Remote Monitoring of Mine Subsidence Using Radar Interferometry

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Summary

Radar interferometry has been increasingly used to generate digital terrain models and to map ground surface displacement. The technology has the potential to monitor subsidence movements in three dimensions over entire coalfields every few weeks. This paper describes some of the experience and challenges associated with using radar interferometry for three dimensional subsidence monitoring.

In conventional differential radar interferometry (DInSAR), the ground surface displacement can be measured along the looking direction of the radar system. DInSAR results of the same area are required from at least three different looking directions to measure vertical and horizontal displacements in three dimensions. DInSAR results generated from data acquired by the European satellite ENVISAT at three different look angles have been used to develop displacement vectors of mining deformation in three dimensions. Interpretation of the ENVISAT results has been complicated by what is called phase unwrapping errors caused by the high displacement gradients at the edge of the subsidence zone. Results derived from data acquired by the new Japanese satellite ALOS is also used here to demonstrate how the high phase gradient problem can be eased by having the interferometric data with longer wavelength and finer imaging resolution.

Keywords: radar interferometry, 3D deformation vectors, ENVISAT, ALOS, mining deformation

1. Introduction

Radar interferometry techniques, including interferometric synthetic aperture radar (InSAR), differential InSAR (DInSAR) and persistent scatter InSAR (PSInSAR), have demonstrated their capabilities to extract geodetic information of the earth surface. They are considered to be cost-effective as a complementary system to conventional ground-based surveying methods. The authors have been studying the dynamics of mine subsidence using DInSAR over a number of sites in the last few years. A mine subsidence profile extracted from a JERS-1 DInSAR result indicated a root mean square error (RMSE) of 1.4cm when compared to the ground levelling data (Ge et al. 2007). Sub-centimetre accuracy of DInSAR result was demonstrated using ERS-1/2 tandem images (Chang et al. 2005; Ge et al. 2007).

As in many other DInSAR studies for land deformation monitoring, the deformation is measured along the line-of-sight (LOS) between the radar antenna and the ground objects. Then the subsidence (vertical surface deformation) is measured with the assumption of negligible horizontal deformation. However, the in situ ground surveying data shows that underground mining activity causes horizontal surface displacement as well. The ERS-1/2 data is less sensitive to horizontal movements because the look angle of the ERS-1/2 is 23^o. The smaller look angle makes the system more sensitive to vertical deformation than horizontal deformation.

In order to study both vertical and horizontal displacement of mine deformation, ENVISAT/ASAR data acquired from multiple ascending and descending orbits are used in this paper. The variation of the swath mode of ENVISAT/ASAR provides the opportunity to investigate the 3-D surface deformation vectors due to underground mining with a range of satellite look angles ranging from 15^o to 45.2^o.

2. Methodology

InSAR utilises two coregistered SAR images of the identical scene and measures the phase difference of the same imaged pixels in the two images. This phase difference product, called the interferogram, contains topographic information, variance of water vapour in the atmosphere and ground movement occurred between the dates of the two SAR images acquired if repeat-pass radar interferometry is used.

DInSAR is the technique to extract the interferometric phase introduced by land surface deformation by eliminating other phase contributors in the interferogram, e.g. topography. The phase difference, $\Delta\phi$, caused by the height deformation, Δd, along the line of sight (LOS) of the radar system is shown in equation (1), where λ is the wavelength of the radar signal. So, one complete phase change (2π) in a differential interferogram represents $\lambda/2$ of height displacement along the LOS of the radar.

$$\Delta\phi = \frac{4\pi\Delta d}{\lambda} \qquad (1)$$

Usually, the amplitude of the vertical height deformation vector, or subsidence, is interpreted by assuming negligible horizontal displacement. In order to resolve the true 3-D deformation vectors, DInSAR results derived from both ascending and descending data need to be combined together. If the deformation is purely vertical, the results derived from both orbits should be the same. Otherwise, horizontal displacements exist.

