Combining SAR interferometric phase and intensity information for monitoring of large gradient deformation in coal mining area

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Abstract
Coal mining usually causes drastic large gradient deformation in the earth’s surface in a short period, which leads to the formation of collapse basin or collapse pit. The drastic deformation renders the generation of dense fringes in interferogram, leading to difficulties in the phase unwrapping step. In this paper we propose using intensity tracking technique to monitor large gradient deformation in the subsidence center. To obtain the small deformation information around the basin and collapse pit, we use Small Baseline Subset (SBAS) interferometry technique to monitor the small deformation, after which we integrate the results under the two methods to obtain complete monitoring results. We take Daliu Tower mining of Shanxi Province in China as an example, using TerraSAR-X satellite data of 13 scenes spanning from 21/11/2012 to 02/04/2013 to conduct deformation monitoring experiment. The experiment result shows that the proposed method has the capability to detect and measure the large gradient deformation, meanwhile, small deformation information is preserved. Moreover, by comparing the experiment monitoring results to continuous GPS measurements, we estimate that the accuracy of deformation monitor is about 8 cm in the range direction.

Keywords: Mining subsidence, subsidence monitoring, InSAR, intensity tracking.

Introduction
Coal is the main energy resource for China. However with the intensive large-scale coal mining activity the consequent collapse of earth surface as well as other environmental disasters are becoming increasingly severe. According to report the collapse area caused by coal mining exceeds 700,000 hectares, economic loss amounting to 50 billion RMB, among which the collapse area in the east of China is 105,000 hectares. In order to reduce the effects of mining subsidence scholars conducted sustentative studies and got great achievements [Feng et al., 2008; Wang et al., 2008; Li et al., 2011; Wang et al., 2011; Song et al., 2012].
Due to the complexity of mining rock mass, current studies are mainly based on documents of field measurement data. Traditional mining subsidence monitoring methods mostly use trigonometric survey, leveling and GPS method, i.e. building measurement line on the principal fracture section of collapse basin to make regular observation and obtaining ground deformation information by data processing and analysis. But conventional measurement methods have such defects as high cost, huge workload and incomplete measurement information.

The appearance of Interferometric Synthetic Aperture Radar (InSAR) technique provides new approach in surface subsidence monitoring. According to the relationship between the phase information and distance from satellite to the earth this technique extracts the three-dimensional information of earth surface as well as elevation change information. Differential InSAR (D-InSAR) is a specialized technique applied to measuring small displacement which is developed on the basis of InSAR technique. According to the working principle of D-InSAR, D-InSAR technique can get small deformation of ground resolution cell and reach millimeter accuracy in theory [Massonnet et al., 1993]. The high-speed, high-precision, large-scale and all-time, all-weather advantages of D-InSAR largely offset the weakness of traditional measurement methods. In the ground deformation monitoring of coal mining areas many successful cases are accomplished by the use of D-InSAR technique [Yang et al., 2010; Fan et al., 2011; Chen et al., 2013; Fan et al., 2014; Li et al., 2014]. Traditional D-InSAR technique is subjected to the influence of temporal and spatial baseline, the newly developed advanced D-InSAR technique is able to extract high coherent points by analysis of time series SAR images and establish mathematical modeling to obtain time series deformation results like Small Baseline Subset (SBAS) interferometry technique. Since the selected coherent points keep stable in the time series respective to their phase and amplitude, they are less likely to be influenced by temporal and spatial baseline, which helps better overcome traditional D-InSAR technique’s vulnerability to temporal and spatial decorrelation. Presently some scholars have already applied this technique to subsidence monitoring in coal mining [Abdikan et al., 2014; Yan et al., 2014; Bateson et al., 2015].

