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DInSAR for Mine Subsidence Monitoring Using Multi-source Satellite SAR Images

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***Abstract* - This paper demonstrates the use of differential interferometric synthetic aperture radar (DInSAR) for mine subsidence monitoring in Australia. The C-band SAR imagery acquired by ERS-1/2 and Radarsat-1 and L-band data acquired by JERS-1 were tested. As the satellites have different re-visit periods so that the mine subsidence occurred during the intervals of 1, 24, 35 and 44 days can be observed. The C-band InSAR results generally have lower coherence over vegetated areas, but the Radarsat-1 fine-beam mode data demonstrated that decorrelation can be reduced by having finer imaging resolution and shorter temporal separation. Another difficulty of DInSAR for mine subsidence monitoring is to resolve the phase ambiguity in interferogram. The L-band SAR data with comparatively longer wavelength than C-band showed it is more suitable for mining subsidence monitoring where large displacement over a small spatial extent occurs.**

***Keywords:* DInSAR, mine subsidence, ERS-1/2, Radarsat-1, JERS-1.**

I. INTRODUCTION

Australia is one of the leading mineral resource extraction nations in the world. It is rich in mineral resources of coal, copper, zinc, diamond, gold, iron, nickel, aluminium, lead, etc. There are both open-cut and underground mines for coal excavation. This paper concentrates on the subsidence monitoring due to underground mining. The exaction is achieved by either 'bord and pillar' or longwall method. It however leads to surface deformation and may change the local ecosystem and impact on man-made facilities. Therefore it has to be carefully monitored throughout the operation.

The underground mining induced surface subsidence is monitored mostly using surveying methods, such as digital levels, total stations and global positioning systems (GPS). These provide a very good height precision ranging from 0.1mm to 5mm on a point basis. In the past few yeas a new space remote sensing technology, radar interferometry using the synthetic aperture radar (SAR) imagery, has demonstrated its operational capability of monitoring the Earth's surface displacement [1-3]. The School of Surveying and Spatial Information Systems at the University of New South Wales (UNSW) started introducing differential interferometric SAR (DInSAR) for monitoring the subsidence induced by underground longwall mining in the State of New South Wales, Australia in 2001. Our previous results showed that ERS-1/2 C-band SAR images suffered severe decorrelation caused by vegetation in comparison to JERS-1 L-band InSAR results. Also the phase gradient in the differential interferograms due to the subsidence is too high to be correctly resolved during phase unwrapping process when the C-band interferometric data were used with time intervals of multiples of 35 days [4]. A similar result has also be reported in an other literature [5].

Recently, 9 newly acquired Radarsat-1 data were received by the UNSW research team. The objective of this paper is to show the DInSAR results derived from Radsarsat-1 data for mine subsidence monitoring, together with the comparison of the earlier results using ERS-1/2 and JERS-1 acquisitions.

II. METHODOLOGY

Repeat-pass spaceborne DInSAR has been used to examine ground displacement due to natural hazards or man-made activities. Two SAR images acquired from two slightly different positions, at different times, are used to observe the geographic information via measuring the phase difference to form the so-called interferogram, between the two acquisitions. Two-pass DInSAR approach with a 1 arc-second photogrammetric DEM was used to measure the displacement of the surface in this paper. The phase change in the interferogram is the composite of topographic information, ϕ_{topo}, surface displacement between the two acquisitions, ϕ_{disp}, atmospheric delay, ϕ_{atmo}, and noise, ϕ_{noise}, as shown in (1). DInSAR aims to isolate the ground displacement phase component by eliminating other terms. Here, the topographic phase was simulated based on the photogrammetric DEM.

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

The height ambiguity given in (2) shows the relationship between the phase change, ϕ_{disp}, and the height displacement, δR, along the slant-range direction. For example, a complete 2π phase change is equivalent to a height displacement of λ/2 in the slant range direction (for JERS-1 λ / 2 = 11.75cm; it is 2.8cm for ERS-1/2 and Radarsat-1). Since the measured phases in the interferogram are wrapped in modulo of 2π, the height displacement map is derived by "phase unwrapping" the interferogram.

