Monitoring Land Surface Subsidence Using Radar Interferometry: The Challenges

Linlin GE, Hsing-Chung CHANG and Chris RIZOS, Australia

Key words: subsidence monitoring, mining, radar interferometry, DInSAR

SUMMARY

Subsidence of the land surface is defined as the vertical surface movement due to the removal of subsurface support. This paper presents the differential interferometric synthetic aperture radar (DInSAR) results derived from the data of various SAR satellites, such as ERS-1/2, Radarsat-1 and JERS-1, for subsidence monitoring. One of the limitations of selecting the suitable interferometric pairs is the interferometric phase noise caused by the decorrelation between the two acquisitions of the interferometric pair. The level of phase noise depends upon both spatial and temporal baselines of the two acquisitions as well as the imaging resolution (pixel size). The phase noise is also subject to the variation of the dielectric characteristics of the objects on the land surface. The limits of the interferometric measurement are discussed in this paper by addressing the issues of the decorrelation and phase gradient.

Monitoring Land Surface Subsidence Using Radar Interferometry: The Challenges

Linlin GE, Hsing-Chung CHANG and Chris RIZOS, Australia

1. INTRODUCTION

Subsidence of the land surface is defined as the vertical surface movement due to the removal of subsurface support. It is due to man-made activities such as underground mining or fluid extraction as well as the natural hazards such as earthquake. The major underground coal mining in Australia is done by longwall technique. Longwall mining provides higher productivity with almost 100% coal recovery. It uses a machine shearer moving back and forth along a coal face normally about 200m long. The roof behind the working face is allowed to collapse and it results in subsidence on the surface. As the mine face advances, the surface subsidence moves along the same direction. At the same time the amplitude of the subsidence is built up continuously until it reaches the maximum possible value which is less than the thickness of the seam being mined. Mine subsidence may cause damages to the buildings, underground gas pipelines and optical fibre communication cables. It may also cause serious environmental issues such as alternation of river hydrology. Therefore, due to the legal obligation, safety and environmental reasons the underground mining induced subsidence need to be monitored carefully throughout the operation.

The dynamic of the subsidence movement is a complicated process both in time and space. It depends on the factors of geological properties of the overburden strata, size of the opening, mining depth and width, seam inclination, topography, hydro-geological conditions and time (Peng and Chiang 1984). The mine subsidence has been monitored using the conventional field surveying instruments, such as total stations, levelling stations and recently GPS which may provide a vertical accuracy of millimetres. Hundreds of surveying marks are normally established at the intervals of approximately 20m along the routes where there is easy access above the longwall tunnels or near the important infrastructures. The spatial coverage of the surveying marks is however very limited. Deformation measurement by conventional surveying techniques is time consuming and labour intensive when applied to large areas. As a result, for the regions where has no surveying marks, the magnitude and shape of the subsidence will be estimated based on the surveying data measured in the neighbouring regions or the subsidence models.

Recently, radar interferometry or interferometric synthetic aperture radar (InSAR) has been used to obtain geodetic information of terrain. InSAR utilizes the phase information contained in the two SAR images acquired over the identical scene at slightly different viewing locations. There are other more advanced radar interferometry techniques using differential InSAR (DInSAR), or using temporally stable pixels in multiple SAR images, e.g. permanent scatter InSAR (PSInSAR), to measure the surface subsidence at the accuracy of sub-centimetre or millimetre level (Ge et al. 2005; Ferretti et al. 2001). PSInSAR is more suitable to detect the small deformation rates over a long period. But, its applicability is limited for the high deformation rates and non-uniform deformation such as mine subsidence. Therefore, the repeat-pass DInSAR is most suitable for the purpose of mine subsidence monitoring.

This paper aims to demonstrate mining subsidence monitoring using DInSAR with the aid of geographic information systems (GIS). The challenges of applying DInSAR with the historical and current spaceborne SAR sensors are also addressed here.