However, when drastic deformation happens in coal mining areas such as ground collapse, its deformation gradient exceeds the maximum detectable gradient range of InSAR, a series of dense interferometric fringes will appear in the interferogram. In this situation the image sampling rate doesn’t meet the requirement of Nyquist sampling principle, easily leading to the aliasing of interferometric phase in which case direct unwrapping of phase is unable to correctly restore deformation phase. Moreover, the over-gradient of deformation unavoidably causes the changes of scatterer characteristics which leads to the loss of temporal coherence in SAR image [Malinverni et al., 2014]. Yang et al. [2010] proposed to use interpolation of multi-look interferogram to improve deformation monitor gradient while Zhao et al. [2014] use single full resolution interferogram for the same end. But both methods have only limited capacity to solve the problem, unable to resolve the problem of large gradient deformation in the subsidence of coal mining (like meter scale deformation).

Besides the use of above mentioned SAR image interferometric phase measurement, employing intensity information of SAR image for deformation measuring is another research focus. The intensity tracking technique, also known as feature tracking, based on intensity information of SAR image has already been successfully used in glacier flow,
landslide, volcanic and earthquake displacement [Casu et al., 2011; Yun et al., 2011; Yan et al., 2012; Fielding et al., 2013; Yan et al., 2013; Li et al., 2014; Manconi et al., 2014]. Compared to phase measurement, intensity tracking technique has the advantages of less vulnerability to temporal decorrelation influence, greater capacity to measure large deformation and easier access to two-dimension deformation. Zhao et al. [2013] used intensity tracking technique for the first time in the ground subsidence monitoring of coal mining area and obtained the subsidence law, the measurement precision being 1/25 pixel. Because the accuracy of intensity tracking technique itself is not high, which is usually 1/20-1/30 pixel under the precondition of precise registration. Therefore only employing this technique in the whole deformation area causes information loss to small deformation area. If centimeter-level deformation happens, the measurement results will cannot be distinguished from measurement error. In this paper, we propose to use intensity tracking technique in the large gradient deformation area, with simultaneous use of high-precision interferometric phase technique to conduct monitor in small deformation area, after which we integrate the two results to obtain the complete monitoring results.

**Method**

**Large gradient time series deformation monitoring using intensity tracking**

To expand deformation monitoring from conventional single and fixed time quantum measurement to the time series measurement category, we follow the same rationale of SBAS interferometry technique. Firstly we group the SAR images according to the length of spatial baseline so as to form small baselines set. Then we use intensity tracking technique to conduct computations on the SAR images of each group, getting the offset value of slant-range direction and azimuth direction respectively. Finally, we apply the SBAS inversion strategy to retrieve the range and azimuth displacement time-series.

Intensity tracking technique is based on the pixel-wise registration of two SAR images with cross-correlation algorithm in order to obtain the displacement of ground deformation from the registration offset [Werner et al., 2001]. While the registration offset is caused by the difference of satellite track, topographic, ground deformation and ionosphere, etc. Since the offset caused by topographic fluctuation is relatively small in the image pairs of small spatial baseline and flat surface, the chosen spatial baseline of image pairs in this paper are all within 500 m, and the studies area is generally flat, therefore the offset caused by topography can be neglected. By contrast the offset caused by ionosphere anomalous is common in polar regions, which is not the consideration of this paper since it focus on the middle and low latitude areas. In this situation the registration offset can be seen as offset groups caused by the difference of satellite tracks and ground deformation:

\[
O_{\text{reg}} = O_{\text{orb}} + O_{\text{def}}
\]

Here \(O_{\text{reg}}\) is the total registration offset, \(O_{\text{orb}}\) is the offset caused by difference of satellite track position, \(O_{\text{def}}\) is the offset caused by ground deformation. The orbital offset \(O_{\text{orb}}\) can be determined by fitting a regression function to the measured offsets between SAR images obtained for stable zones in the scene. In SAR image, except for the drastic deformation right above mining working face, there is hardly any deformation on the ground far from
the working face which can be regarded as a stable area. Therefore, orbital offsets can be simply determined using stable reference points. After subtraction of the orbital offsets, the remaining pixel offsets in slant-range and azimuth directions are related only to the surface displacement. Similar to SBAS technique, the following equation is set up [Berardino et al., 2002]:

\[ B\tilde{v}_x = \Delta x \quad [2] \]

\[ B\tilde{v}_y = \Delta y \quad [3] \]

