RADAR INTERFEROMETRY FOR SAFE COAL MINING IN CHINA

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ABSTRACT:

Land surface deformation due to underground mining is always a concern to the local communities and environment. The underground coal mines at the study site in Northern China are located quite closely to each other. In order to ensure safe mining as well as to prevent illegal mining activities, differential radar interferometry (DInSAR) was introduced for monitoring mine subsidence. The spaceborne SAR data acquired by ENVISAT (C-band) and ALOS (L-band) were tested in this paper. The limits of radar interferometry were discussed by addressing the issues of decorrelation and deformation phase gradient. The ALOS results show it is more suitable for monitoring the rapid and large land deformation due to underground mining. However, the data acquired in summer season (June – September) have higher noise, which may be caused by the local agriculture.

1. INTRODUCTION

Land deformation caused by underground mining becomes more and more a concern for many areas in China. Especially the population density in China is very high by comparing with many other countries. In order to ensure safe mining as well as to prevent illegal mining activities, the implementation of an effective mining monitoring scheme is important. Conventional subsidence monitoring measurement is done by precision digital levels, total stations and GPS receivers. Both digital level and total station can deliver 0.1 mm in height resolution while GPS can sense 5 mm changes in static mode. However, applying leveling and GPS surveys over a large area are not just labour intensive, but also very time consuming. Ideally, the mine subsidence should be carefully monitored with a surveying network. However, surveying over the entire network may take a few weeks. The coverage of the surveying network may also be limited due to site accessibility. The maintenance of the survey marks are another important and yet difficult issue. Differential radar interferometry (DInSAR) technique has been demonstrated its capability of monitoring land subsidence (Ge et al., 2007). DInSAR can monitor the land deformation at sub-centimetre accuracy over a large area (at the radar swath width of 50~100km). D-InSAR method is a land deformation mapping technology, which is complementary to other surveying methods.

The test site in this study locates in the middle of Huabei plain, China. It covers about 570km^2. The mine has been excavated since early 20th century. Today, the region is one of the most important coal mining areas in China, producing about 2,700 million tones of coal per year. There are about 500 collieries built up in this region, and some new collieries are planned to be constructed in the near feature. As a result, the region has been environmentally degraded. And the subsidence is expected to become more severe in the future. The land-use is a mixture of villages and farmlands of wheat and corns.

2. METHODOLOGY

Repeat-pass spaceborne DInSAR is used here to derive ground displacement maps. The basic theory of radar interferometry can be found in great details in (Bamler and Hartl, 1998; Gabriel et al., 1989; Rosen et al., 2000; Zebker and Goldstein, 1986). In short, two SAR images acquired from two slightly different positions, at different times, are used to measure the phase difference, or so-called interferogram, between the two acquisitions. Interferogram consists of topographic information, land deformation occurred between the two acquisitions, atmospheric disturbances, orbit errors and noise. DInSAR is the process to measure the phase variation due to land deformation by eliminating or minimising the other components. The topographic phase contribution can be simulated by introducing a digital elevation model (DEM). A 3 arc-second SRTM DEM (approximately 90m resolution) is used in this paper to simulate the topographic phase, which 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 & 2004). 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.

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 and ALOS L-band 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. Finally the unwrapped phase can be converted to height change.

3. INPUT DATA

ENVISAT and ALOS SAR imagery were tested using DInSAR for monitoring the ground deformation due to mining at the study area shown in Table 1. The spatial and temporal separations between the images of the interferometric pair are indicated as perpendicular baseline (Bperp) and temporal baseline (Btemp).

Sensor	Master (dd/mm/yyyy)	Slave (dd/mm/yyyy)	Bperp (m)	Btemp (day)
ALOS / PALSAR	14/6/2007*	30/7/2007*	515	46
	30/7/2007*	14/9/2007*	143	46
	15/12/2007**	30/01/2008**	351	46
ENVISAT / ASAR	3/1/2008	7/2/2008	361	35

Table.1. Interferometric pairs tested using DInSAR for monitoring mine subsidence at the study area. Note: * and ** denote the ALOS data acquired in single and dual polarization mode, respectively.