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

III. Input Data

Both C- and L-band microwave SAR images acquired by ERS-1/2, Radarsat-1 and JERS-1 were used to study the mine subsidence. The test site of the underground mines is approximately 72km south-west from Sydney. There are 5 ERS-1 and 13 ERS-2 image acquisitions available from September 1995 to May 1996, and October 1995 to October 2001, including 3 ERS tandem pairs. There are 13 JERS-1 images available over the test site from August 1993 to January 1996. Nine recently acquired Radarsat-1 SAR images in fine-beam mode are also available from July 2004 to March 2005. The size of wavelength, imaging resolution and scene coverage of the SAR imagery are summarised in Table I. It is therefore possible to examine the relationship between the conserved coherence corresponding to the various wavelengths and image resolutions.

IV. Results

Due to the fact that the shorter wavelength of the electromagnetic wave in the microwave spectrum at around 5cm is sensitive to vegetation, the C-band SAR imagery have been used for the study of agriculture and crop mapping and forest volume estimation. It also has the drawback of greater temporal and spatial decorrelation when the studied area has vegetated cover.

TABLE I
THE CHARACTERISTICS OF MULTI-SOURCE SATELLITE SAR IMAGERIES.

Satellite	Band	λ (cm)	Repeat cycle	Pixel resolution	Scene Coverage
ERS-1/2	C	5.6	35 days	25m x 25m	100km x 100km
Radarsat-1 fine beam	C	5.6	24 days	8.9m x 6m	50km x 50km
JERS-1	L	23.5	44 days	18m x 18m	75km x 75km

TABLE II.
RADARSAT-1 REPEAT-PASS INTERFEROMETRIC PAIRS.

Pair No.	Master (date)	Slave (date)	⊥ Baseline (m)
1	29 / 07 / 2004	22 / 08 / 2004	98
2	22 / 08 / 2004	15 / 09 / 2004	262
3	15 / 09 / 2004	09 / 10 / 2004	571
4	09 / 10 / 2004	02 / 11/ 2004	226
5	02 / 11 / 2004	26 / 11 / 2004	998
6	13 / 01 / 2005	06 / 02 / 2005	484
7	06 / 02 / 2005	02 / 03 / 2005	1004

