Mining area subsidence monitoring using Multi-band SAR data

Abstract—Generally, the extraction of mine 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 lane way, timbering, and so on. DInSAR technique has been applied to the monitoring of mining induced land subsidence in many areas. In this paper, the DInSAR technique is used to process the space borne SAR data including C band ENVISAT ASAR and L band JERS, PALSAR SAR data to derive the temporal land subsidence information in Fengfeng coal mine area, Hebei province in China. Since JERS do not have precise orbit, an orbit adjustment must be accomplish before the DInSAR interferogram was formed, we designed a method based on the imaging geometry of interferometric SAR, we set a coordinate system called RXA. Since the external DEM is not always perfectly corresponding to the SAR image, we add a DEM co registration step for DEM coregistrating to the SAR image. And there are 8 differential interferograms are derived from JERS SAR, PALSAR, ENVISAT ASAR data, In our analysis, the DInSAR results are compared with leveling data, the comparison results show the DInSAR subsidence results are consistent with the leveling results. Then the characteristic of pattern of phase on these C band and L band deformation interferograms are compared, we can see that in most situation, the deformation pattern on the surface is not the same of L and C band. And at last the author analyzed the feasibility and limitation in mining area subsidence monitoring use DInSAR technology. The experimental result shows that both C band and L band can accomplish monitoring mining area subsidence, but C band has more restrict conditions of its perpendicular baseline. In order to get a satisfactory outcome in mining area subsidence by DInSAR method, the time series of SAR images of every visit period and SAR deformation interferograms should be archived.

I. INTRODUCTION

Surface subsidence is a very common situation around mining area and extraction of coal mine will always cause large extend of mine goaf. The monitoring of land subsidence may give information of the location of the underground excavation activities, this information is important for the local government to decide whether the mining is in the permitted area or not [1] [2]. Meanwhile 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 conventional method for subsidence monitoring including leveling, GPS method and etc..., but these methods need field works and cost amount of human and material resources [3], meanwhile these methods are all point wise measurements, lack of area information.

DInSAR is one promise remote sensing technology for surface subsidence monitoring; it gathered synthetic radar imaging theory and electromagnetic wave interferometric technology. Utilizing this technology precise Digital Earth modal and millimeter surface subsidence could be achieved theoretically [4] [5]. DInSAR method can monitor the ground target in continuing time, varied weather condition, and a high space resolution about tens of meter scale on very large extend of area, so the cost is relative lower than conventional methods; on the other hand, the extraction activities underground will cause mined-out area and subsequent sinking the bedrock layer then cause the surface subsidence after sometime of mine extraction. This indicated that the mine extraction progress could be inferred from surface subsidence under certain area and proper geological circumstance. Now there are many groups working on the relationship between surface subsidence and mine extraction activities [6] [7] [8], and the technology is developing very quickly. Benefit from the DInSAR technology, although the mining activity has spatial and temporal uncertainty, through periodical SAR data acquirement and generated large extend of subsidence distribution maps, it do help on monitoring and predicting the surface subsidence.

This paper is focusing on the feasibility of mining area subsidence monitoring using DInSAR technology, JERS L band, PALSAR L band and ASAR C band data are used as data source, the monitoring ability in test site is analyzed as well.
PRINCIPLE FOR DInSAR MONITORING SURFACE SUBSIDENCE

A. DInSAR principle

The interferogram of SAR interferometry contains the phase difference between the two paths which the microwave traveled of the two images’ acquisition time. The path is effect by position of the satellite, the atmosphere condition, the moving of the ground target. If the atmosphere phase is ignored, then after remove the topography related interferogram phase, the deformation phase could be obtained. There are several methods to remove the topography related interferogram phase, commonly used methods are two pass and three pass methods, for three pass method may introduce noise of APS, in this paper, two pass method is used.