The new spaceborne SAR sensors have various scanning modes with a range of incidence angles. ENVISAT/ASAR provides acquisitions of the same region in seven different swath modes. So, the same surface deformation can be measured not only in both ascending and descending orbits, but also at different viewing angles. This study examines the applicability of combining the DInSAR results derived from 1 ascending and 2 descending orbits of ENVISAT data to reveal the 3-D deformation vectors of mine subsidence.

Sircar et al. (2004) demonstrated that the 3-D deformation vectors can be calculated from the DInSAR results derived along three independent lines of sight with the ascending and descending Radarsat-1 data. The deformation vector along the LOS of radar system (D_{LOS}) is a composite of up (D_U), east (D_E) and north (D_N) deformation vectors. The deformation measured in the differential interferogram is the sum of vertical and horizontal deformations projected onto the LOS. The contributions of D_U, D_E and D_N towards D_{LOS} are shown in equation (2).

$$\begin{bmatrix} -\cos(\theta) & \sin(\theta)\cos(\alpha) & \sin(\theta)\sin(\alpha) \end{bmatrix} \begin{bmatrix} D_U \\ D_E \\ D_N \end{bmatrix} = [D_{LOS}] \qquad (2)$$

where θ is the radar incidence angle and α is the azimuth of the satellite heading vector (positive clockwise from North). D_U is defined as negative for downward subsidence movement.

3. Input Data and Results

Three ENVISAT interferometric pairs are used to test the 3-D deformation vector analysis for mine deformation. Also, a newly received ALOS interferometric pair is tested as a comparison to the ENVISAT results. Some characteristics of ENVISAT and ALOS SAR sensors are summarized in Table 1. The ENVISAT acquisitions over the test site are listed in Table 2, where pair 1, 2 and 3 were acquired in the swath modes IS4, IS3 and IS2, respectively. The maximum temporal difference is only 3 days between pair 1 and 3. Therefore, the temporal coverage of the pairs is suitable for 3-D deformation analysis.

The DInSAR results of pair 1~3 were derived and a high phase gradient near the centre of the subsidence bowl was noticed. There was a phase unwrapping error in pair 3 due to the ambiguous phases. Unwrapping error occurs when the deformation gradients are high and it becomes difficult to determine how many wavelength shifts or phases have occurred.

Therefore only the deformation vectors derived from pair 1 and 2 were used for the 3-D deformation analysis with the assumption of small horizontal movement along north-south direction. The geocoded deformation maps in slant range direction are shown in Figure 1. The estimated 3-D deformation vectors along East, North and Up directions are shown in Figure 2.

Table 1. Characteristics of ENVISAT and ALOS SAR sensors.

Sensor	Band	λ (cm)	Altitude (km)	Resolution (m)
ENVISAT ASAR	C	5.6	786	~30
ALOS PALSAR	L	23.6	692	~10

Table 2. Three ENVISAT interferometric pairs used in this study with all 35day temporal separation between master and slave images.

Pass	Pair	Master dd/mm/yyyy	Slave dd/mm/yyyy	B_{perp} (m)
desc	1	8/12/2006	12/01/2007	234
asc	2	10/12/2006	14/01/2007	238
desc	3	11/12/2006	15/01/2007	310

4. Validation

The ENVISAT results do not reflect the true mine subsidence as the high phase gradient at the centre of the subsidence bowl makes the phase ambiguous. Therefore, the discontinuous or wrapped phase values in the differential interferograms cannot be recovered to continuous phase values without errors.

On the other hand, a previous study showed that the mine subsidence measured by DInSAR using JERS-1 data can achieve a RMS error of 1.4cm by comparing to ground survey (Ge et al. 2007). In the comparison, the surveying line was not across the centre of the subsidence bowl.

Therefore, the maximum subsidence measured along this surveying line was about 16cm. According to the ground survey data, the mining activity would cause the maximum subsidence in the order of 86cm to 93cm in the area. And about 65% of this subsidence (50cm) occurred within 2~3 weeks of the passage of the first longwall panel. This large amount of vertical ground movement near the centre of subsidence bowl causes the phases in the differential interferogram to be ambiguous during phase unwrapping. This problem can be solved or eased by having the interferometric pairs with higher imaging resolution, longer wavelength and/or shorter site revisit cycle. It is demonstrated in the next section with the new ALOS data.