In the formula \( B \) is the SAR image coefficient matrix related to the small baseline set (see Berardino et al. [2002]). \( \Delta x \) and \( \Delta y \) represents the offset value on the slant-range direction and azimuth direction respectively, \( \tilde{v}_x \) and \( \tilde{v}_y \) are the mean offset velocities between time adjacent SAR acquisitions for the range and azimuth directions, respectively. The constraint of small baseline in the calculation of offset may make matrix \( B \) become rank deficient matrix if the overall data are separated into different subsets. Therefore, the optimal solution of \( \tilde{v}_x \) and \( \tilde{v}_y \) in the least squares sense is obtained by applying singular value decomposition (SVD). The average offset rate \( v_x \) and \( v_y \) obtained here represent deformation per year, but since the ground subsidence caused by coal mining has the features of nonlinearity and non-continuity in time and space, the average offset rate cannot accurately describe the mining subsidence rule, due to which here we conduct time dimension integration to get the final deformation time sequence.

**Intensity measurement and phase measurement results integration**

The characteristic of mining subsidence is that the ground subsidence is the most drastic right above mining working face usually forms funnel-shaped basin, while it’s relatively moderate in the periphery of subsidence basin. Therefore to get the complete description of ground subsidence information we apply high-precision phase measurement to monitor the slow deformation area to obtain the small deformation information besides we use intensity tracking technique to get large gradient deformation in the drastic subsidence areas. Among the various advanced D-InSAR technologies, Permanent Scatterer InSAR (PS-InSAR) and SBAS technique are the brilliant representatives. Contrasted with PS-InSAR technique, SBAS technique does not require the unique common master image, it can generate interferometric pairs through setting threshold values to spatial baseline so as to form more interferograms, thus increase the number of phase observation and extra observation quantity, both of which contribute to improving the precision of the final monitoring result. The precision and reliability of this technique have been verified by many scholars [Cascini et al., 2006; Dehghani et al., 2013; Hu et al., 2014]. In this paper we use SBAS technique as an supplement to intensity tracking technique to conduct measuring in the slow deformation area. After obtaining the two deformation fields through intensity tracking and phase measurement respectively, proper approaches need to be used to integrate them so as to get a unified deformation field. As phase measurement is subjected to the influence of coherence, the coherence is considered here to be the integration principle of
the two monitoring results.
Massonnet and Feigl [1998] proposed the concept of deformation gradient for the first time and gave the theoretical equation of maximum detectable deformation gradient of InSAR:

$$d_{\text{max}} = \frac{\lambda}{2\mu} \quad [4]$$

$d_{\text{max}}$ represents the maximum detectable deformation gradient by InSAR, $\lambda$ is the wavelength of radar, $\mu$ represents the pixel size. According to Equation 4, we can know that there is a large difference for maximum detectable deformation gradient values between different sensors, e.g., the maximum detectable deformation gradient is $1.4 \times 10^{-3}$ (pixel resolution 20 m x 20 m with 5 looks) for Envisat (Environmental Satellite) C-band sensor and $11.5 \times 10^{-3}$ (pixel resolution 10 m x 10 m with 3 looks) for ALOS (Advanced Land Observing Satellite) L-band sensor, respectively. For our study case, TerraSAR-X data (pixel resolution about 1 m x 1 m with one look), the maximum detectable deformation gradient is about $1.55 \times 10^{-2}$. Based on above analysis, we can know that sensors of long-wave band and high-resolution images have the advantage of monitoring greater deformation gradient in theory. Massonnet's deformation gradient model did not consider the influence of external source errors, i.e., assuming there is no noise in the radar images. However, in practical applications, the detectable deformation gradient of InSAR is always smaller than theoretical value as the influence of various decorrelation factors such as temporal decorrelation, spatial baseline decorrelation, thermal noise decorrelation, Doppler cancroids dispersion and atmospheric delay, etc., and more and less, noise in interferogram. Therefore, this ideal model of the deformation gradient can not meet the needs of practice. Baran et al. [2005] studied the relationship between deformation gradient and coherence by simulation experiment, analyzed and built the deformation gradient function model through empirical statistics:

$$D_{\text{max}} = d_{\text{max}} + 0.002(\gamma - 1) \quad [5]$$

Here $D_{\text{max}}$ represents the maximum detectable deformation gradient value, $\gamma$ represents the coherence of the interferogram and it is the quantitative evaluation criteria of echo signal affected by a variety of decorrelation factors. It can be seen from the above equation, the maximum detectable deformation gradient of InSAR is a linear function of the coherence, which generally increases with coherence increasing. When the coherence is equal to 1, the model becomes the theoretical formula of Massonnet’s maximum deformation gradient. With this model we can know that when the coherence coefficient is about 0.3 the maximum detectable deformation gradient by InSAR becomes zero, i.e. no deformation is detected. In practice, we adopt the integration strategy used by Zhao et al. [2014], i.e. we take coherence of a differential interferogram as a quality map, and the coherence is estimated with a $5 \times 5$ moving window. Then, we set the coherence threshold as 0.5 by checking the unwrapping interferogram. Finally, the pixels with the coherence larger than 0.5 will keep the high-accuracy phase measurement; otherwise, offset measurements will be assigned.
Experiment area and data

Experiment area
The experiment area is located in the Daliu Tower mining area in Shanxi Province, China. The area is covered by loess, full of ravines and gullies, the topographic relief is large, therefore the ground subsidence caused by coal mining has particular characteristics, mainly demonstrated in the larger subsidence coefficient, smaller displacement angle, vulnerability to generating step-like collapse, landslide and other derivative disasters. To conduct real-time monitoring of subsidence, ground GPS observation stations are built above the working face. As Figure 1 shows, two observation lines are laid out along the profile A direction, Z1-Z50 and along profile B direction, Q1-Q25, the carmine circle represents observation stations. From date of ground observation stations we can know that the total subsidence above the working face during 11/2012 and 04/2013 is over 4 m. The appearance of large deformation gradient makes it difficult to have comprehensive monitoring with traditional D-InSAR technique. Chen and Deng [2014] have applied traditional D-InSAR technique to this area to conduct deformation monitoring experiment and obtained the range of influence and the trend in the development of coal mining subsidence. However, it just made interpolation process to the central large deformation area, so precise large deformation information in the deformation center is not obtained.

To verify the feasibility of the proposed approach in this paper we apply this method to the above mentioned area. The working face length of the studied area is 4547 m, the width of the working face range from 147 to 300 m. The coal seam structure is simple, with seam inclination ranging from 1° to 3°, and the depth of the mine is approximately 200 m. Mining at this site began in November 2012, and the mining direction is from southeast to northwest. The ground surface is covered by quaternary unconsolidated sediments, whose average thickness being 30 m. The overlying bedrock is composed mainly of siltstone and packsand whose average thickness is 205 m. The location of the working face is shown in Figure 2.

Figure 1 - The location map of GPS observation stations, profile A: Z1-Z50, profile B: Q1-Q25.
Experiment data
The satellite data used in this experiment is High Resolution SpotLight mode of TerraSAR-X, azimuth resolution being 0.85 m, range direction resolution being 0.91 m. Time span is from 21/11/2012 to 02/04/2013, 13 scenes data altogether. For more detailed satellite data see Table 1.

| No. | Acquisition time | Perpendicular baseline, $B_\perp$ (m) | Temporal baseline, $\Delta T$(days) |
|-----|-----------------|-------------------------------------|-------------------------------|
| 1   | 2012/11/21      | -34.10                              | 77                            |
| 2   | 2012/12/02      | -171.73                             | 66                            |
| 3   | 2012/12/13      | -149.38                             | 55                            |
| 4   | 2012/12/24      | -51.92                              | 44                            |
| 5   | 2013/01/04      | 8.70                                | 33                            |
| 6   | 2013/01/15      | 82.91                               | 22                            |
| 7   | 2013/01/26      | 20.28                               | 11                            |
| 8   | 2013/02/06      | 0                                    | 0                             |
| 9   | 2013/02/17      | -117.89                             | 11                            |
| 10  | 2013/02/28      | -26.06                              | 22                            |
| 11  | 2013/03/11      | 51.97                               | 33                            |
| 12  | 2013/03/22      | 116.73                              | 44                            |
| 13  | 2013/04/02      | -38.41                              | 55                            |