\[ \phi_{\text{ifg}} = \frac{4\pi}{\lambda} \left( \sqrt{r_1^2 + B^2 - 2B \cdot \vec{r}_1 - r_1} \right) + \frac{4\pi}{\lambda} \Delta r \]

\[ \vec{B} \cdot \vec{r}_1 \] is the dot product of baseline vector and looking vector, \[ \frac{4\pi}{\lambda} \left( \sqrt{r_1^2 + B^2 - 2B \cdot \vec{r}_1 - r_1} \right) \] is the phase related with topography, and \[ \frac{4\pi}{\lambda} \Delta r \] is the phase related with deformation of the target. The topography phase can be simulated using the external Digital Elevation Model and the orbit information according to the SAR imaging geometry, say it \[ \phi_{\text{simulation}} \], then the subsidence value can be expressed as:

\[ \Delta r = \frac{\lambda}{4\pi} \left( \phi_{\text{ifg}} - \phi_{\text{simulation}} \right) \]

III. EXPERIMENTAL AREA AND DATA

Coal mine extraction underground will form goaf, upon the force of the gravity of the rock layer, in certain geological circumstance, the rock layer may deformation and form caving zone from goaf and this will cause surface subsidence. Fig. 2 gives demonstration of the relationship between mine extraction and subsidence of the most common used long-wall mining method. The highest subsidence speed always occurs the months just after the goaf is formed, the speed may reach centimeters per day, the atmosphere effect could be ignored this time. For SAR can image a large area, ideally using DInSAR method could monitoring area surface subsidence of mining area.

Fengfeng coal mine has a long history more nearly 100 years, it is one of the biggest coal mine in China. The location is from 114°3′E to 114°16′40"E and 36°34′31"N to 36°20′40"N, located at the south of Hebei province of China (Fig. 3). The area is about 560km², the mining depth of most area is about 500 meters, and the coal layer thickness is from 1.2 meters to 6 meters. Since the heavily mining extraction underground, there occurs serious surface subsidence, some
subidence areas has turn out to be crevasse, on ground some buildings and constructions such as dikes were damaged by subidence. Local government has devoted to the monitoring and recovering of such kind of subidence, and obtains some result.

![Figure 3. Fengfeng coal mine, Hebei province, P.R.China](image)

### A. Leveling data

During ASAR data acquisition, optical leveling was undertaken at the same time, in Dashucun coal mine (Fig. 6A black circle), 104 bench marks were installed in an area of 3 km². Tab. I shows the differential leveling results of 2006-Oct-28, 2007-Jan-08 and 2007-Mar-10. These subidence results by leveling will be compared with the DInSAR results.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sensor</th>
<th>Master</th>
<th>Slave</th>
<th>Temporal Baseline</th>
<th>Spatial Baseline</th>
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<td>-82</td>
</tr>
<tr>
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<td>8</td>
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</tbody>
</table>

### Spaceborne SAR data

The SAR data used to monitor the subidence area including JERS1 data, ASAR data and PALSAR data. Data used in this experiment is listed in Tab. II.

<table>
<thead>
<tr>
<th>No.</th>
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<th>Slave</th>
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<td>JERS1</td>
<td>19971223</td>
<td>19980617</td>
<td>220</td>
<td>180</td>
</tr>
</tbody>
</table>

### External 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.

### IV. DInSAR DATA PROCESSING

Several components make up of the phase on SAR interferogram, including reference phase, topographic phase, deformation phase, APS and noise, etc., if the deformation velocity is quick, then the APS and noise could be ignored, after remove the reference phase, topographic phase, the deformation phase could be obtained. In this study, the open source software DORIS from TU-Delft is used. For ASAR data processing, the precise orbit from ESA or from TU-Delft could be used, the precise orbit is about 5 cm radial and about 15 cm in along and cross-track direction, so based on the precise orbit, the reference phase and topographic phase could be easily removed; For JERS1 data, there is no precise orbit information provided by JAXA, and the orbit information are stored in ephemeris come from SLR measurements, the accuracy is about tens of centimeters, a precise orbit re-estimation method should be developed to avoid errors when using the ephemeris data in DInSAR processing: For PALSAR data, since ALOS has a GPS instrument on board, the orbit error is smaller than JERS1, but since the ephemeris time gap is one minute, the orbit interpolation method will cause errors during DInSAR Processing.