5. High Phase Gradient Problem

The maximum phase gradient in interferograms to prevent incoherence was defined in (Massonnet and Feigl 1998). The maximum detectable deformation gradient is one fringe per pixel. The maximum phase gradient is also restricted when phase unwrapping the differential interferogram. The common phase unwrapping techniques assume the phase difference between the two adjacent pixels in the interferogram is less than π. Otherwise, the wrapped phase in the interferogram becomes ambiguous and cannot be unwrapped to continuous phase without errors.

In this application of using DInSAR for monitoring the land deformation caused by longwall mining, the maximum subsidence usually happens along the centre of longwall panel. At the test site, the longwall panel has a width of 200~250m. Due to the rectangular layout of longwall, the subsidence gradient across the longwall panel is much greater than along the longwall. So, the phase gradient in the differential interferogram is at its maximum in the direction across the longwall panel.
Due to the longwall geometry, the centre of subsidence bowl normally lies along the centre of the panel. For example, for a longwall panel with a width of 250m, the centre of the subsidence bowl should be about 125m from the edge of the panel (pillar). That is equivalent to about 4 pixels for ENVISAT data with a spatial resolution of 30m. In order to avoid phase unwrapping error, the maximum height displacement over these 4 pixels has to be less than 4π. Therefore, better imaging resolution of SAR sensor improves the maximum detectable height displacement without increasing phase unwrapping errors.

A newly received interferometric pair of ALOS PALSAR data is used here to demonstrate the benefits. ALOS can operate in 5 different imaging modes: fine beam single polarisation (FBS), fine beam double polarisation (FBD), direct downlink (DSN), ScanSAR and polarimetry (PLR). For DInSAR process, we used the data acquired in FBS modes with a resolution of 10m and 46 days apart (single repeat cycle) as shown in Table 3. The differential interferogram of ALOS shown in Figure 3 clearly indicates the fringes caused by mine subsidence at the same mine site which is more distinguishable than the results derived by ENVISAT data.

By applying the wavelength of 23.6cm and an incidence angle of 38.7^0, the height displacement map in Figure 4 shows the maximum height displacement near the centre of the subsidence bowl is over 40cm. This result agrees better with the subsidence movements measured by ground survey. More detailed validation is needed with ground truth data of the same or similar spatial and temporal coverage.

Table 3. Interferometric pair of ALOS data

Pass	Incidence Angle	Master dd/mm/yyyy	Slave dd/mm/yyyy
ascending	38.7^0	27/12/2006	11/02/2007

6. Further Work

As illustrated in the previous section, using ALOS data (or SAR data acquired in longer wavelength) may ease the problem of high phase gradient in interferogram caused by large and rapid ground deformation such as mine subsidence.

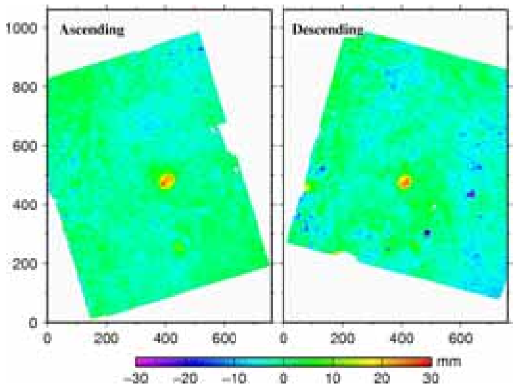

Figure 1. Deformation vectors along the slant range direction of pair 1 (descending) and pair 2 (ascending).

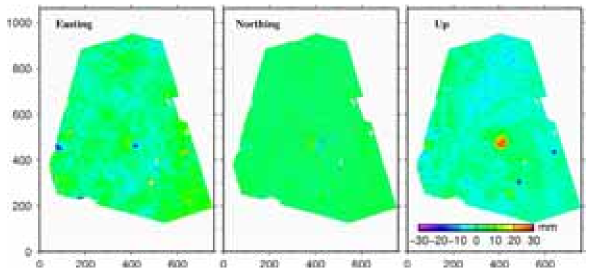

Figure 2. 3-D deformation vectors of mining subsidence over 35 days in easting, northing and up directions.