2. METHODOLOGY

Repeat-pass spaceborne DInSAR is used here to derive ground displacement maps. The geometry of the interferometric configuration is shown in Figure 1. Two SAR images acquired from two slightly different positions, at different revisit times, are used to measure the phase difference, or so-called interferogram, between the two acquisitions. The interferogram consists of topographic information, surface displacement between the two acquisitions, atmospheric delay, orbit errors and noise. DInSAR is the process to measure the surface displacement by eliminating or minimising the other components. The topographic phase contribution can be simulated by introducing a digital elevation model (DEM). A photogrammetry DEM with 1 arc-second ground resolution (approximately 30m) is used there to simulate the topographic phase hence it can be removed from the interferogram. The atmospheric component is primarily due to fluctuations of water vapour in the atmosphere between the satellite and the ground. The atmospheric delay can be identified using the fact that its fringe structure is independent over several interferograms, or can be modelled by using a GPS network (Ge et al. 2003). As the volume of the water vapour in the atmosphere varies with low spatial frequency, it is sometimes negligible in the applications such as mining subsidence monitoring where the spatial frequency is much higher.

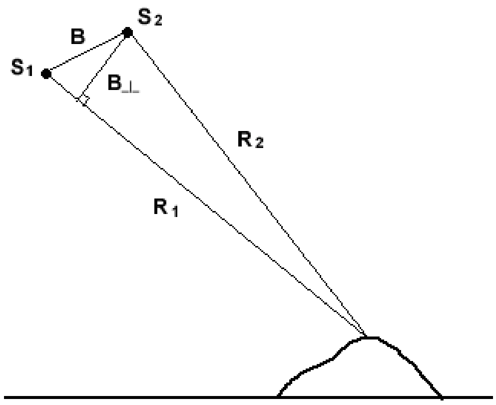


Figure 1. Geometry of repeat-pass interferometric configuration. S_1 and S_2 are the locations of the two acquisitions; R_1 and R_2 are the range between the satellite and the ground object; B is the baseline between S_1 and S_2; $B_{\perp}$ is the perpendicular baseline.

In the differential interferogram a complete 2π phase change is equivalent to a height displacement of half of the wavelength of the radar signal in the slant range direction. That is

11.75cm for JERS-1 data. Since the measured phases in the interferogram are wrapped in modulo of 2π, the height displacement map can be derived by 'phase unwrapping' the interferogram.

The results of radar interferometry would be degraded by the noise which is primarily caused by the decorrelation between the selected interferometric SAR image pair. Decorrelation is site specific. It varies with the local climate, land use, water content, terrain, as well as the characteristics of the SAR data such as wavelength, imaging resolution and repeat-cycle. Decorrelation normally can be divided into 3 main categories: spatial, temporal and volume decorrelation. These are discussed in more detail in session 4.1.

3. TEST SITE

The test site is located in the Southern Highlands of State of New South Wales, Australia. The mining depth is approximately 500m. The longwall mining technique is used and its underground panels are shown in the Figure 2.

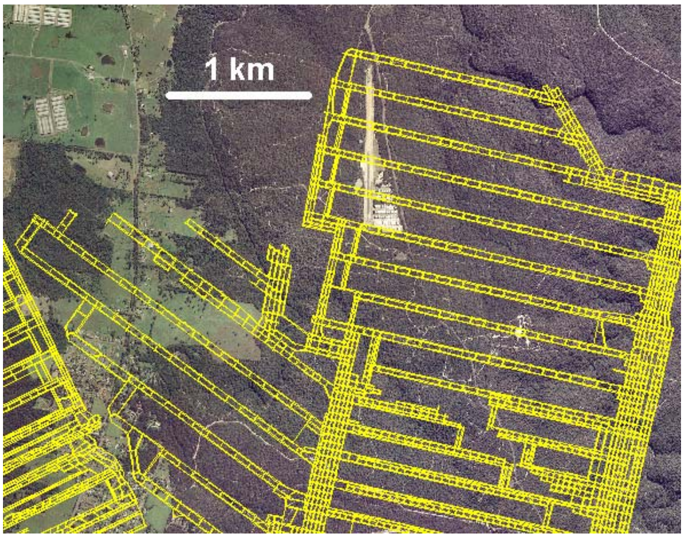


Figure 2. The aerial photography of the test site overlaid with the underground longwall mining plan (yellow lines).

