

# COAL MINE LAND SUBSIDENCE MONITORING BY USING SPACEBORNE INSAR DATA-A CASE STUDY IN FENGFENG, HEBEI PROVINCE, CHINA

Li Cao <sup>a</sup>, Yuehua Zhang <sup>a</sup>, Jianguo He <sup>a</sup>, Guang Liu <sup>b</sup>, Huanyin Yue <sup>b</sup>, Runfeng Wang <sup>a</sup>, Linlin Ge <sup>c</sup>

<sup>a</sup> Hebei Bureau of Surveying and Mapping, No.495, Zhongshandong Road, Shijiazhuang, Hebei, P.R.China, 050031, email: licao@hebsm.gov.cn

<sup>b</sup> Center for Earth Observation and Digital Earth, Chinese Academy of Sciences, Beisihuanxi Road, Zhongguancun, Haidian District, Beijing, P.R.China, 100080, email: (djslg, yuehuanyin)@126.com

<sup>c</sup> Satellite Navigation and Positioning Group, School of Surveying and Spatial Information Systems, the University of New South Wales, UNSW Sydney NSW 2052 Australia, email: l.ge@unsw.edu.au

**KEY WORDS:** Spaceborne InSAR, DInSAR, Land Subsidence, Coal Mine

## ABSTRACT:

In this paper, the DInSAR technique is used to process the spaceborne SAR data including 32 C band ENVISAT ASAR, 21 L band JERS SAR data to derive the temporal land subsidence information from 1993 to 2007 in Fengfeng coal mine area, Hebei province in China. 20 differential interferograms are derived from JERS SAR, ENVISAT ASAR data to show the temporal change of the land subsidence range and position. At the acquisition time of ENVISAT ASAR, the leveling in Dashucun coal mine in Fengfeng area was carried on from April 2006 to June 2007, the historical excavation data in 8 coal mines in Fengfeng area from 1992 to 2007 were collected as well. In our analysis, the DInSAR results are compared with leveling data and historical excavation data, the comparison results show the DInSAR subsidence results are consistent with the leveling results and the historical excavation data, the L band DInSAR shows more advantages than C band in the coal mining induced subsidence monitoring in rural area. The possibility of coal mine land subsidence monitoring by spaceborne InSAR data including ENVISAT ASAR, ALOS PALSAR data are discussed, and the possibility of underground mining activity monitoring by spaceborne InSAR data is evaluated.

## 1. INTRODUCTION

The coal output of China account for 35% of the whole coal output of the world, generally, the excavation will result in land subsidence within some time delay from several days to several years depending on many factors such as the geological environments, the width of laneway, timbering, and so on. The monitoring of land subsidence may give information of the location of the underground excavation, this information is important for the local government to decide whether the mining is in the permitted area. Also the monitoring of the land subsidence is useful for the assessment of environmental impacts of the coal mining and the prediction of the possible damage of the buildings on the ground above the coal mine.

The monitoring of land subsidence by means of conventional methods such as leveling and Global Positioning System (GPS) can reveal deformation with millimeter to centimeter accuracy on localized areas; however, they can only provide point information of deformation in the study area with great cost and measurement time.

Differential SAR Interferometry (DInSAR) provides an alternative and complementary method to investigate the land subsidence phenomena, which can provide two dimensional deformations on the line of sight (LOS) of radar on areas of thousands square kilometers (Massonnet et al., 1998). DInSAR technique has been applied to the monitoring of mining induced land subsidence in many areas (Urs Wegmuller, et al., 2005; Spreckels V., 2001; Andrew Jarosz and Dieter Wanke, 2004). Because the low coherence areas always exist in many coal mine, recently, the permanent scatterers technique was tried in the mining induced subsidence monitoring in order to overcome the decorrelation phenomena (U. Wegmuller, et al., 2004; Michaela Kircher et al., 2003;). However, the land subsidence

in the coal mine area is very dynamic in time and location with high deformation rate for the long wall mining, the subsidence finished generally within several months; the permanent scatterers technique is not the proper one in such case.