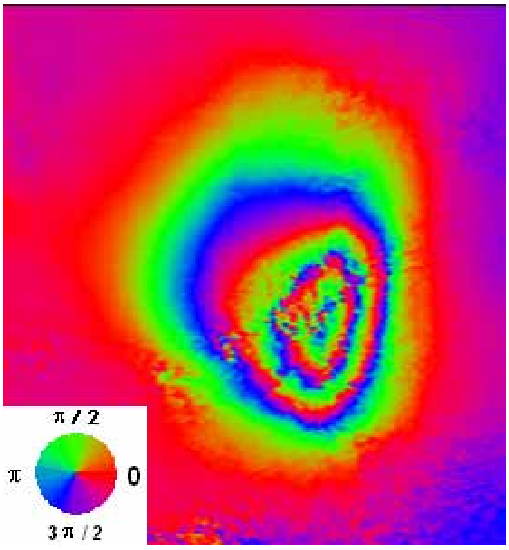

Figure 3. Differential interferogram of the mine subsidence generated from ALOS data.

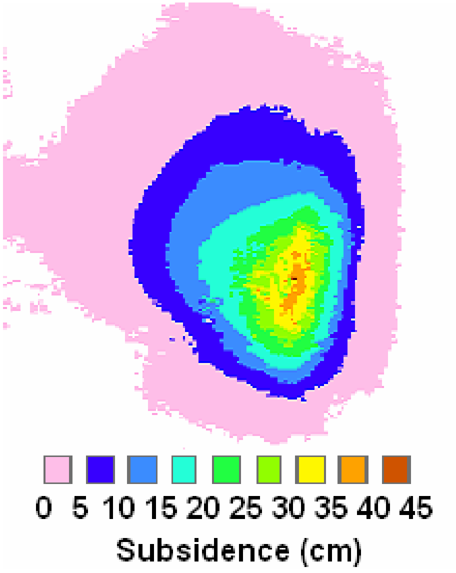

Figure 4. Mine subsidence map based on the differential interferogram in Figure 3.

Other alternatives to avoid high phase gradient are to have the interferometric pairs with finer imaging resolution and/or shorter time span.

Two new SAR satellites, TerraSAR-X and COSMO-SKYMED, were recently launched in June 2007. Both satellites have SAR sensors operating in X-band.

Their finest imaging resolution is less than 3m. The repeat cycles of TerraSAR-X and a single COMSMO-SKYMED are 11 and 16 days, respectively. In future studies, X-band data will be used to test their performance for mine subsidence monitoring.

The 3-D surface deformation vectors can also be measured using the SAR pixel matching technique (Tobita et al. 2001; Werner et al. 2001). This method was used to measure the land deformation caused by earthquakes (Michel et al. 1999). This pixel matching technique will be tested for mining subsidence monitoring. The results will be cross validated with the DInSAR results.

7. Concluding Remarks

This study illustrates that 3-D deformation vectors of mining subsidence can be measured using DInSAR results derived from the combination of ascending and descending orbit data in different swath modes of ENVISAT/ASAR. When 3 deformation vectors along different SAR line of sight are available, it is possible to measure the deformation vectors in Up, East and North directions. This method is limited by having 3 interferometric pairs with good coherence and covering a similar period of time or 2 ascending and descending pairs with a good estimation of the deformation in the third dimension.

This study shows that high phase gradient in the differential interferogram caused by mine deformation is unavoidable using ENVISAT data without having finer imaging resolution or shorter revisit orbit cycle. Therefore, errors occur when unwrapping the interferogram. Consequently errors are found in the final height displacement map.

ALOS/PALSAR has longer wavelength and also finer imaging resolution than ENVISAT/ASAR. The result derived from ALOS demonstrates the problem caused by high phase gradient is reduced. The new TerraSAR-X and COSMO-SKYMED data with shorter site revisit cycle and finer imaging resolution will be tested for their capability of monitoring mining deformation.

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