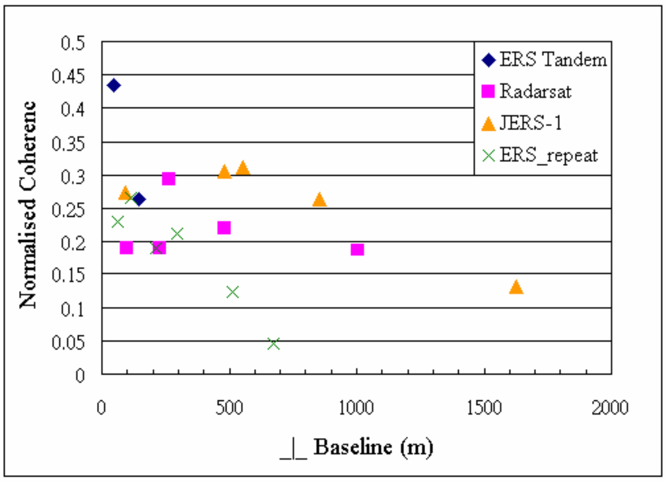


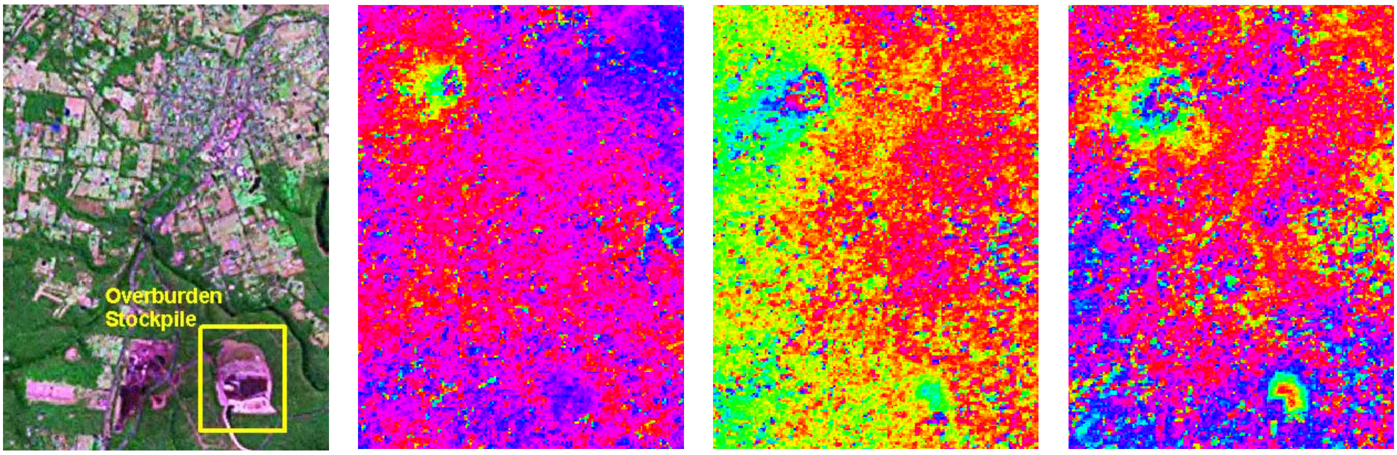
Figure 1. The normalised mean value of the coherence of the ERS-1/2, Radarsat-1and JERS-1 InSAR results with their single repeat-pass period.

The decorrelation limits the number of useable C-band interferometric pairs from all the acquisitions due to the restrictions on the perpendicular baseline and temporal separation. Also, as mentioned earlier the phase gradient in the interferogram is higher for C-band data than L-band for the same amount of height change, therefore it makes the phase unwrapping rather difficult and inaccurate. This paper discusses the conservation of coherence and the phase gradient in the differential interferograms derived from the multi-source SAR images in the following two parts.