In this paper, the DInSAR technique is used to process the spaceborne SAR data including C band ENVISAT ASAR and L band JERS SAR data to derive the temporal land subsidence information from 1993 to 2007 in Fengfeng coal mine area, Hebei province in China, the DInSAR results are compared with leveling data and historical excavation data, the L band shows some advantages in the coal mining induced subsidence monitoring in rural area.

## 2. DESCRIPTION OF FENGFENG COAL MINE AND DATA

### 2.1 Fengfeng coal mine

Fengfeng coal mine area locates at the south of Hebei province of China with the size of 560 km<sup>2</sup> from 114°3'00''E to 114°16'40''E and 36°20'40''N to 36°34'31''N, 14 coal mines distribute in this area, the mining depth and coal layer thickness are different in every coal mine, the range of mining depth is from 150m to 1500m, but the mining depth in most coal mines is about 500m, the coal layer thickness is from 1.2m to 6m. The location of Fengfeng coal mine area and the distribution of coal mines are showed in Fig.1.

Fengfeng has 50 years coal mining history, serious land subsidence happened in this area, some subsidence areas has turn to be small lakes, some buildings and constructions were damaged by inhomogeneous deformation. In order to avoid the damage of buildings, recently the coal under buildings is not

excavated or some other safety techniques are adopted. Because of the different geological conditions, the magnitude and range of subsidence are different in every coal mines. Generally the subsidence with the magnitude of several dozen centimeters happens in one to three months after the excavation and almost finish within 3 months; the residual subsidence may last for one year.

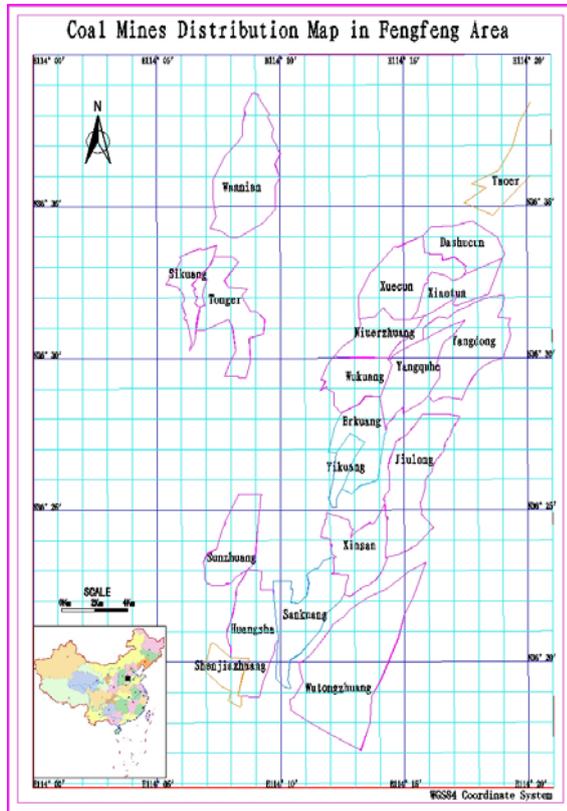


Figure.1. The distribution of coal mines in Fengfeng, Hebei province, China

## 2.2 Historical data of coal mining

The historical data of coal mining from 1992 to 2007 was collected, the data include the mining time and position, depth of lane, thickness of coal layer and the ground water condition. In order to make it comparable to the DInSAR results, we collected the mining data between the time of three months earlier than the acquisition date of master image and the date of the slave image for each interferometric pair and draw them into a map.

## 2.3 Leveling data

In order to test the DInSAR results, optical leveling was undertaken at the same time as the ENVISAT ASAR data acquisition. In Dashucun coal mine, 104 bench marks were installed in an area of 3 km<sup>2</sup>, the distribution of these bench marks are shown in Fig. 2. The leveling started on April 10th, 2006 and finished on August 5th, 2007 at each time the ENVISAT flies over, so we got 15 leveling data sets, we can derive the subsidence results by the differential values between any two data sets. One of the subsidence contour maps is shown in Fig.2. These subsidence results by leveling will be compared with the DInSAR results.