4. LIMITATIONS OF DINSAR MEASUREMENT

Radar interferometry is the technique to measure geodetic information, e.g. elevation or height change, by exploiting the phase information of at least two images. The precision of the result depends on not only the wavelength of the microwave signals emitted by the SAR antenna, but also the geometry of interferometric pair. Shorter wavelengths are more sensitive to the height change of terrain than the longer wavelengths. However, the shorter wavelengths can be more influenced by vegetations. Geometry of interferometric pair determines the sensitivity of interferometric phases with respect to topography. After all, the precision of radar interferometry depends on how accurate the process is to convert the interferometric phases to height or height changes. The limitations of DInSAR measurement are discussed in the following subsections.

4.1 Decorrelation

The interferometric quality of an identical imaging pixel in two SAR images can be assessed by measuring the correlation between the pixels. The quantity of correlation, or the so-called coherence, can be considered as a direct measure for the similarity of the dielectric properties of the same imaging pixels between two SAR acquisitions. Decorrelation degrades the coherence between two SAR images and results phase noise.

Decorrelation is site-specific. It depends upon local climate conditions, vegetation cover, complexity of the terrain (moderate v.s. hilly or mountainous), land use, etc. As a rule of thumb, decorrelation is more severe for the area having heavily vegetated cover, complex terrain or constantly changing climate conditions. Decorrelation can be classified into three main categories: spatial, temporal and volume decorrelation (Zebker and Villasenor, 1992).

Spatial decorrelation is caused by the physical separation, or so-called perpendicular baseline, between the locations of the two SAR antennas. The maximum allowable baseline before the pixels get totally decorrelated is often referred to as the critical baseline (Zebker et al., 1994). The perpendicular baseline of the

interferometric pair for DInSAR processing is therefore preferred to be as small as possible.

Temporal decorrelation is caused by the variation of the dielectric properties of ground objects over time between two repeat-pass acquisitions. In repeat-pass interferometry the sub-resolution properties of the imaged scatterers (sub-scatterers) may change between surveys, e.g. by meteorological differences at the time of image acquisitions, the movement of leaves and branches, water surface, or vegetation growth. Therefore, urban regions normally illustrate much higher coherence than vegetated/agricultural areas over a period of time.

Volume decorrelation is also about the phase stability of the imaging cell (pixel) over time, especially over vegetated regions. The dielectric properties and alignments of tree leaves and branches in the canopy may result in the variation of the backscattered radar signals. They are also affected easily by the local weather conditions, such as rains and winds. Therefore, it is desirable to have a finer SAR imaging resolution in order to minimise the variation of the random scattering phases.

The histograms of the coherence value of 4 selected interferometric pairs as given in Table 1 are shown in Figure 1. The mean coherence of the ALOS pair, 15/12/2007 – 30/01/2008, illustrated higher value than other two ALOS pairs acquired in June, July and September in 2007.

It is interesting to note that even the perpendicular baseline of the ALOS pair, 30/7/2007 – 14/9/2007, is 143m its coherence over the selected scene is not as good as expected. After comparing this coherence map to a high resolution optical image of the identical area, the areas showing low coherence value (<0.3) are actually farmlands. It suggests the local agriculture pattern may cause additional noise in the scene. Based on the coherence value shown in Figure 1, the decorrelation due to agriculture is more severe in summer (June – September) than winter (December – February). In addition, the ALOS data acquired on 15/12/2007 and 30/01/2008 are in single polarization mode, which has twice better imaging resolution than the images acquired in dual polarization mode. Therefore, the interferometric pairs with better imaging resolution will be less subject to volume decorrelation, hence high interferometric coherence value.

The ENVISAT pair covers a similar period as the 3rd ALOS pair. However, it has less mean coherence of 0.379. The decorrelation may be caused by the spatial decorrelation as the perpendicular baseline of this ENVISAT pair is about 361m.