3.1 Input data

The retired and current operating spaceborne SAR sensors are listed in Table 1. Even though the ERS-2 is still functional after 11 years, it only acquires the data casually now. The ALOS was launched in January this year. It is still in the calibration and validation phase of the operation. This paper used ERS-1/2, Radarsat-1 fine beam mode and JERS-1 data to measure the mining subsidence.

Satellite	Band	λ (cm)	Repeat cycle	Resolution	Status
ERS-1	C	5.6	35 days	< 30m	Retired
ERS-2	C	5.6	35 days	< 30m	Current
ENVISAT	C	5.6	35 days	30m	Current
Radarsat-1 fine beam	C	5.6	24 days	8m	Current
JERS-1	L	23.5	44 days	18m	Retired
ALOS	L	23.6	46 days	7~88m	Current

Table 1. The characteristics of the SAR satellites.

4. THE CHALLENGES: LIMITS OF THE INTERFEROMETRIC MEASUREMENT

The limitation of DInSAR is restricted by the ambiguity caused by decorrelation and high phase gradient. Coherence can be considered as a direct measure for the similarity of the dielectric properties of the same imaging cell between two SAR acquisitions. The decorrelation can lead to low coherence in the image. Decorrelation is site-specific. It depends upon the local climate conditions, vegetation cover, complexity of the terrain (moderate v.s. hilly or mountainous), land use, etc. As a rule of thumb, the decorrelation is more severe for the area having heavily vegetated cover, complex terrain or various climate conditions. However, high coherence can still be reserved over 4 years in desert due to low levels of precipitation and sparse vegetation (Fialko and Simons 2001). Over a vegetated area, C-band signal is expected to have higher decorrelation than the comparatively longer wavelength in L-band. The temporal separation between the two acquisitions of the interferometric pair is also the key for both temporal decorrelation and high phase gradient.

4.1 Decorrelation

The decorrelation can be referred to as spatial, temporal and volume decorrelation depending on its causes. The spatial decorrelation is caused by the physical separation between the exact locations of the satellite when the data was acquired at the revisit orbit. The temporal decorrelation is caused by the variation of the dielectric properties of the ground objects between the two repeat-pass acquisitions. The volume decorrelation is about the phase stability of the imaging cell (pixel) over time. As a rule of thumb, the smaller perpendicular and temporal baselines, and the imaging resolution would reduce the decorrelation. As mentioned earlier the decorrelation is site specific, therefore the coherence of ERS-1/2, Radarsat-1 and JERS-1 interferometry results were calculated and compared over the regions of urban and vegetation respectively. The coherence for the pairs with single repeat cycle of each sensor was compared. In order to compare the coherence over the similar period, the coherence of the 2 repeat cycles of Radarsat-1 data was plotted. The results are shown in Figure 3.

It is clear that the coherence degrades with the increase of the perpendicular baseline. For baseline less than 500m, the coherence for all the sensors are between 0.2 ~ 0.5 over the urban or the built-up area while they drop to 0.1 ~ 0.3 over the vegetation. Also, the JERS-1 L-band data is less sensitive to the vegetation as its coherence is better conserved than the C-band data over the vegetation. The impact of volume decorrelation is evident by comparing the ERS-1/2 and Radarsat-1 data as the coherence of ERS-1 degrades faster than Radarsat-1 with respect to the increase of the perpendicular baselines.