Figure.2. Distribution of bench marks in Dashucun coal mine and one contour map of land subsidence derived by the leveling data

## 2.4 Spaceborne interferometric SAR data

We collected 20 JERS SAR data from 1992 to 1998, 37 ENVISAT ASAR data from 2003 to 2007 in Fengfeng area. JERS SAR is an L band sensor with incidence angle of 35 degree and 44 days revisit, but JERS stopped working in 1998. ENVISAT ASAR is a C band sensor with incidence angle of 23 degree and 35 days revisit. Because of the spatial and temporal decorrelation, we only selected the interferometric pairs with small spatial and temporal baseline in the InSAR processing, and then selected 15 interferometric pairs with high coherence to do the differential InSAR processing; all the 15 interferometric pairs are listed on Table.1. These interferometric pairs cover some time intervals from 1993 to 2007, which can reveal the land subsidence changes in Fengfeng coal mine area.

## 2.5 DEM data

The external DEM is SRTM 3 arc second data downloaded from the seamless data distribution system of the Earth Resources Observation and Science of USGS, the data covers the whole processing area in Fengfeng.

## 3. DIFFERENTIAL INTERFEROMETRIC SAR DATA PROCESSING AND RESULTS

The SAR interferometric phase has several components as topographic phase, deformation phase, flat earth phase, atmospheric phase and noise, if we ignore the atmospheric effect, the differential phase is derived by subtracting the topographic phase and flat earth phase from the interferometric phase. Typically the differential InSAR technique includes three pass method, external DEM method, in this paper we used the external DEM method.

The differential InSAR data processing based on free software DORIS. For ENVISAT ASAR data, the precise orbit data can be used to estimate the spatial baseline and register the DEM to SAR coordinates, and then remove accurately the topographic phase and flat earth phase. For JERS data, the ephemeris data in the leader file is not accurate enough, which leads several hundred meters error in spatial baseline estimation and about 2 km shift in DEM registration. In order to avoid such errors, we developed precise spatial baseline re-estimation method to remove the flat earth phase, and co-registration method of DEM to SAR coordinates.

No.	Sensor	Master orbit	Master acquisition time	Slave orbit	Slave acquisition time	Temporal baseline(days)	Spatial baseline(m)
1	JERS SAR	05722	19930227	06381	19930412	44	1172.9
2		22856	19960416	23515	19950530	44	3474
3		26810	19970105	28787	19970517	132	-251
4		30105	19970813	30764	19970926	44	-1117.2
5		32082	19971223	32741	19980205	44	-1170.5
6		32082	19971223	33400	19980321	44	-1491
7		32082	19971223	34059	19980504	88	634.5
8		32082	19971223	34718	19980617	176	180
9		32741	19980205	33400	19980321	44	-325.4
10		33400	19980321	34059	19980504	44	2120.6
11	ENVISAT ASAR	09333	20031213	09834	20040117	35	560
12		12840	20040814	15345	20050205	175	140.7
13		24542	20061109	25544	20070118	70	-82.5
14		24542	20061109	26546	20070329	140	-119.7
15		25544	20070118	26546	20070329	70	-94.1

Table.1. Interferometric SAR image pair list

### 3.1 Data processing

#### 3.1.1 Baseline rectification of JERS InSAR data processing

According to the imaging geometry of interferometric SAR, we set a coordinate system called RXA, where R is a vector directing from the scene center to the corresponding position on the orbit, A is the vector of satellite velocity, X is normal to both R and A to construct a right hand coordinate system. Generally the spatial baseline error can be described as (Liu Guang, 2007):

$$\delta\vec{B}_l = (a_0 + a_1 \cdot l + a_2 \cdot l^2 + \dots + a_n \cdot l^n)\hat{B}_\perp + (b_0 + b_1 \cdot l)\hat{B}_\parallel \quad (1)$$

Where the first part of this equation is perpendicular baseline error:

$$\delta B_\perp^l = a_0 + a_1 \cdot l + a_2 \cdot l^2 + \dots + a_n \cdot l^n \quad (2)$$

The second part of this equation is parallel baseline error:

$$\delta B_\parallel^l = b_0 + b_1 \cdot l \quad (3)$$

And  $l$  is the line number in the SAR image.

