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# Mapping accumulated mine subsidence using small stack of SAR differential interferograms in the Southern coalfield of New South Wales, Australia

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ABSTRACT

The Southern Coalfield is located in the Sydney Basin, in the state of New South Wales (NSW), Australia. The coal seams of the Southern Coalfield contain high quality, hard coking coals which are mostly used for steel production. This paper describes an approach developed to study the subsidence associated with underground coal mining activity in the West Cliff colliery in the Southern Coalfield of NSW using multiple SAR differential interferograms. Accumulated subsidence maps have been derived using the approach within the study area. Results obtained by processing ten (10) ALOS PALSAR images showed that the land surface had subsided by more than 700 mm in the area of West Cliff colliery longwall 32 during the period of image acquisitions, June 2007 to October 2008. The results have been compared with deformation predicted by modelling as well as with the available GPS field survey data. High correlation has been observed between the DInSAR-derived subsidence results and the predicted mining-induced deformation. By comparing the DInSAR-measured subsidence with the GPS-derived results between September 2007 and March 2008, the magnitude and trend of the deformation has been confirmed. The absolute differences range from 0 to 45 mm, with a standard deviation of 8 mm and an average absolute difference of 12 mm.


## 1. Introduction

Australia is the world's 4th largest coal producer, and the world's largest coal exporter. Coal mining is therefore a significant contributor to the Australian economy. Australia's export earnings rely heavily on coal export; the major mineral export contributing nearly 25% of Australia's total export earnings. In Australia, most underground coal mines that operate at a depth greater than 300 m employ the 'longwall' mining technique. Longwall mining is widely implemented due to the safety, productivity and cost considerations (NSWDoP, 2008). A long 'wall' of coal is mined in a single slice, (shear), in order to maximise the quantity of recovered coal. The overlying seams are designed to collapse behind the shearer, as a result longwall mining is considered safer than traditional mining methods as the subsidence is more uniform and predictable. However, the resulting subsidence caused by this underground mining technique can be very large, occurring immediately after or during mining. Generally, the scale of vertical displacement is meters, with a spatial extent of several kilometres. This significant change in the overlying ground topography can therefore cause serious problems, for example, changing the river courses or damaging building foundations. The areal extent and amount of mining-induced subsidence is dependent on a number of factors, including the depth of cover, overlying strata properties, seam thickness, panel width, chain pillar size and surface topography (Nestbitt, 2003). Mining-induced subsidence is a major concern to the mining industry, to government, environmental groups, and other stakeholders.

Several methods are currently used for mine subsidence monitoring, including levelling, total station surveys, and GPS field surveys (Schofield, 1993). However these techniques have limitations, primarily because they measure subsidence on a point-by-point basis. Spaceborne radar interferometry is a well-known technique that can measure the ground movement of a wide-area, and which has been widely used for monitoring subsidence due to underground mining (Stow and Wright, 1997; Perski, 1998; Perski and Jura, 1999; Carnec and Delacourt, 2000; Wegmuller et al., 2000; Strozzi et al., 2001; Ge et al., 2007; Ng et al., 2009). The differential interferometric SAR (DInSAR) technique has the potential to precisely observe the ground displacement along the LOS with an accuracy down to a few millimetres (Gray and Farris-Manning, 1993). However, four main problems have prevented its use on a fully operational basis (Ferretti et al., 2000, 2001): (1) temporal decorrelation of surface scatterers due to vegetation or other surface change processes, (2) spatial decorrelation due to the large baseline between SAR image acquisitions, (3) atmospheric disturbances causing variation in signal delays, and (4) resolving the phase ambiguity.

PSI (Persistent Scatterer Interferometry) is an extension of conventional InSAR techniques which allows for millimetre precision ground

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deformation mapping based on the utilisation of long time series of interferometric SAR image data, in order to overcome the problems of the InSAR techniques mentioned above. The most well-known of these are: PSInSAR (Ferretti et al., 2001), Coherent Target Monitoring (Van der Kooij et al., 2005), Coherent Pixel technique (Mallorqui et al., 2003), Interferometric Point Target Analysis (IPTA) (Werner et al., 2003), Small Baseline Subset Approach (SBAS) (Beradino et al., 2002), Spatio-Temporal Unwrapping Network algorithm (STUN) (Kampes, 2006) and Stanford Method for Persistent Scatterers (StaMPS) (Hooper, 2006). These PSI techniques have been used in several studies to estimate the long-term ground deformation due to underground mining (Herrera et al., 2007; Jung et al., 2007; Perski et al., 2009). However there are several factors which have limited the applicability of PSI techniques to map the mining-induced subsidence in the Southern Coalfield of New South Wales, Australia.