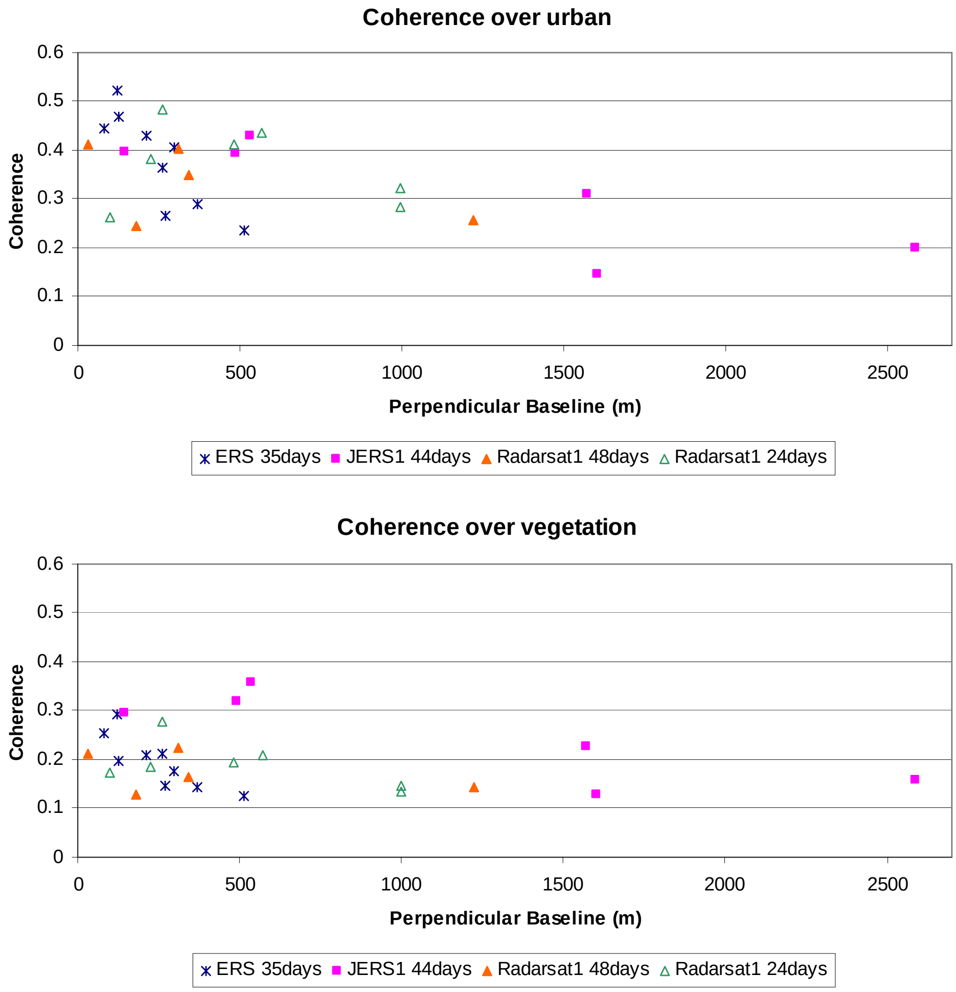


Figure 3. The coherence of the interferometric pairs of ERS-1/2, JERS-1 and Radarsat-1 for (top) urban and (bottom) vegetation regions.

4.2 Phase slope

Besides phase noise, another important factor to cause the phase discontinuity in the differential interferogram is the high phase slope. It happens when large subsidence occurred over a small spatial extent. It causes high phase slope or even saturated phase in the interferogram. Consequently, it is very difficult or even impossible to resolve the phase values to the height correctly during the phase unwrapping process. In addition, the radar system is coherent and has some intrinsic noise. Normally, multi-looks and filtering techniques are applied for noise reduction. However, the information of the deformation with large phase gradient may be lost during the filtering. The differential interferogram of Radarsat-1 data is shown in Figure 4. The different adaptive filter window sizes were used. It remains as a challenge to find the optimal filter to remove the phase noise while keeping the details of the deformation.

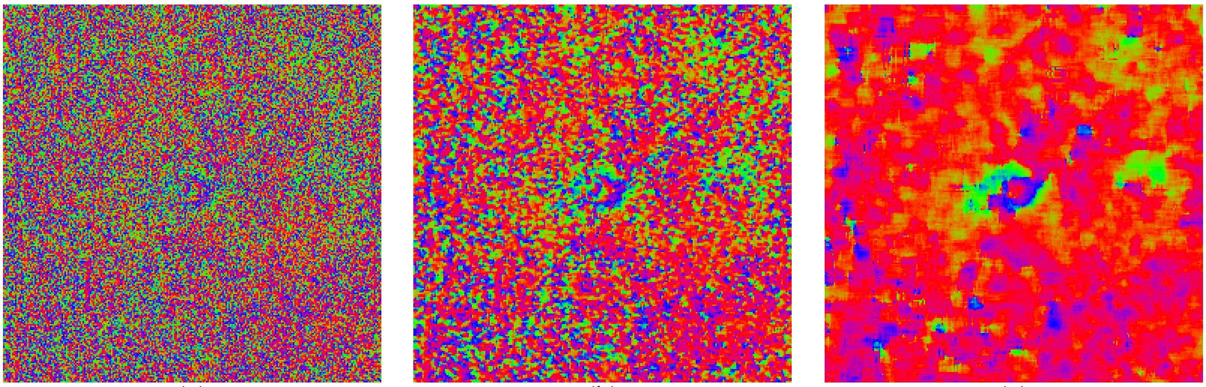
Mine subsidence is a very good example for causing the high phase slope. The excavation of underground mining may lead to several to tens of centimetres of subsidence within the following few months. The maximum subsidence can be up to 1 metre after one year when the over-burden became stable. It depends on the depth of mining as well as the geological characteristics of over-burden.