4.2 High phase gradient

As mentioned earlier, the interferometric phase variation caused by land deformation is linearly depending on the height change of terrain. Therefore, a large vertical ground movement over a small spatial extent causes the rapid changes of phases in the differential interferogram. When the phase gradient gets too large, it becomes ambiguous and it is impossible to recover the height change accurately. The problem can be solved or reduced by having interferometric pairs with higher imaging resolution, signals with longer wavelength and/or a shorter site revisit cycle. This is demonstrated in Figure 2 by comparing the DInSAR results derived using ENVISAT (C-band, wavelength = 5.6cm) and ALOS (L-band, wavelength = 23.5cm) data.

For the same amount of ground deformation, the induced DInSAR phase fringes will be denser in the results generated using shorter radar wavelength (e.g. C-band) than the ones generated using longer wavelength (e.g. L-band). Figure 2 (a) shows the high phase gradient within the subsidence bowl causing the phase ambiguous. As a result, the phase fringes cannot be fully recovered, even after being filtered.
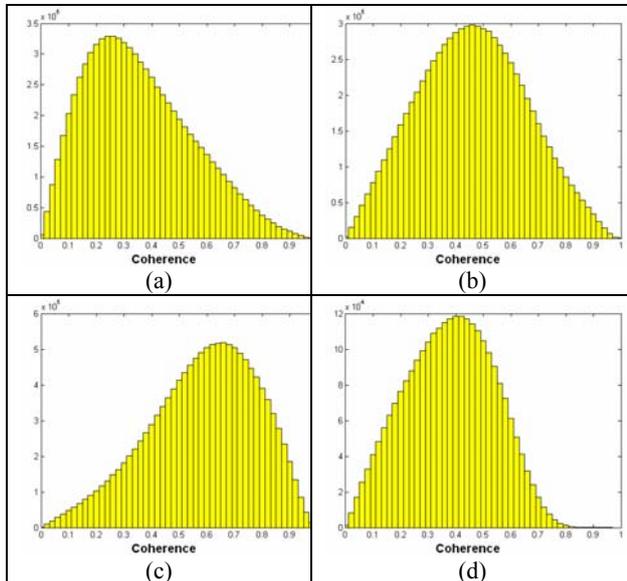

Figure 1. Histograms of coherence values of (a) - (c) ALOS interferometric pairs: 14/6/2007 - 30/7/2007 Bperp = 515m, 30/7/2007 - 14/9/2007 Bperp = 143m, and 15/12/2007 - 30/01/2008 Bperp = 351m, and (d) ENVISAT pair: 3/1/2008 - 7/2/2008 Bperp = 361m, respectively. The mean coherence value of these 4 pairs are 0.355, 0.461, 0.586 and 0.379.
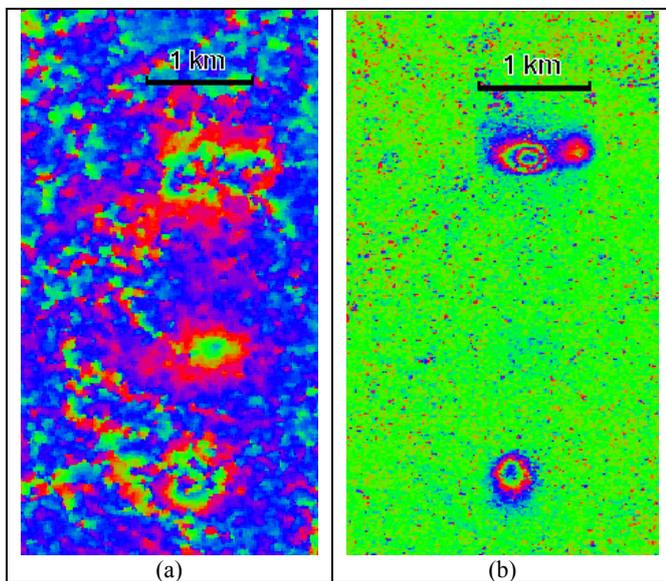

Figure 2. Enlarged DInSAR phase fringes induced by ground deformation of (a) ENVISAT (C-band) pair: 3/1/2008 - 7/2/2008 Bperp = 361m, and (b) ALOS (L-band) pair: 15/12/2007 - 30/01/2008 Bperp = 351m.