There are two steps in our baseline rectification process, which are perpendicular baseline rectification and parallel baseline rectification. In perpendicular baseline rectification, we select some lines randomly in the interferogram  $(l_0, l_1, l_2, \dots, l_n)$  and estimate the phase frequency by Fourier Transformation to calculate the perpendicular baseline error in every line, then use equation (2) to estimate  $(a_0, a_1, \dots, a_n)$ . In parallel baseline rectification, we do the similar processing in the azimuth direction to estimate  $(b_0, b_1)$ . In this processing, the singular

value of phase frequency was removed by the DIA method (Teunissen, 2000).

#### 3.1.2 DEM registration to JERS InSAR data

The DEM was first moved manually to cover the interferogram without much precision, then an iteration process is adopted to move the DEM with a step of one meter both in azimuth and range direction until we get the best differential fringe map.

### 3.2 DInSAR results

The area we cropped locates at the east of Fengfeng coal mine area, covering 8 coal mines, the center coordinates is 114.25°E, 36.25°N with a size of 25km in the azimuth and 15 km in the range. Fig.3 shows the 15 differential interferometric results which has been filtered to reduce the noise.

The land subsidence results derived from JERS data are shown in Fig.3a to Fig.3j, the results derived from ASAR data are shown in Fig.3k to Fig.3o. In all these interferograms, the spatial baseline is smaller than 1172 meters in L band and 140.7 meters in C band, the temporal baseline is smaller than 176 days in L band and 175 days in C band. Normally, interferometric pairs with small spatial baselines in the same season have higher coherence.

Because most area in Fengfeng are covered by crops or grass from spring to autumn, L band radar signal can penetrate the vegetation much easier than C band, generally the JERS data have higher coherence than ASAR data in these 15 interferograms, the deformation fringes are much clearer. Because of the changes on the surface in different seasons, most interferometric pairs of JERS with higher coherence are in the same season, it is very hard to get deformation results by the ASAR data in different seasons, all the deformation results of ASAR data except for Fig.3l are in winter without the influence of crops and grass. The villages have good coherence but generally no deformation because no excavation was undertaken under such places.

Although the L band interferometry can keep higher coherence, the C band interferometry is more sensitive to the surface deformation, it can detect deformation with smaller magnitude.

For 3 centimeters deformation, it reveals 1/4 fringes on L band interferogram, whereas more than one fringe on C band interferogram. Generally the deformation decreases from the highest value to zero when it goes from the subsidence center to

the edge, so the C band interferometry can detect a bigger range of subsidence with more fringes, but with lower coherence than the L band.