The high phase slope can be eased by having either longer SAR wavelength or shorter temporal separation between the interferometric pair. For example, our earlier results in (Chang et al. 2005) showed that when shorter time interval is available C-band data still can reveal the subsidence of 1cm occurred over 24 hours using ERS-1/2 tandem image pair. But the phase is saturated near the centre of the subsidence basin for the period of 35 days.

Although Radarsat-1 uses the same wavelength as ERS-1/2, it has a revisit cycle of 24 days which is approximately two third of ERS-1/2's. In addition, Radarsat-1 fine beam imaging mode has finer resolution of 8m. The shorter repeat-cycle and finer spatial resolution help to reduce the large phase slope.

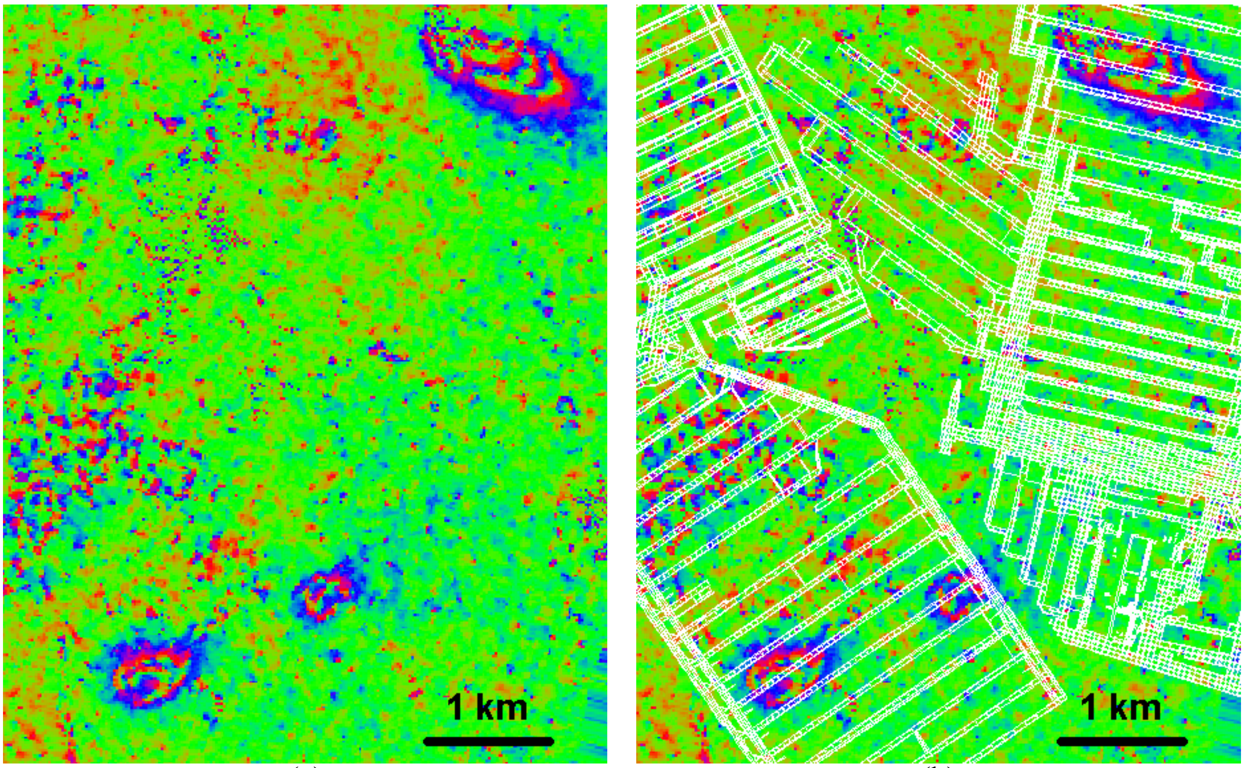
In contrast, the longer wavelength of L-band revealed the subsidence over a period of 132 days. The differential interferogram was geo-referenced and overlaid with the mine plan using GIS as shown in Figure 5. It showed two subsidence basins at the lower mine, which were induced by the excavation near the end of the previous panel and the beginning of the next one. The mining subsidence normally has the typical feature of concentric phase fringes. The longwall mining subsidence is constrained by the mining structure. Therefore, the fringes are in the elliptical shape. It is shown clearly at the top right corner in Figure 5.