5. RESULTS AND DISCUSSIONS

The study area is about 24km x 25km. The differential interferograms of the selected four interferometric pairs (3 from ALOS and 1 from ENVISAT) are shown in Figure 3. In the results, over 21 mine subsidence spots are identified using DInSAR technique. The magnitude of ground deformation due to underground mining can be more accurately measured or recovered if the interferometric pair illustrates high coherence over the scene and at the same time the deformation phases are not ambiguous. In this study, the ALOS pair with the mean coherence value of 0.586 shows the deformation fringes quite clearly as shown in Figure 2 (b).

Figure 4 shows the final deformation map derived from the ALOS pair, 15/12/2007 - 30/01/2008. The result is overlaid on a high resolution optical image with the aid of geographic information systems (GIS). The maximum subsidence detected due to active underground mining activities over a period of 46 days is about 36cm.

There are several coal collieries in the local area and they are closely located to each other. Even though the proposed mining location and mining schedule are recorded, it is still hard to track the precise locations of mining activities. But it is extremely important for ensuring the safety of the miners as well as the local residents when the mining progress at the two collieries are close to each other. The results of DInSAR derived from successive acquisitions were post-analysed against other supporting spatial data in geographic information systems (GIS). By comparing the locations against the proposed mining schedule, any illegal mining activities can also be identified.