(1) The mining-induced subsidence in the Southern Coalfield commonly reaches 20 to 60 cm in the 1–2 months after the collapse of the roof of the longwall panel, and up to 80–100 cm over a full year after mining has ceased (Holla and Barclay, 2000). The large deformation gradient due to the mining activities and strong temporal decorrelation due to vegetation implies that SAR images from the Radarsat-1 and ENVISAT missions are not suitable (Ng et al., 2009). As a consequence, L-band ALOS PALSAR data are used in this study. Unfortunately, the amount of ALOS PALSAR data available is limited (10 images for this study), whereas PSI techniques require larger image stacks (>20 images) to precisely estimate the deformation (Colesanti et al., 2003). (2) The problem of resolving the ambiguity of phase measurements prevents the PSI technique from being able to monitor rapidly changing deformations (Colesanti et al., 2002). The mining-induced subsidence exceeds the absolute limit imposed by the sampling theorem on ALOS, ENVISAT and Radarsat-1 observations if there is no a priori information available. In addition, it is complex to resolve the phase ambiguity in time with small datasets, especially when the deformation is very large and its gradient is too steep. Spatial phase unwrapping is preferred prior to the analysis. ALOS PALSAR pairs with the shortest revisiting times were selected to address the problem of resolving ambiguity of phase measurements. If the displacement between neighbouring pixels is too large, the spatial unwrapping algorithm is unlikely to be unwrapped correctly (the term “phase saturation” is used to denote this problem). Phase saturation occurs in nearly all ALOS PALSAR pairs separated by two or more revisiting cycles, that is 92 days or more. This suggests that both common master (single reference image (Ferretti et al., 2001)) and short baseline (Beradino et al., 2002) methods are not appropriate for mapping the near field (rapidly changing deformation area) deformation time series due to underground mining. (3) The deformation due to underground mining is very large and is highly non-linear. Significantly non-linear ground motion may not be captured by PSI techniques, therefore very few PS points are expected to be identifiable in the area of interest because of the large deformation gradient (see Raucoules et al., 2009). (4) PSI techniques measure deformation time series on a point-by-point basis, whereas deformation measured on a pixel-by-pixel basis could provide more information to aid understanding of the mine subsidence phenomenon. (5) PSI techniques carry out measurements on stable scatterers that are coherent in time across all images. The collieries in the Southern Coalfield are mostly located in rural areas, where low PS density is expected.

This paper describes an approach to map the cumulative mining-induced subsidence in the Southern Coalfield based on a PSI technique. The approach utilises the differential interferograms that are generated by conventional DInSAR processing and addresses the issues listed above. The main aim of this approach is to estimate the atmospheric disturbances of each differential interferograms with small number of SAR data. The topographic error and area influenced by mine subsidence are addressed for precise estimation of the atmospheric disturbances. The authors present results obtained for the period 2007 to 2008 by the ALOS PALSAR satellite sensor for the West Cliff colliery to demonstrate the capability of the proposed approach for mapping accumulated mining-induced subsidence.

This paper is arranged as follows. Section 2 presents the geological information on the Southern Coalfield and describes the test site. Section 3 describes the processing procedure. The generated results are analysed in Section 4. Validation of the obtained results with the deformation predicted by modelling, as well as the GPS field survey, is discussed in Section 5. Section 6 presents the conclusions and discusses further development work to be undertaken.

## 2. Geology of the Southern Coalfield test site

The main coal resources of New South Wales (NSW) are located in the Sydney–Gunnedah Basin, and comprise five major coalfields: Gunnedah, Hunter, Western, Newcastle and Southern. The Southern Coalfield is part of the Sydney Basin, and contains a large number of coal seams in late Permian sediments. The Southern Coalfield, covering an area from Campbelltown and Tahmoor to the Illawarra, south to Berrima and Sutton Forest, and west to Warragamba Dam, has premium quality, hard coking coals favoured for steel production. It is in fact the only source of hard coking coals in NSW.

Most collieries in the Southern Coalfield are recovering coal from the Bulli or Wongawilli Seams. The study site, West Cliff colliery, are extracting the coal from the Bulli Seam (NSWDPI, 2006; NSWDoP, 2008), which is in the top coal seam layer of the Southern Coalfield. The location of the study area is shown in Fig. 1. The two underground coalmines, West Cliff and its adjacent coalmine, Appin, employ the longwall mining technique. The mining characteristics of the West Cliff longwall number 32 are given in Table 1.

The longwall plan projected on an aerial photograph of the area, with the dates of mining progress, is shown in Fig. 2. In February 2007, mining of longwall number 31 (LW31) was completed, and was mined 30 m up to George's River. Mining of LW32 started on 12 February 2007, but at slow speed due to engineering issues, with the mining face having only moved a couple of hundred meters by mid-April 2007. After that date the extraction rate was back on schedule and the mining speed was around 32–45 m per week. The extraction rates were 253 m, 167 m, 153 m in October, November and December (2007), respectively. The extraction speed during January 2008 was 223 m. There was about 700 m remaining to the end of LW32 by mid-February 2008, and was completed in mid-June 2008. The total length of LW32 was approximately 3222 m. Work commenced on LW33 at the end of July 2008.

## 3. Methodology

SAR interferometry utilises the phase information from the SAR images to compute the geometry between the satellite position and the target on the ground. The differential phase in interferogram k, in the pixel of azimuth and range coordinates (x,y), from the SAR acquisitions at times $t_B$ and $t_A$ after the removal of topographic phase, is given by (Ferretti et al., 2001):

$$\Delta\phi^{k}_{x,y} = \phi^{t_A}_{x,y} - \phi^{t_B}_{x,y} \approx -\frac{4\pi}{\lambda}\left(d^{t_A}_{x,y} - d^{t_B}_{x,y}\right) - \frac{4\pi}{\lambda}\left(\frac{B^{k}_{\perp_{x,y}}\Delta h_{x,y}}{R\sin}\theta\right) + \left(\phi^{t_A}_{atm_{x,y}} - \phi^{t_B}_{atm_{x,y}}\right) + \phi^{k}_{orbit_{x,y}} + \Delta n^{k}_{x,y} \quad (1)$$

where $\lambda$ is the wavelength of the radar signal and $d^{t_A}_{x,y} - d^{t_B}_{x,y}$ is displacement that has occurred between the two radar acquisitions at times $t_B$ and $tA$ in the line-of-sight (LOS) direction. The second term in Eq. (1), represented by $(B^{k}_{\perp x,y}\Delta h_{x,y}/R\sin\theta)$, is the phase error due to inaccuracies in the reference digital elevation model (DEM) in the DInSAR processing. $\Delta h_{x,y}$ is the height difference of the point, between