One of the disadvantages of using the historical data is the lack of ground truth data. It is not easy to find the match between the DInSAR results and the ground survey data both spatially and temporally. One of our earlier JERS-1 DInSAR results showed the RMS error of 1.4 cm when compared to ground truth (Ge et al. 2005).



(a) (b) (c)

Figure 4. The differential interferogram of Radarsat-1 data acquired on 9 October 2004 and 02 November 2004 with a perpendicular baseline of 225m. (a) No filtering; (b) filter window size2; (c) filter window size10.



(a) (b)

Figure 5. (a) JERS-1 DInSAR interferogram showing the subsidence occurred during 09 November 1993 ~ 21 March 1994; (b) same interferogram overlaid with the mine plan.

5. DINSAR OUTLOOK

5.1 Horizontal Displacement Measurement

This paper and most of the other deformation monitoring using DInSAR measure the surface deformation along the line of sight of the satellite. Because of the size of the look agnle, this is strongly sensitive to the vertical but less sensitive to the horizontal displacement. When the horizontal displacement vector does exist, it is possible to be resolved by combining the InSAR results derived from both ascending and descending imaging orbits (Fialko and Simons 2001) or using multiple interferograms (Wright et al. 2004). Fialko demonstrated using two ERS interferograms acquired in both ascending and descending modes with an additional azimuthal offsets by cross-correlating pre- and post-seismic radar amplitude images to derive the vector displacement field in East, North and Vertical.

It is even more challenging to determine the 3D displacement vector for mine induced deformation. The surface deformation is a continuous process corresponding to the active mining face. Therefore, in order to determine the horizontal displacement precisely the temporal overlap between ascending and descending acquisitions have to be as close as possible. The ascending and descending acquisitions with one day time difference is mostly preferred.

5.2 SAR satellite availability

The usage of the data for many applications of radar interferometry is restricted to the decorrelation. The preferred wavelength varies with the applications. For mining subsidence monitoring, the longer wavelength such as L-band and the shorter repeat-cycle are highly preferred as to reduce the high phase gradient in the interferogram. There are more SAR satellites planned to be launched in the coming years.

TerraSAR-X is scheduled to be launched on 31 October 2006. A second TerraSAR-X satellite will be launched in 2008 and operate with the first one in tandem mode. It operates in X-band (3.1cm) with the highest resolution of 1m and repeat-cycle of 11 days.

The Radarsat-2 is scheduled to be launched in March 2007. It will join the service of Radarsat-1 with the same wavelength, C-band 5.6cm, and repeat-cycle of 24 days. The highest spatial resolution is 3m.

China proposed a national project, *The Small satellite Constellation for Environment Protection and Disaster Monitoring*. Eight small satellites will be launched by the end of 2010 and 4 of them are the SAR satellites operating in the S-band with the resolution of 20m and average repeat-cycle of 2 days.