Experiment process analysis
The SAR image acquired on 26/02/2013 is used as reference image in the experiment, the spatial baseline threshold value is 300 m. Since part of the data is obtained during the vegetation growing period, the maximum temporal baseline is simultaneously set to be 100 days in order to prevent temporal decorrelation. Grouping SAR images with the above mentioned two threshold values, 72 interferometric pairs are generated, the interferometric baseline compositions are seen in Figure 3.
Figure 3 - Interferometric Baseline Composition.

Figure 4 - The time series deformation results obtained by traditional SBAS technology. Among them A: 2012/11/21-2012/12/02, B: 2012/11/21-2012/12/13, C: 2012/11/21-2012/12/24, D: 2012/11/21-2013/01/04, E: 2012/11/21-2013/01/15, F: 2012/11/21-2013/01/26, G: 2012/11/21-2013/02/06, H: 2012/11/21-2013/02/17, I: 2012/11/21-2013/02/28, J: 2012/11/21-2013/03/11, K: 012/11/21-2013/03/22, L: 2012/11/21-2013/04/02.
We first use traditional SBAS technique to process data and obtain the time series deformation result along the line of sight direction (see Fig. 4). During the process of SBAS technique, to reserve more deformation information, we do not conduct multi-look process, i.e. a full full-resolution interferogram is used and we set a coherence threshold as 0.3 to choose PS. The SRTM DEM, with a spatial resolution approximately 90m × 90m and a vertical accuracy of about 16 m, was used as an external DEM to remove the topographic phase. In Figure 4 the red rectangle represents the center area of coal mining. From Figure 4 we can see that traditional SBAS technique can well monitor the range of influence and the trend in the development of mining subsidence but for the center of the subsidence basin, excessive deformation gradient changes the ground surface echoing characteristics, resulting in the almost non-existence of PS in the center area as well as the missing of large gradient deformation information.

Then we use intensity tracking technique to obtain the deformation sequence from 21/11/2012 to 02/04/2013, search window is set as 32×32 according to the size of experiment area (in this paper, size of experiment area is 2000 pixel ×1800 pixel). To guarantee sufficient sampling point density, we apply a per-pixel search strategy here and set the oversampling factor as 2 in order to more accurately position the maximum correlation value. As mining-induced surface deformation is nearly vertical and only the slant range offsets are sensitive to vertical motion, therefore, here we just obtain the time series deformation along slant range direction. Though the azimuth offset field is not sensitive to vertical motion, it can be used to analysis the horizontal deformation. Therefore, we also obtain the whole azimuth offset field from time 21/11/2012 to 02/04/2013, the obtained deformation results in the range direction and azimuth are seen in Figures 5 and 6 respectively.

Figure 5 - Time series deformation results obtained by intensity tracking technique. Among them A: 2012/11/21-2012/12/02, B: 2012/11/21-2012/12/13, C: 2012/11/21-2012/12/24, D: 2012/11/21-2013/01/04, E: 2012/11/21-2013/01/15, F: 2012/11/21-2013/01/26, G: 2012/11/21-2013/02/06, H: 2012/11/21-2013/02/17, I: 2012/11/21-2013/02/28, J: 2012/11/21-2013/03/01, K: 2012/11/21-2013/03/22, L: 2012/11/21-2013/04/02.
Compared to Figure 4 (L), the maximum detectable monitoring subsidence in Figure 5 improved greatly from the original 0.7 m to about 4 m. But at the same time the information of small deformation is lost in Figure 5, with the major monitored deformation concentrated in the meter-level, which is related to intensity tracking technique precision. Moreover, from Figure 6 we can know that the maximum deformation exceeds 1m in the azimuth direction, which indicates ground fissure may occur under such huge horizontal displacement. The filed observation verified the above conclusion and Figure 7 is a photo taken when we were conducting GPS observation of ground fissure in the experiment area.
From the above analysis we can know that although merely using SBAS technique can obtain the range of influence and the trend in the development of coal mining subsidence, the large gradient deformation information in the center area is likely to be missing. By contrast although merely using intensity tracking technique can acquire the information on large deformation, that on the small deformation area is unable to be correctly detected due to limited precision. That’s the reason why we proposed a method integrating the two results. In the integrating step it’s worth mentioning that SBAS technique is relative measurement, i.e. choosing a reference point, assuming it’s stable in the time series and doing consequent analysis. While intensity tracking is absolute measurement. Compatibility between datasets in the joint inversion procedure was ensured by selecting the SBAS reference point in an area where also SBAS shows no deformation over time. Take the whole time span from 21/11/2012 to 02/04/2013 for example, considering the coherence principle simultaneously to integrate the two deformation results, the integrated result is shown in Figure 8, the red rectangle frame represents the center area of mining working face.