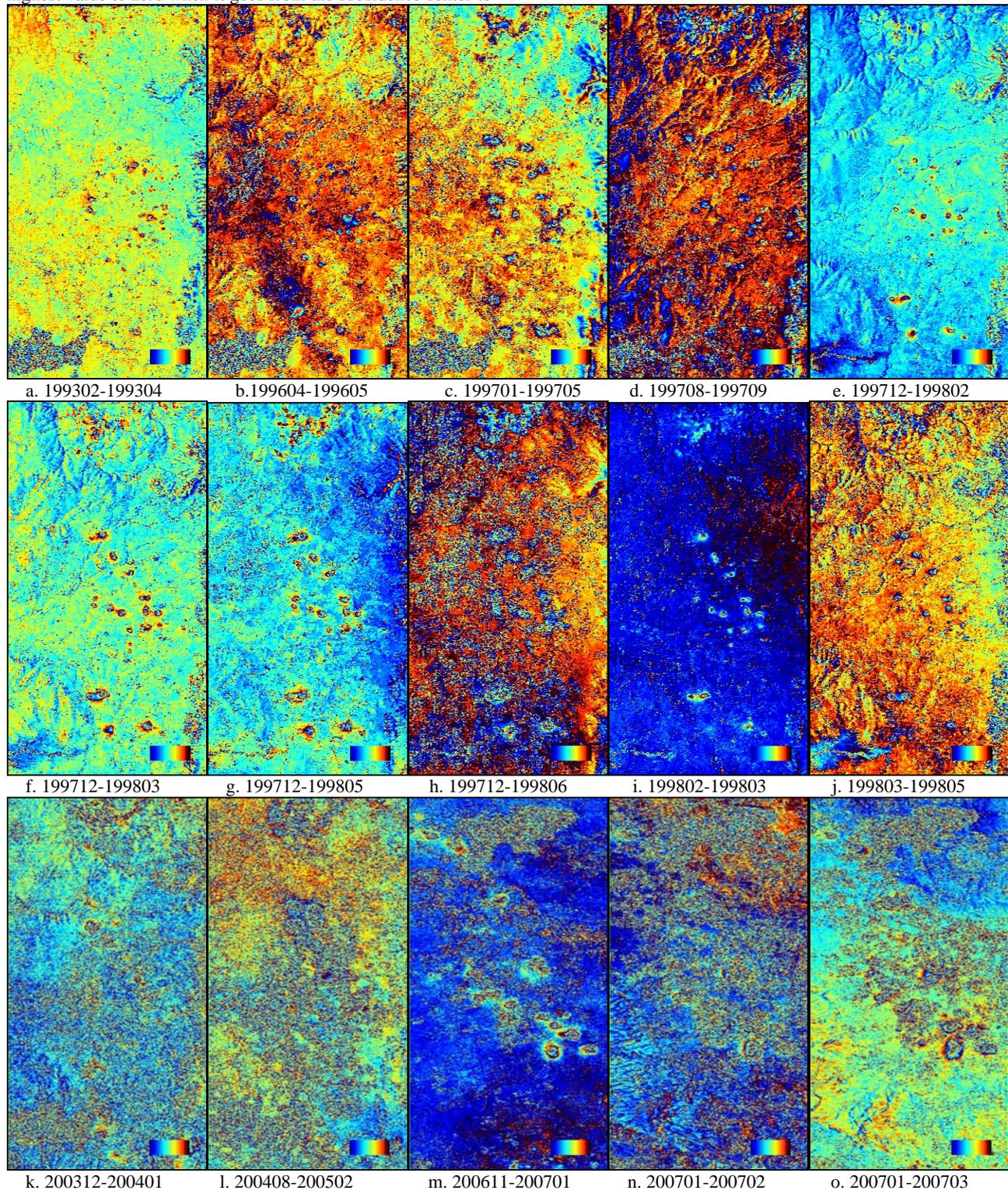


Figure.3. Land subsidence results derived by DInSAR processing in different time intervals

#### 4. ANALYSIS AND DISCUSSIONS

After we derived the surface deformation map by differential InSAR processing, we geo-coded the deformation results to WGS84 coordinate system by selecting 20 ground control

points in each interferograms, the leveling data and the historical excavation data are overlaid with the DInSAR deformation maps. The leveling results are used to test the correctness of the DInSAR deformation fringes, the historical excavation data are used to analyze whether the DInSAR

deformation can reveal the underground mining activities. Based on this analysis, we discussed the possibility of using spaceborne InSAR data to monitor the underground mining activities.

#### 4.1 Leveling results and DInSAR results

The leveling was designed to be undertaken at the SAR image acquisition time of Frame2871, Track261, but there is no good differential interferometric results derived from the data set of Frame2871, Track261, all the effective differential interferometric results are derived from the data set of Frme729, Track440, so there is a delay between the time of leveling and the SAR image acquisition.

We overlaid the leveling results and the differential InSAR results, which are showed in Fig.4a-Fig.4c. From all the maps of Fig.4, we can see the subsidence position of leveling results and the differential results are consistent with each other. In Fig.4a, the maximum subsidence value of DInSAR result is about 30 centimeters, the maximum subsidence value of leveling results is 35 centimeters. In Fig.4b, the maximum subsidence value of DInSAR result is 18 centimeters, the maximum subsidence value of leveling results is 20 centimeters. In Fig.4c, the maximum subsidence value of DInSAR result is 25 centimeters, the maximum subsidence value of leveling results is 30 centimeters.

#### 4.2 DInSAR results and historical coal mining data

After we validate the correctness of the DInSAR results, we overlaid each geo-coded interferogram with the historical excavation data. The interferogram covers 8 coal mines in Fengfeng area, it is impossible to analyze all the coal mines in one paper, we only select Xuecun coal mine as our test site. Fig.5 shows the temporal changes of the range and position of land subsidence and the mining location.