6. CONCLUDING REMARKS

This paper demonstrated the capability of DInSAR for underground mining subsidence monitoring. The SAR data acquired by ERS-1/2, JERS-1 and Radarsat-1 were tested. The results between the various SAR wavelengths, spatial resolution and repeat-cycles were compared. The results showed that ERS-1/2 interferometric pairs, which have a spatial resolution of 25m, suffer severe decorrelation at the study area. Therefore, the phase noise is higher in the interferogram. In contrast, the Radarsat-1 fine resolution (about 8m) interferometry results showed that the suitable baseline and temporal separations for maintaining sufficient coherence are much greater than the ERS-1/2 data. The L-band data is preferred to be used for the application of mining subsidence monitoring due to its longer wavelength and less sensitivity to the vegetation. The future availability of the SAR satellites is also discussed in this paper.

ACKNOWLEDGEMENT

This research work has been supported by the Cooperative Research Centre for Spatial Information project 4.2, whose activities are funded by the Australian Commonwealth's Cooperative Research Centres Programme. The Australian Research Council (ARC) has been supporting DInSAR research at UNSW over a number of years. The Australian Coal Authority Research Program (ACARP) has also supported research into ground subsidence monitoring using DInSAR. The support from BHPBilliton for data validation is acknowledged. The authors wish to thank Prof. Makoto Omura of Kochi Women's University, Japan, for providing the L-band data, ESA and ACRES (the Australian Centre for Remote Sensing) for providing the C-band SAR images. Radarsat-1 data are supported by the CRC-SI participants, UNSW and Apogee International.

REFERENCES

Chang, H.-C., L. Ge and C. Rizos (2005). ERS tandem DInSAR: the change of ground surface in 24 hours. IEEE International Geoscience and Remote Sensing Symposium, IGARSS '05., Seoul, Korea, 25-29 July. **7**. 5265-5267.

Ferretti, A., C. Prati and F. Rocca (2001). "Permanent scatterers in SAR interferometry." IEEE Transactions on Geoscience and Remote Sensing, **39**(1): 8-20.

Fialko, Y. and M. Simons (2001). "The complete (3-D) surface displacement field in the epicentral area of the 1999 Mw 7.1 Hector Mine earthquake, California, from space geodetic observation." Geophys. Res. Lett. **28**(16): 3063-3066.

Ge, L., H. C. Chang, et al. (2003). The integration of GPS, radar interferometry and GIS for ground deformation monitoring. 2003 Int. Symp. on GPS/GNSS, Tokyo, Japan, 15-18 November. 465-472.

Ge, L., H.-C. Chang and C. Rizos (2005). Dual-band radar interferometry. Spatial Sciences Institute Biennial Conference, SSC2005, Melbourne, Australia, 12-16 September. 241-250.

Peng, S. S. and H. S. Chiang (1984). Longwall mining. New York, Wiley.

Wright, T. J., B. E. Parsons and Z. Lu (2004). "Toward mapping surface deformation in three dimensions using InSAR." Geophysical Research Letters **31**(1): L01607.

BIOGRAPHICAL NOTES

The authors are all with the School of Surveying and Spatial Information Systems at the University of New South Wales (UNSW), Sydney, Australia. Dr Linlin Ge is currently a Senior Lecturer of remote sensing and GPS. He received his BEng (1st Hons) in Optical Engineering from the Wuhan Technical University of Surveying and Mapping (1985), MSc in Crustal Deformation from the Institute of Seismology (1988), and PhD in GPS and remote sensing from the UNSW (2001). His current research interests include microwave and optical remote sensing, structural deformation monitoring, kinematic interpretation of CGPS data (the so-called “GPS seismometers”), interpretation of CGPS data by incorporating synthetic aperture radar interferometry (InSAR), mitigation of atmospheric disturbance in InSAR, and analysis of single-frequency GPS observations with the aid of dual-frequency GPS data.

CONTACTS

Dr. Linlin Ge
Senior Lecturer & Coordinator of Academic Affairs
School of Surveying and Spatial Information Systems
The University of New South Wales
Sydney, NSW 2031
AUSTRALIA
Tel. +61-2-9385 4177
Fax + 61-2-9313 7493
Email: l.ge@unsw.edu.au or linlin.ge@ieee.org
Web site: http://www.gmat.unsw.edu.au/LinlinGe