![Figure 8 - The deformation results after integrating](image)

From Figure 8 we can see the maximum detectable monitoring subsidence of deformation results after integrating is about 4 m, and the small deformation on the periphery of large deformation (centimetre-level) information is also sufficiently preserved.

To verify the accuracy and reliability of the experiment results, we now compare the monitored subsidence values of GPS observation (i.e. along the line of sight projected GPS vertical displacement) with the integrated results, comparison results are seen in Figure 9a and 9b. From Figure 9a and 9b, we can see that the subsidence curve of integration data
is consistent with subsidence curve of observation station data and two curves are almost overlap in the edge of subsidence basin, while a slight fluctuation occurs in the center of subsidence basin. To quantify analysis integration results, we also provide the error statistics between integration results and GPS measurement results (see Tab. 2). From Table 2 we can see that in the profile A direction, the average error is about 87 mm, maximum absolute error is 197 mm, relative error of maximum subsidence is 3.2% and in the profile B direction, the average error is about 95 mm, maximum absolute error is 243 mm, relative error of maximum subsidence is 5.1%, which is able to meet the requirement of coal mining subsidence monitoring. The experiment result shows that the method proposed in this paper can be used in the ground large gradient deformation monitoring of coal mining areas. We also plot the comparison results obtained by SBAS technique and intensity tracking technique along profile A and B direction respectively for the area where two different kinds deformation monitoring information is available (see Fig. 10a and 10b). From Figure 10a and 10b we can know that the monitoring results obtained by SBAS technique are well in agreement with GPS results, but a relatively large deviation is appeared between monitoring results obtained by intensity tracking technique and GPS results. This is the reason why we employed SBAS technique to monitor the small gradient deformation field.

Figure 9 - The deformation comparison between GPS measurements and integration results: (a) the deformation curves comparison between GPS measurements and integration results along profile A direction, data from 2012/11/21 -2013/4/2; (b) the deformation curves comparison between GPS measurements and integration results along profile B direction, data from 2012/11/21-2013/4/2.
Figure 10 - The deformation monitoring comparison between SBAS measurements and intensity tracking results for the area where two different kinds deformation monitoring information is available: (a) the deformation curves comparison between SBAS measurements and intensity tracking results along profile A direction, data from 2012/11/21 -2013/4/2; (b) the deformation curves comparison between SBAS measurements and intensity tracking results along profile B direction, data from 2012/11/21 -2013/4/2.

Table 2 - Error analysis table.

| Type of error                              | Error value (mm)   |
|--------------------------------------------|--------------------|
| Maximum absolute error                     | Profile A direction: 197  
                                           | Profile B direction: 243 |
| Mean absolute error                        | Profile A direction: 87  
                                           | Profile B direction: 95   |
| Maximum absolute error of maximum subsidence| Profile A direction: 137 
                                           | Profile B direction: 205  |
| Relative error of maximum subsidence       | Profile A direction: 3.2%  
                                           | Profile B direction: 5.1%  |
Conclusions
The drastic large gradient deformation caused by coal mining activity is non-linear in time, non-continual spatially, which is presented as a series of intensive interferometric fringes, making the image sampling rate unable to meet the requirement of Nyquist sampling principle, causing aliasing of phase, and debilitating the restoration ability of deformation phase in the phase unwrapping process.