### A. Conception for Baseline Reestimation

Spatial baseline is an important factor in SAR interferometry, for JERS, RADARSAT1 and most of SAR satellites they have no GPS on board, baseline reestimation is needed for DInSAR processing, or otherwise the orbit error will propagate into the phase of interferogram and cause wrong result. Nowadays, most of the baseline reestimation methods are based on linear baseline error model; this is not accuracy enough, since all the software now using a high degree polynomial or spline function to model satellite orbit, theoretically it will be reasonable to model the baseline error as high polynomial or spline function.

In this study, a dynamical coordinate system called RXA is setup, where R is a vector directing from the target 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 [10]:

![image]


\[
\delta \mathbf{B}_t = (a_0 + a_1 l + a_2 l^2 + \cdots + a_n l^n) \mathbf{B}_\perp + (b_0 + b_1 l) \mathbf{B}_f
\]  

(3)

A high degree polynomial is used to model the baseline error, where the first part of this equation is perpendicular baseline error:

\[
\delta \mathbf{B}_\perp = (a_0 + a_1 l + a_2 l^2 + \cdots + a_n l^n)
\]  

(4)

The second part of this equation is parallel baseline error:

\[
\delta \mathbf{B}_f = b_0 + b_1 l
\]  

(5)

And \( l \) is the line number of the SAR image. Since the existed coupling between perpendicular baseline error and parallel baseline error, a “two steps” method is used to decoupling the baseline error [10]. In perpendicular baseline rectification, we select some lines \((h_0, h_1, \cdots, h_m)\) randomly in the interferogram and estimate the phase frequency by Fourier Transformation so as to calculate the perpendicular baseline error on lines, and then use Eq. 4 to estimate \((a_0, a_1, \cdots, a_n)\). Do the similar processing in the azimuth direction to estimate parallel baseline error, the parameters \((b_0, b_1)\) could be obtained. In this processing, the singular value of phase frequency was removed by the DLA method [11].

B. DEM Autocoregistration to SAR image

In order to get the information of surface subsidence, the topography phase has to be removed. In this study “two pass” method is used, it use an external DEM and sensor orbits, in virtue of the SAR imaging geometrical relationship to simulate the topographic phase, this method is quite straight, and it is usually preferred. Still there is a problem of this phase simulated method, because of the positional errors and geometrical distortion of external DEM, the simulated phase image then may have a small shift to SAR image, this always cause wrong phase information for monitoring subsidence.

Here the author presents a method to reduce the positional error of external DEM in phase simulation method. First the intensity SAR image are simulated, there are two factors effect SAR image intensity, one is the surface characteristic, the other one is the local incidence angle, the relationship could be expressed as equation [12]:

\[
\text{Intensity} = D_{\text{const}} \left( \frac{\cos I}{\text{sin}I + 0.1 \text{cos}I} \right)^3
\]  

(6)

\( I \) is the local incidence angle, in common situation, the local incidence angle have dominant effect when SAR imaging the ground target. Local incidence angle is related to the incidence angle and surface normal, when local incidence angle equal to zero, then we will get a largest backscattering, when the angle is large than 90° (positive in clockwise direction), then there have shadows, and if angle is small than 90°, layover will happen. In SAR intensity image simulation, the key point is to find out the incidence angle for every pixel on the SAR image. So, now the question is simplified, and the solution is simple. First for every point on the external DEM, the position \((l, p)_{\text{DEM}}\) on the master image coordination system could be computed, the number of \((l, p)_{\text{DEM}}\) is always not a integer, then for every grid position \((l, p)_{\text{SAR}}\) on SAR image, we can find three nearest points \((l, p)_{\text{DEM}}\), we say \((l, p)^A_{\text{DEM}}, (l, p)^B_{\text{DEM}}, (l, p)^C_{\text{DEM}}\), this is a 3D space triangle, and the all these three points have its own 3D coordination, using a simple relationship for triangle we can compute the surface Normal:

\[
\hat{n} = [(l, p)^A_{\text{DEM}} - (l, p)^B_{\text{DEM}}] \times [(l, p)^A_{\text{DEM}} - (l, p)^C_{\text{DEM}}]
\]  

(7)

For incidence angle, there is a trick, we are not computing this angle directly, but, the incidence vector is computed using SAR image geometry, and the local incidence angle is computed as an inner product of Surface Normal and Incidence vector. After get the simulated SAR intensity image, we can compute the co registration polynomial for the simulated intensity image and SAR image, using the same co registration polynomial, the simulated phase image can be resampling into a “correct” position, and then be removed.