#### 4.3 Possibility of coal mining activities monitoring by DInSAR data

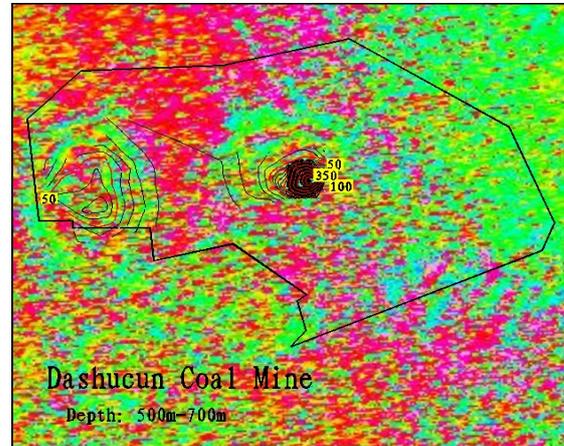
In the above contents we shows the DInSAR technique is feasible to monitor the coal mining induced land subsidence, the position of DInSAR land subsidence is coincidence with the position of underground excavation. In order to see whether the DInSAR technique can monitor the mining activities, we need further analysis.

We need to know the land subsidence difference between the interferograms before and after coal mining activity. Fig.6 shows one example of surface changes above the local mining lanes. From Fig.6 we can see there is no subsidence before the excavation, however, when the mining happens, the DInSAR can detect the subsidence induced by coal mining, so the coal mining position and time can be detected by the DInSAR, although there is several months delay.

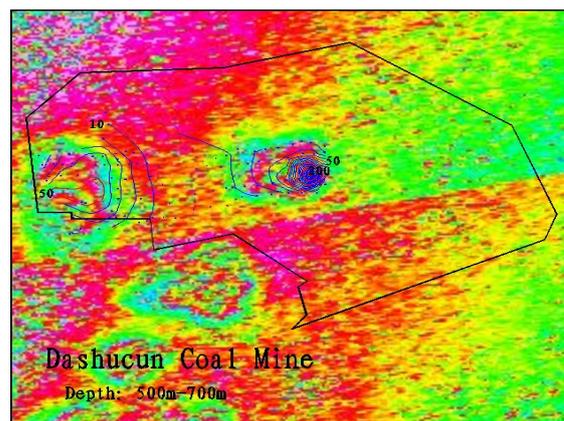
### 5. CONCLUSIONS

Spaceborne interferometric SAR data can be used to derive the valid land subsidence map in coal mines, which is useful information in monitoring the underground coal mining activities from space. However high coherence of the interferometric pair is necessary in such application, a small spatial baseline and a small temporal baseline in the same season are required especially in the rural area. Compared to L band SAR, C band SAR interferometry need much smaller

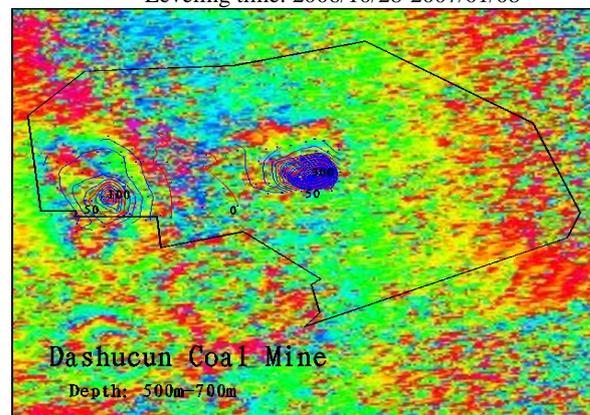
spatial and temporal baseline. For long temporal baseline of C band SAR data, it is very hard to derive good DInSAR results because the seasonal changes on the ground. When we try to monitor the coal mine land subsidence by C band SAR data, it is necessary to use all the images of different tracks in every visit and form time series SAR data set to acquire high quality interferometric pair with small spatial and temporal baseline.



a. DInSAR time: 2006/10/5-2007/2/22  
Leveling time: 2006/10/28-2007/02/01



b. DInSAR time: 2006/11/9-2007/01/18  
Leveling time: 2006/10/28-2007/01/08



c. DInSAR time: 2007/01/18-2007/03/29  
Leveling time: 2007/01/08-2007/03/10

Figure.4. Comparison between the DInSAR result and leveling result in Dashucun coal mine. The unit of the values of leveling data is millimeter