In this paper we combined the use of SAR image phase measurement and intensity measurement to monitor large gradient deformation. We first used the intensity tracking technique to monitor large gradient deformation, then used Small Baseline Subset (SBAS) interferometric measurement to conduct monitoring in small deformation area, followed by the integration of the two deformation results. Compared with merely using phase measurement technique, the integrated results can obtain the deformation information in the large gradient deformation area. Likewise, compared with merely using intensity tracking technique, the integrated results can get more accurate small deformation information. Besides, we also got the deformation along the azimuth direction, detected the occurrence of ground fissure, and verified the results through field measurement.

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References
Abdikan S., Arıkan M., Sanli F.B., Cakir Z. (2014) - Monitoring of coal mining subsidence in peri-urban area of Zonguldak city (NW Turkey) with persistent scatterer interferometry using ALOS-PALSAR. Environmental Earth Sciences, 71: 4081-4089. doi: http://dx.doi.org/10.1007/s12665-013-2793-1.
Baran I., Stewart M., Claessens S. (2005) - A new functional model for determining minimum and maximum detectable deformation gradient resolved by satellite radar interferometry. IEEE Transactions on Geoscience and Remote Sensing, 43: 675-682. doi: http://dx.doi.org/10.1109/TGRS.2004.843187.
Bateson L., Cigna F., Boon D., Sowter A. (2015) - The application of the Intermittent SBAS (ISBAS) InSAR method to the South Wales Coalfield, UK. International Journal of Applied Earth Observation and Geoinformation, 34: 249-257. doi: http://dx.doi.org/10.1016/j.jag.2014.08.018.
Berardino P., Fornaro G., Lanari R., Sansoti E. (2002) - A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. IEEE Transactions on Geoscience and Remote Sensing, 40: 2375-2383. doi: http://dx.doi.org/10.1109/TGRS.2002.803792.
Cascini L., Ferlisi S., Fornaro G., Lanari R., Peduto D., Zeni G. (2006) - Subsidence monitoring in Sarno urban area via multi-temporal DInSAR technique. International Journal of Remote Sensing, 27: 1709-1716. doi: http://dx.doi.org/10.1080/01431160500296024.
Chen B.Q., Deng K.Z. (2014) - Integration of D-InSAR technology and PSO-SVR algorithm for time series monitoring and dynamic prediction of coal mining subsidence. Survey Review, 46: 392-400. doi: http://dx.doi.org/10.1179/1752270614Y.0000000126.

Casu F., Manconi A., Pepe A., Lanari R. (2011) - Deformation time-series generation in areas characterized by large displacement dynamics: the SAR amplitude pixel-offset SBAS technique. IEEE Transactions on Geoscience and Remote Sensing, 49 (7): 2752-2763. doi: http://dx.doi.org/10.1109/TGRS.2010.2104325.

Chen B.Q., Deng K.Z., Fan H.D., Hao M. (2013) - Monitoring large-scale deformation in mining area by D-InSAR and 3D laser scanning technology integration. International Journal of Mining Science and Technology, 23: 555-561. doi: http://dx.doi.org/10.1016/j.ijmst.2013.07.014.

Dehghani M., Valadan Zoej M.J., Hooper A., Hanssen R., Entezam I., Saatchi S. (2013) - Hybrid conventional and Persistent Scatterer SAR interferometry for land subsidence monitoring in the Tehran Basin, Iran. ISPRS Journal of Photogrammetry and Remote Sensing, 79: 157-170. doi: http://dx.doi.org/10.1016/j.isprsjprs.2013.02.012.

Fan H., Deng K., Ju C., Zhu C., Xue J. (2011) - Land subsidence monitoring by D-InSAR technique. Mining Science and Technology, 21: 869-872. doi: http://dx.doi.org/10.1016/j.mstc.2011.05.030.

