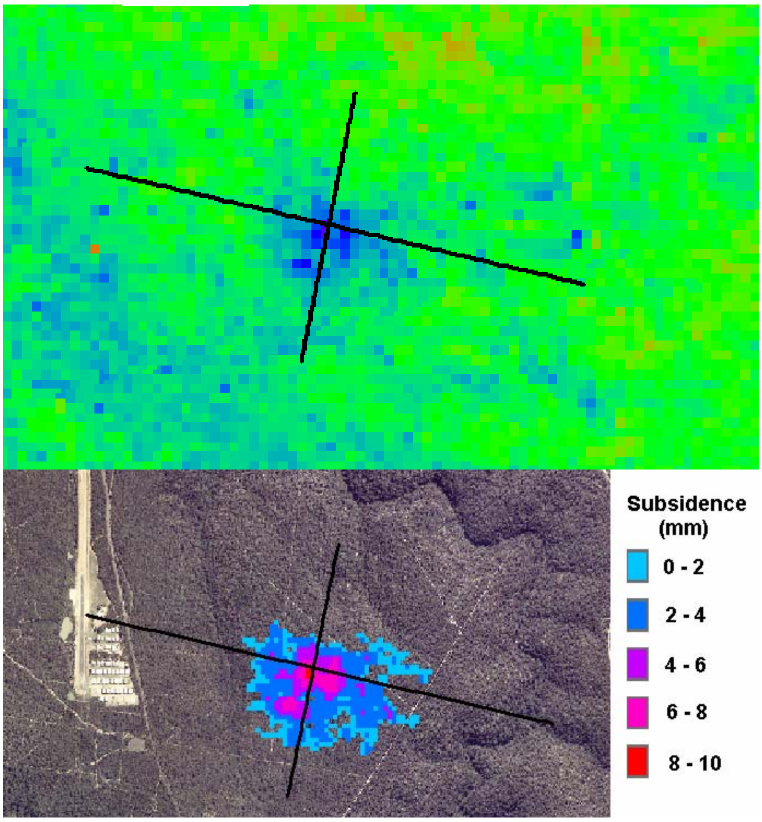

Figure 4. The interferogram (top) and height displacement map with aerial photo as background (bottom) of the tandem DInSAR pair acquired on 29 and 30 October 1995. The two profiles were drawn along the major (longer) and minor (shorter) axes as indicated in the figures.

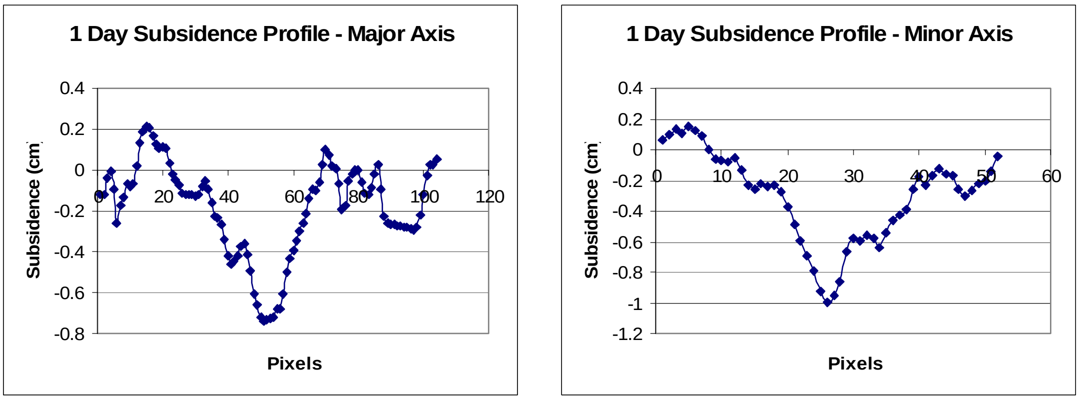

Figure 5. Profiles derived from tandem DInSAR of Figure 4, showing subsidence along the two axes.

For the same test site the DInSAR results derived from JERS-1 images indicate better coherence even over a period of 3 satellite repeat cycles (1 repeat cycle is 44 days for the JERS-1 satellite). Several ground surface displacement maps have been derived. However, only one result, shown in Figure 6 over the period of 26 September ~ 09 November 1993, has ground survey data against which it can be compared. The field survey along levelling line 900 was conducted in August, September and November 1993.