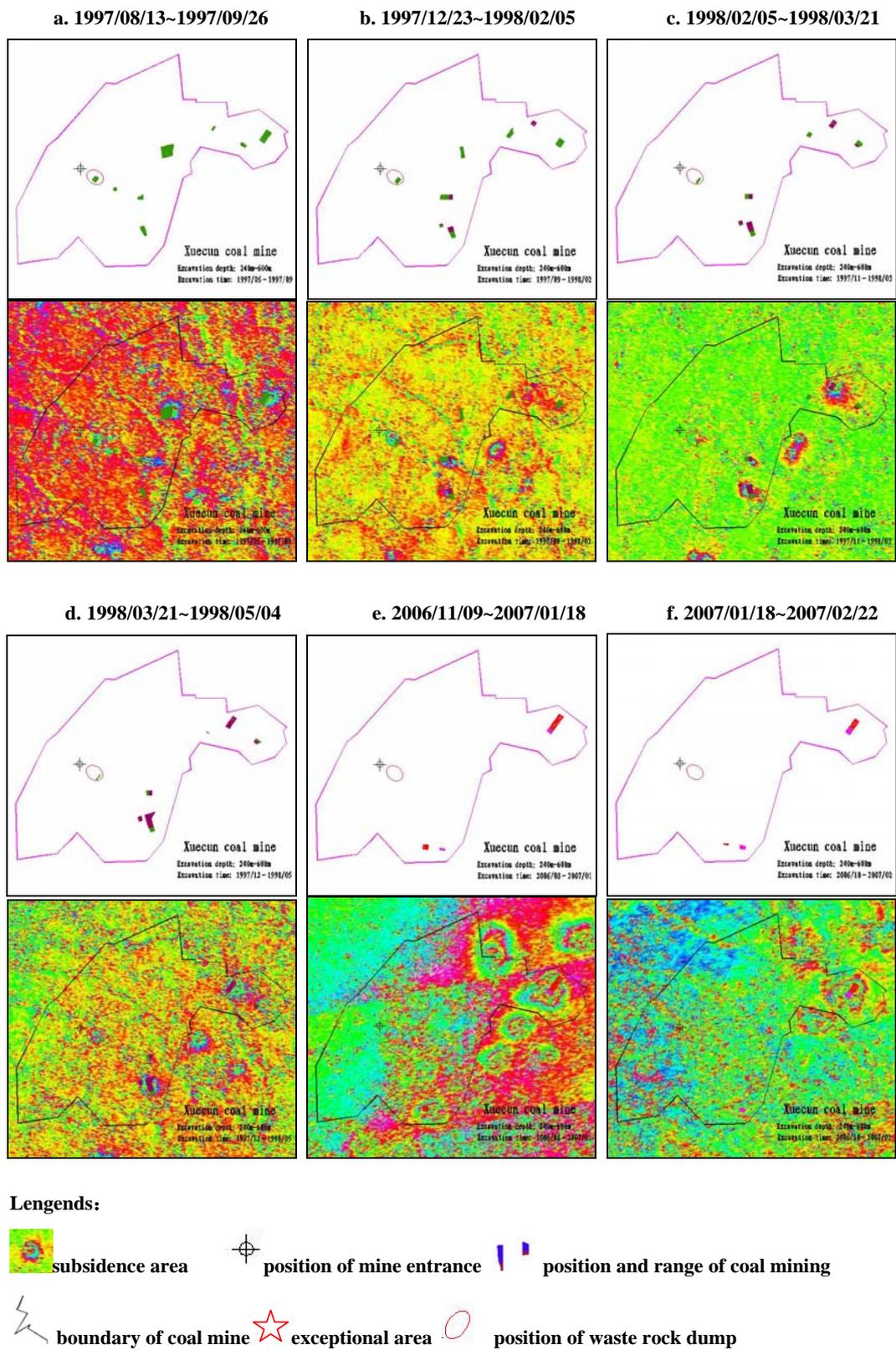
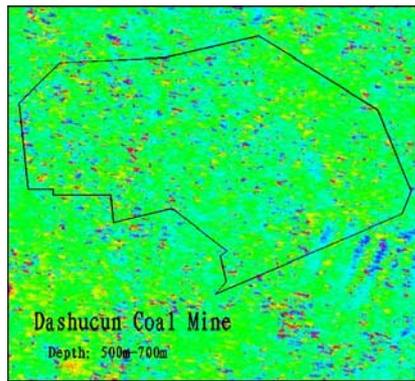
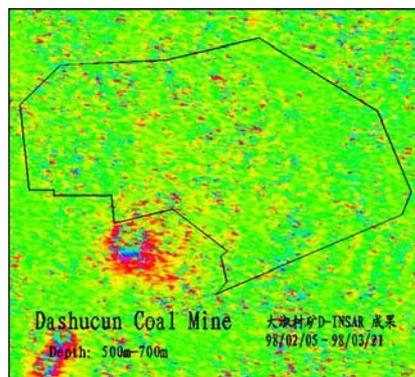