V. RESULTS AND ANALYSIS

Standard DInSAR processing are applied on every interferometric pairs listed in Tab. 2, Fig.4, Fig.5, Fig.6 are DInSAR results of JERS1, ASAR and PALSAR separately.

First take a look at the leveling data and the DInSAR results, the subsidence from leveling of the first period (2006-Oct-28->2007-Jan-08) is about 20 centimeters 70 days; the second period (2007-Jan-08->2007-Mar-10) is about 30 centimeters 62 days. For ASAR DInSAR pair 5 (Fig. 5A) and pair 6 (Fig. 5B), they are almost the same period with leveling, since the quick subsidence of the surface, there have obviously decorrelation on the interferogram. The conclusion could be obtained is that the surface subsidence is far larger than wavelength of ASAR. For JERS1 data, the deformation phase on Fig. 4B and Fig. 4C are clear, Fig.4B shows there exists one more circle, more than 30 centimeters on Fig. 4B and Fig. 4C are clear, Fig.4B shows there exists one cycle of this period, about 15 centimeters 88 days, Fig. 4C shows there are two more circles, more than 30 centimeters 176 days, the subsidence velocity measured by DInSAR method is less than leveling data, since this period is more than ten years ago, the mining extraction is much slow than nowadays, that maybe one reason. For PALSAR data, Fig. 6A and Fig. 6B, there are about one cycle on the DInSAR interferogram, it corresponding to 15 centimeters 46 days; this is close to leveling data. However, the result from DInSAR can only reflect the deformation of LOS direction, this is one reason of the difference between the DInSAR result and leveling result. If ascending and descending DInSAR pairs could be obtained, more precise result could be achieved.
Second the phase pattern of DInSAR interferogram is analyzed. From Fig. 4, Fig. 5 and Fig. 6 we can see for C band and L band, there is big difference of the phase pattern on the interferogram. For example Fig. 4C and Fig. 5A has a similar surface subsidence, but on Fig. 5A there are far more large visual subsidence area on the interferogram, this is because the wavelength of C band is small than L band, if there exists 3 centimeter surface subsidence, on C band interferogram it will show one cycle, but for L band SAR interferogram, there are only 1/4 cycles. So small subsidence could only be reflecting on C band DInSAR Interferogram, but not on L band’s. On another hand, if we want to use C band, then the temporal baseline should be small. Concerning L band, the deformation center could be clear on the interferogram if the subsidence is under a certain amount, this is obvious on Fig. 4 and Fig. 6, and the predominance of L band is that the maintains of coherence, even temporal baseline is larger than six month, the correlation is still fine, and we could see clear cycles on Fig. 4D.

In addition, the extraction activities are clearly showed on the DInSAR interferogram, not only for C band ASAR or L band JERS and PALSAR. And from comparing different DInSAR result we could see, most of coal mine extraction activities are still ongoing. The detail coal mine extraction activities could be studied if we put all these maps in a stack carefully; it is not studied in this paper. Besides if we have a map of the legal mine, then we could easily distinguish the illegal one.

In the above contents we shows the DInSAR technique is feasible to monitor the coal mining induced land subsidence, the position of land subsidence from DInSAR will reflect the position of underground 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.
VI. CONCLUSIONS

DInSAR technology using SAR image phase information to derive the surface subsidence, under certain geology circumstance, the excavation of the mining area could be detected. However high correlation of the interferometric pair is necessary in such applications, small spatial and temporal baseline in the same season are required. Compared with L band SAR such as PALSAR and JERS, C band SAR need much smaller spatial and temporal baseline and the subsidence center will always lose information because of decorrelation, but it obviously more sensitive to the deformation. So, C band is suitable for small subsidence with short time gap, while L band will have advantage for longer time gap. If we want to monitor the coal mine land subsidence by C band SAR data, it is necessary to use all the images of the same area and form time series SAR dataset.

ACKNOWLEDGMENT

REFERENCES