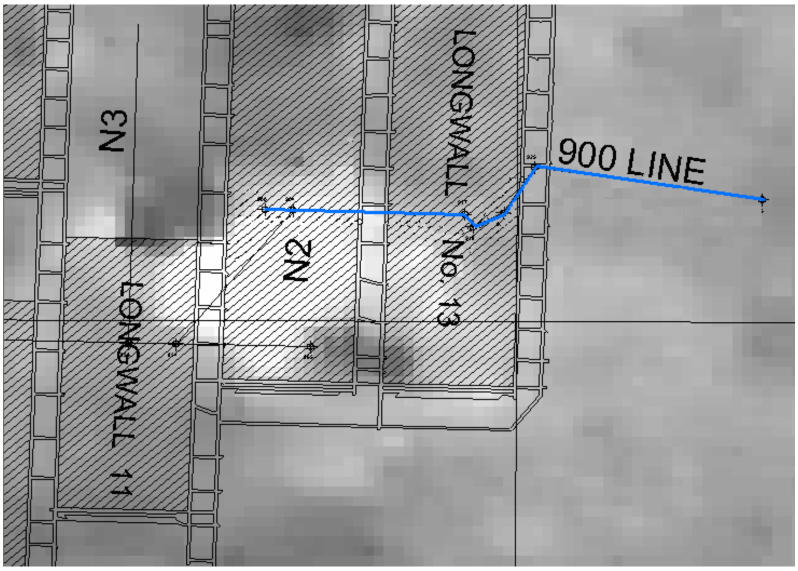

Figure 6. DInSAR result showing the detected mining subsidence over the period 26/09/1993 ~ 09/11/1993 (44 days) as presented on the mine plan data.

Figure 7 gives a comparison of the DInSAR-derived profile and the field survey data. The root mean square (RMS) error is ***1.4*cm** when comparing this JERS-1 repeat-pass DInSAR result to ground survey data. In addition, a subsidence contour map derived from the DInSAR result using GIS is shown in Figure 8, to illustrate the subsidence-affected areas.

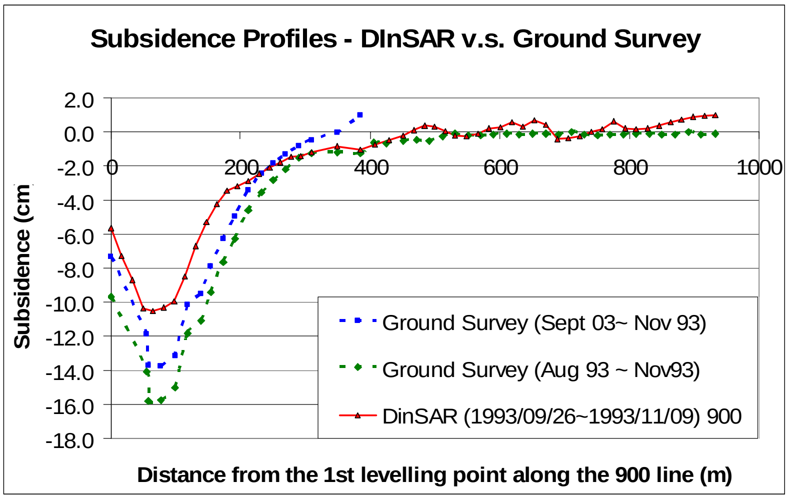

Figure 7. Comparison between repeat-pass DInSAR-derived profile and ground survey data.