6. CONCLUDING REMARKS

This paper demonstrated the capability of differential radar interferometry (DInSAR) for monitoring the ground surface deformation caused by underground mining activities. The study area chosen in this paper is in the Northern China. ENVISAT and ALOS SAR data acquired in C- and L-band respectively were tested in this paper. Within an area of approximately 24km x 25km, more than 20 subsidence spots are identified using DInSAR. The results show ALOS data are more suitable for mine subsidence monitoring. The L-band radar signal and the high imaging resolution (8m) of ALOS reduce the problems caused by high deformation phase gradient and improve the scene coherence. It is also found that the local agricultural areas may introduce noises into the interferometric results, especially during summer season. Nevertheless, the area of impact of mine subsidence at multiple collieries can be monitored at the same time using DInSAR. The DInSAR deformation map is complementary to the ground surveys and assists to identify any abnormal subsidence behaviour. Together with other spatial data, it helps to ensure the safety of the local communities as well as the mine workers.
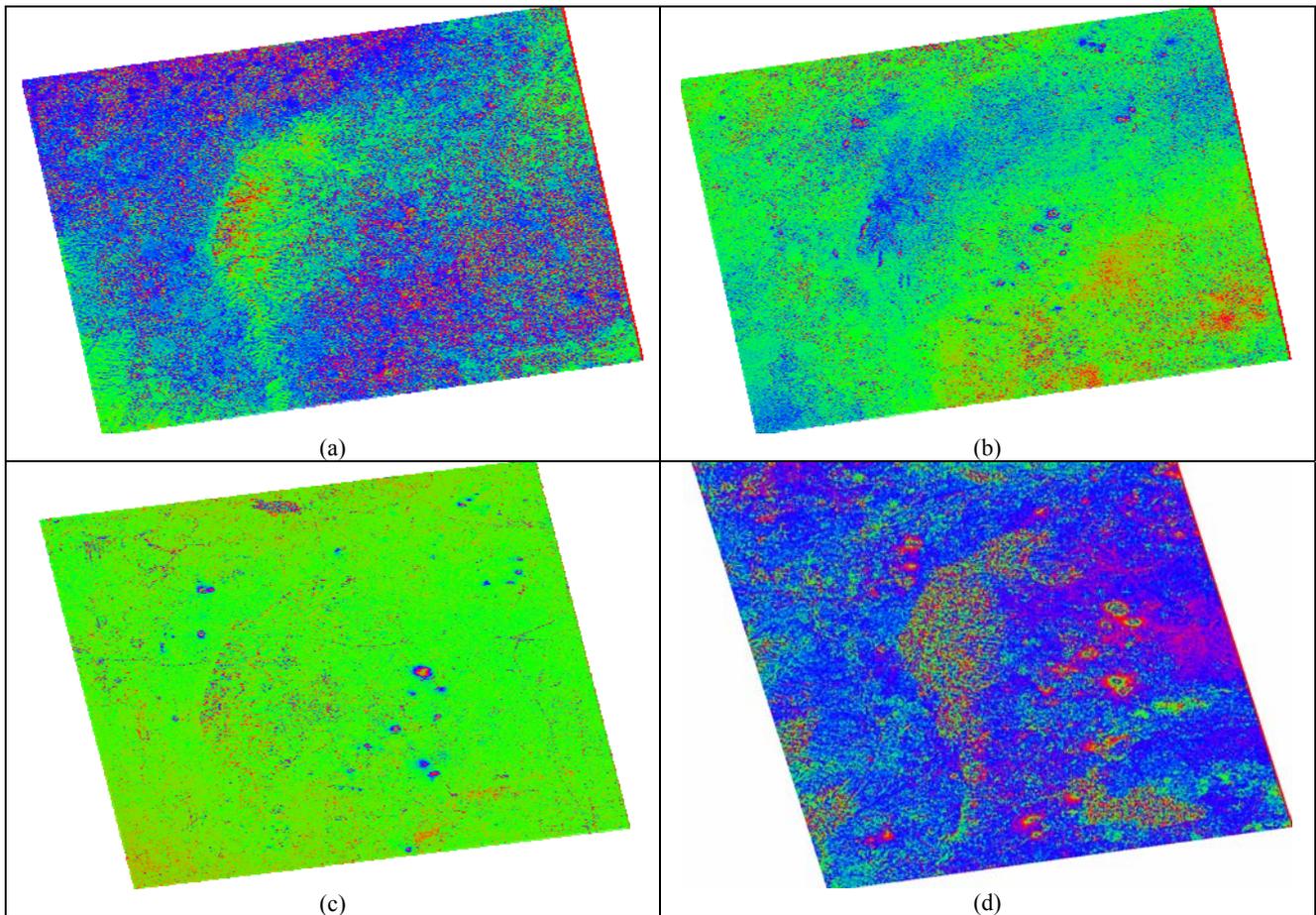
Figure 3. DInSAR interferograms of (a) – (c) ALOS interferometric pairs: 14/6/2007 - 30/7/2007 Bperp = 515m, 30/7/2007 - 14/9/2007 Bperp = 143m, and 15/12/2007 - 30/01/2008 Bperp = 351m, and (d) ENVISAT pair: 3/1/2008 - 7/2/2008 Bperp = 361m respectively.
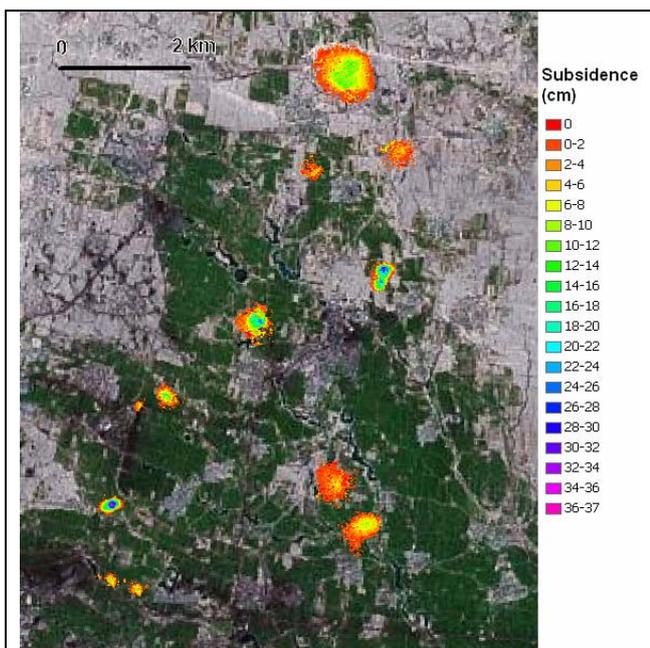

Figure 4. Ground deformation map derived from the ALOS interferometric pair: 15/12/2007 - 30/01/2008, overlaid on an optical image.

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