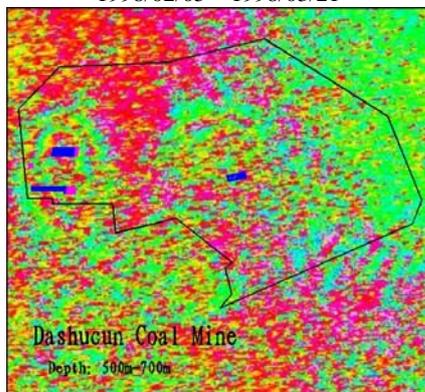
Figure.5. Comparison between DInSAR land subsidence results and historical excavation data in Xuecun coal mine



1993/02/27~1993/04/12



1998/02/05~1998/03/21



2006/10/05~2007/02/22

Fig.6. Land subsidence difference before and after coal mining activity

Compared to C band data, L band SAR interferometry can keep higher coherence, although the accuracy of subsidence detection of L band is lower than C band, time series L band SAR data can form more effective differential InSAR results. Currently, only ALOS has the L band SAR sensor, it is a good choice to use ALOS PALSAR data to do the coal mine land subsidence monitoring in rural area, but there is the same orbital problem of ALOS as JERS, the ephemeris data of ALOS is not as accurate as that of ENVISAT, the orbit rectification need to be solved when ALOS PALSAR data is used in the coal mining induced land subsidence monitoring.

## 6. REFERENCES

Massonnet, D. and Feigl, K., 1998, Radar interferometry and its application to changes in the Earth's surface. *Reviews of geophysics*, 4, pp.441-494.

Urs Wegmuller, Volker Spreckels, Charles Werner, Tazio Strozzi and Andreas Wiesmann, Monitoring of mining induced surface deformation using L-band SAR interferometry, IGARSS'05, Seoul, Korea, 25029 July 2005.

Spreckels V., J. Musiedlak, U. Wegmuller, T. Strozzi, and C. Wichlacz, Detection of underground coal mining-induced surface deformation by differential InSAR data, ISPRS WG I/2,I/5,IV/7 Workshop on High resolution mapping from space, Hannover, Germany, 19-21 Sep.2001.

Research on orbits adjustment and image coregistration in time series radar interferometry, PhD Thesis, Liu Guang, 2007, Institute of Remote Sensing Applications Chinese Academy of Sciences, China

Andrew Jarosz and Dieter Wanke, Use of InSAR for monitoring of mining deformation, Proc. of FRINGE 2003 Workshop, Frascati, Italy, 1-5 December 2003.

U. Wegmuller, C. Werner, L. Petrat, T. Strozzi, A. Wiesmann, and N. Benecke, EOMD mining project-improvements to the EO service part, ENVISAT-ERS Symposium, Salzburg 2004.

Michaela Kircher, Jorn Hoffmann, Achim Roth, Bert Kampes, Nico Adam and Horst J. Neugebauer, Application of permanent scatterers on mining-induced subsidence, Proc. Of FRINGE 2003 Workshop, Frascati, Italy, 1-5 December 2003.

P.J.G. Teunissen, Adjustment theory: an introduction, Delft University Press, Delft, 1 edition, 2000.

## 7. ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Project no. 40301032) and ESA CAT-1 project no.4288 and JAXA ALOS RA2 project.