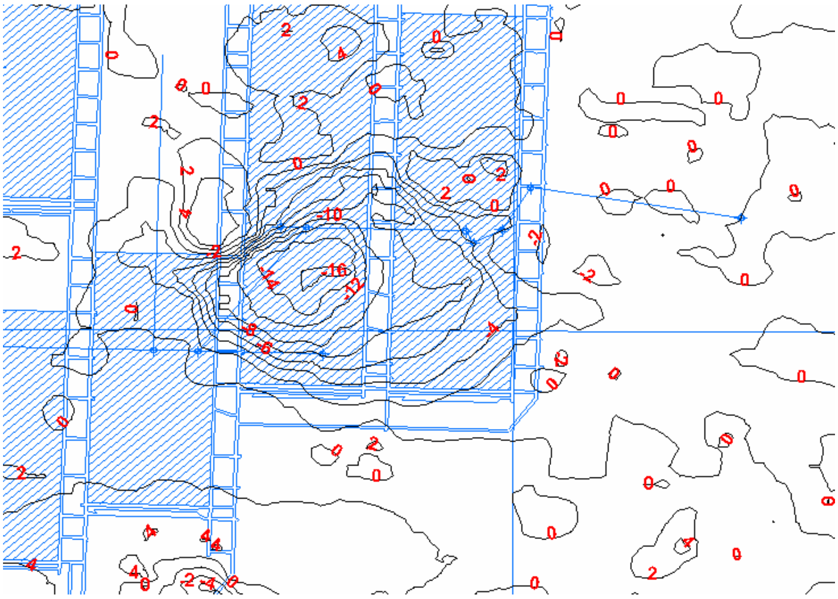

Figure 8. Subsidence contour map with 2cm interval derived from DInSAR result in Figure 6.

4. FUTURE STUDIES

The subsidence fringes detected in the interferogram are the ground deformation in radar look direction, or the so-called slant range direction. Phase-unwrapped subsidence maps are calculated based on the assumption that only vertical displacement (i.e. subsidence) has occurred. Most studies of land subsidence to date have neglected horizontal displacements.

When horizontal displacement occurs, it is possible to measure it by comparing the DInSAR results from ascending and descending satellite passes. If the displacement maps derived from the interferograms from different acquisition geometries differ significantly, this infers the presence of horizontal displacements. This approach allows two components (vertical and horizontal) of the displacement vectors to be resolved (Hoffmann and Zebker, 2003).

Nevertheless, spaceborne radar interferometry systems require high quality radar images of assured and availability. This paper has demonstrated that shorter satellite revisit time will not only reduce the phase noise but also the gradient of deformation fringes caused by underground mining activities in interferograms. Having less dense fringes in the interferogram would result in more accurate phase-unwrapped surface deformation maps.

ENVISAT (C-band), the European satellite launched in March 2002, carries on the SAR service of the highly successful ERS1/2 missions. ALOS (L-band), the next generation of JERS1 from Japan, is scheduled to be launched later this year. RADARSAT-2 (C-band), a Canadian satellite, will provide data continuity from RADARSAT-1 with up to 3 metres resolution, and will be launched in 2005. The first German SAR satellite, TerraSAR-X (X-band), is expected to be launched in 2006.

In addition of the new SAR satellites already ‘in the pipeline’, the NASA solid Earth science program has recommended the launch of a single dedicated L-band InSAR satellite with weekly global coverage for the purpose of surface deformation monitoring (possible launch in the next 1 ~ 5 years). A long-term goal is a constellation of InSAR satellites for daily deformation map generation, a goal to be realised over the next 5 ~ 10 years (Solomon et. al, 2003).

With such a promising availability of SAR satellites in the future, DInSAR will be used to monitor the ground deformation in a very cost effective and complementary manner to other high quality geodetic techniques.

5. CONCLUDING REMARKS

This paper has demonstrated the feasibility of environmental impact assessment of mining subsidence using the spaceborne DInSAR technique. The results of the integration of satellite radar interferometry and GIS has shown that they can be used as an operational technology to monitor at centimetre-level resolution ground subsidence due to underground mining. The C-band tandem DInSAR and L-band repeat-pass DInSAR results indicate a vertical resolution of +/- 2mm and RMS error of 1.4cm respectively.

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BIOGRAPHICAL NOTES

Chris Rizos is a graduate of The University of New South Wales, Sydney, Australia; obtaining a Bachelor of Surveying in 1975, and a Doctor of Philosophy in 1980 in satellite geodesy. Chris is currently a professor and Head of the School of Surveying and Spatial Information Systems.

Chris has been researching the technology and high precision applications of GPS since 1985. He has published over 200 papers, as well as having authored and co-authored several books relating to GPS and positioning technologies.

Chris is a Fellow of the Australian Institute of Navigation, a Fellow of the International Association of Geodesy, chair of the IAG’s Commission 4 “Positioning and Applications”, and a member of the Governing Board of the IGS.

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