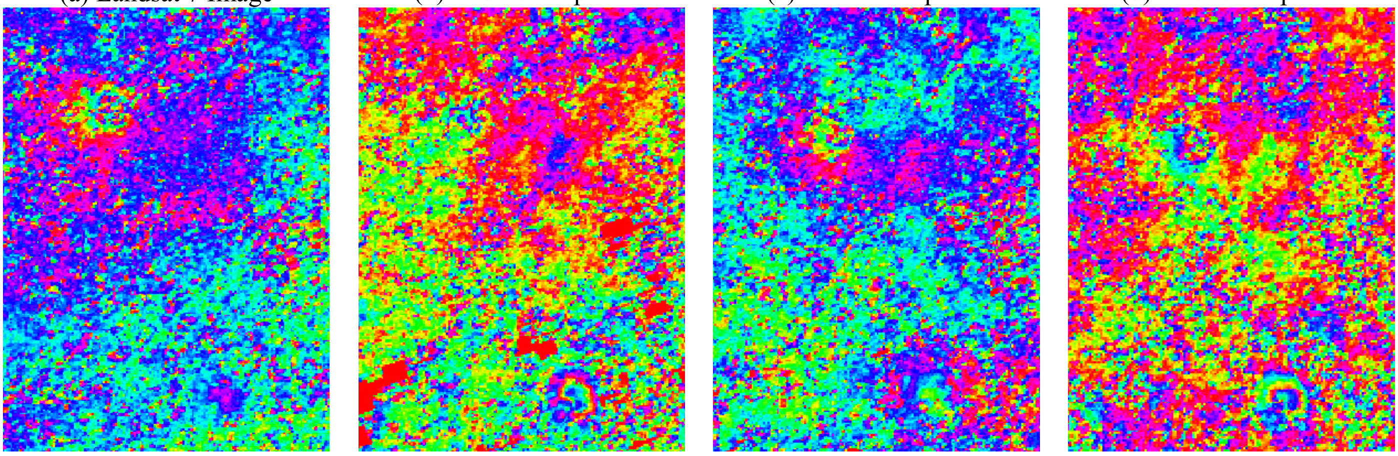
A. Coherence

The test site has a mixed land cover of grass, forest and buildings. Our previous results [4] indicated that ERS-1/2 data would have low coherence for this area especially when the perpendicular baseline is larger than 400m even though the temporal separation is one or two repeat cycles which is 35 or 70 days. For the L-band JERS-1 data, the coherence could be reasonably conserved for a baseline up to 1000m or more. The newly arrived Radarsat-1 SAR data were also acquired using the wavelength in C-band at 5.6cm but in much finer resolution. The interferometry results derived from the pairs listed in Table II showed surprisingly reasonable coherence even though the baseline was over 1000m if the temporal separation is limited to the single repeat-cycle, i.e. 24 days.

The mean coherence values over the test site derived from ERS-1/2 tandem pairs, and pairs of single repeat-cycle ERS-1/2, JERS-1 and Radarsat-1 combinations were calculated and plotted in Figure 1. The tandem InSAR results show that the coherence can be well conserved for C-band SAR data if both the temporal separation and perpendicular baseline are very small. Figure 1 also suggests that finer imaging resolution (smaller pixel size) would improve the coherence value derived using C-band data over a baseline greater than 500m, even over 1000m.



(a) Landsat 7 Image (b) Radarsat-1 pair1 (c) Radarsat-1 pair 2 (d) Radarsat-1 pair 3



(e) Radarsat-1 pair 4 (f) Radarsat-1 pair 5 (g) Radarsat-1 pair 6 (h) Radarsat-1 pair 7

Figure 2. Landsat 7 image (a) and Radarsat-1 C-band differential interferograms derived from InSAR pairs listed in Table II with time interval of 24 days (b)~(h).

B. DInSAR Mine Subsidence Mapping

In [4], it showed that tandem DInSAR analysis has revealed 1cm subsidence in 24 hours in the shallow underground mining region with a resolution of +/- 3 mm in height change. One of the JERS-1 DInSAR results showed the RMS error of 1.4 cm when compared to ground truth. In the repeat-pass ERS-1/2 DInSAR results with the intervals of multiples of 35 days, the location of mine subsidence can be clearly identified but the high phase gradient over a small spatial extent made the phase fringes undistinguishable.

The full scene Radarsat-1 data cover 3 actively ongoing underground mines. One of them has been studied using DInSAR while the work for other two are still in progress when this paper is written. Based on the previous experience, only the interferometric pairs at single repeat-cycle, i.e. 24 days, as listed in Table II, were tested for mapping mine subsidence in order to avoid high phase gradient in the differential interferograms.

The Landsat 7 image in Figure 2 (a) shows the information of the land cover at the mining site. The phase fringes caused by mining subsidence can be clearly identified at the top left corner of the differential interferograms in Figure 2 (b) ~ (h). The phase differences are at least 1~2 cycles of 2π, that is equivalent to the height displacements of 2.8cm~5.6cm along the satellite slant range direction. Figure 2 (a) also indicates an ‘overburden stockpile’ at the bottom right corner in the image. The fluctuation of the amount of coal kept at the stockpile can also be seen in the results. Due to the large baseline distances in pair number 5 and 7, the interferograms shown in Figure 2 (f) and (h) are relatively nosier than the others. High phase noise makes the phase unwrapping very difficult. Nevertheless, the impact areas can still be identified visually. The phase unwrapped height displacement result of Radarsat-1 pair 3 is coloured coded and shown in Figure 3 as an example. It shows the mine subsidence was about 5cm and at the location of ‘overburden stockpile’ the surface elevation increased about 2~3cm. The ground truth data surveyed by the mine company has been requested and it is not yet available.

Rasarsat-1 data acquired in fine-beam mode has the advantages of shorter re-visit time and finer imaging resolution. These have reduced the decorrelation and phase noise over the vegetated area compared to ERS-1/2 DInSAR results.

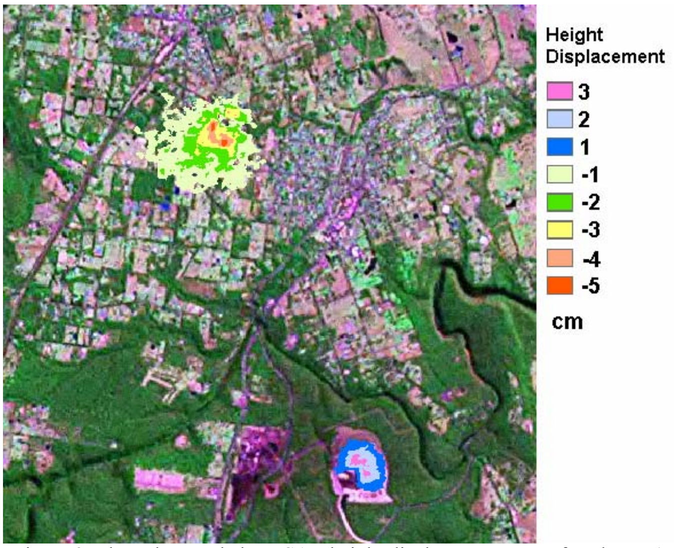


Figure 3. The colour coded DInSAR height displacement map of Radarsat-1 pair number 3. Positive height displacement indicates the increase of surface height and vice versa.

The phase gradient in differential interferogram can be reduced by not only having finer imaging resolution and shorter satellite re-visit time but also the longer wavelength of microwave. Sequentially, the accuracy of phase unwrapped displacement map can be improved. One full cycle of phase change in the interferogram using L-band data is equivalent to 11.7cm height displacement which is more than 4 complete cycles of phase change if C-band data are used. Therefore, L-band or longer wavelengths are more suitable for the application of mine subsidence monitoring where the magnitude of height displacement is in few tens of centimetres within the first few months after the excavation. In addition, the decorrelation due to the vegetation has much less impact on L-band or longer wavelength as the signal can penetrate through the vegetation.

JERS-1 is the first L-band SAR satellite. Its operation ended in 1998 and since then there have been no spaceborne L-band SAR data available. The next Japanese L-band SAR satellite, ALOS, is scheduled to be launched in late 2005. Also Radarsat-2 with C-band SAR is scheduled to be launched in early 2006. The new SAR data will be used for further DInSAR research on monitoring mine subsidence in Australia.

V. CONCLUDING REMARKS

Conventional two-pass DInSAR was used for mine subsidence monitoring. This paper used 18, 13 and 9 SAR images acquired by ERS-1/2, JERS-1 and Radarsat-1 respectively. The ERS-1/2 tandem DInSAR gave highest conservation of coherence and was able to measure the subsidence at the height resolution of subcentimetre level. However, for the 35 day interval, the ERS-1/2 DInSAR process was restricted by the decorrelation mainly due to vegetation and high phase gradient in the interferogram caused by mine subsidence. Radarsat-1 fine-beam mode data demonstrated that the decorrelation can be reduced with finer imaging resolution and shorter temporal separation. The high phase gradient can be reduced by using L-band SAR imagery. One of the Radarsat-1 DInSAR results revealed the mine subsidence at about 5cm and also the height increased about 2~3cm at the location of ‘overburden stockpile’. The ground truth data for the same time intervals of the Radarsat-1 results has been requested but are not yet available.

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