Fan H., Gu W., Qin Y., Xue J., Chen B. (2014) - A model for extracting large deformation mining subsidence using D-InSAR technique and probability integral method. Transactions of Nonferrous Metals Society of China, 24: 1242-1247. doi: http://dx.doi.org/10.1016/S1003-6326(14)63185-X.

Feng Q.Y., Liu G.J., Meng L., Fu E.J., Zhang H.R., Zhang K.F. (2008) - Land subsidence induced by groundwater extraction and building damage level assessment - a case study of Datun, China. Journal of China University of Mining and Technology, 18: 556-560. doi: http://dx.doi.org/10.1016/S1006-1266(08)60293-X.

Fielding E.J., Lundgren P.R., Taymaz T., Yolsal-Cevikbilen S., Owen S.E. (2013) - Fault-slip source models for the 2011 M 7.1 Van earthquake in Turkey from sar interferometry, pixel offset tracking, GPS, and seismic waveform analysis. Seismological Research Letters, 84: 579-593. doi: http://dx.doi.org/10.1785/0220120164.

Hu B., Wang H.S., Sun Y.L., Hou J.G., Liang J. (2014) - Long-term land subsidence monitoring of Beijing (China) using the small baseline subset (SBAS) technique. Remote Sensing, 6: 3648-3661. doi: http://dx.doi.org/10.3390/rs6053648.

Li G., Lin H., Li Y., Zhang H., Jiang L. (2014) - Monitoring glacier flow rates dynamic of Geladandong Ice Field by SAR images Interferometry and offset tracking. In: IEEE International Geoscience and Remote Sensing Symposium, 13-18 July 2014, Quebec City, pp. 4022-4025.

Li P.X., Tan Z.X., Yan L.L., Deng K.Z. (2011) - Time series prediction of mining subsidence based on a SVM. Mining Science and Technology (China), 21: 557-562. doi: http://dx.doi.org/10.1016/j.mstc.2011.02.025.

Li Z.W., Yang Z.F., Zhu J.J., Hu J., Wang Y.J., Li P.X., Chen G.L. (2014) - Retrieving three-dimensional displacement fields of mining areas from a single InSAR pair. Journal of Geodesy, 2014: 1-16. doi: http://dx.doi.org/10.1007/s00190-014-0757-1.

Malinvern, E.S., Sandwell D.T., Tassetti A.N., Cappelletti L. (2014) - InSAR decorrelation to assess and prevent volcanic risk. European Journal of Remote Sensing, 47: 537-556.
Chen et al. - Combining SAR phase and intensity information for monitoring of large gradient deformation
doi: http://dx.doi.org/10.5721/EuJRS20144730.

Manconi A., Casu F., Ardizzone F., Bonano M., Cardinali M., De Luca C., Gueguen E., Marchesini I., Parise M., Vennari C., Lenari R., Guzzetti F. (2014) - Brief communication: rapid mapping of landslide events: the 3 December 2013 Montescaglioso landslide, Italy. Natural Hazards and Earth System Science, 14: 1835-1841. doi: http://dx.doi.org/10.5194/nhess-14-1835-2014.

Massonnet D., Feigl K.L. (1998) - Radar interferometry and its application to changes in the earth's surface. Reviews of Geophysics, 36: 441-500. doi: http://dx.doi.org/10.1029/97RG03139.

Massonnet D., Rossi M., Carmona C., Adragna F., Peltzer G., Feigl K., Rabaute T. (1993) - The displacement field of the Landers earthquake mapped by radar interferometry. Nature, 364: 138-142. doi: http://dx.doi.org/10.1038/364138a0.

Song J.J., Han C.J., Li P., Zhang J.W., Liu D.Y., Jiang M.D., Zheng L., Zhang J.K., Song J.Y. (2012) - Quantitative prediction of mining subsidence and its impact on the environment. Mining Science and Technology, 22: 69-73. doi: http://dx.doi.org/10.1016/j.ijmst.2011.07.008.

Wang J., Peng X.G., Xu C.H. (2011) - Coal mining GPS subsidence monitoring technology and its application. Mining Science and Technology, 21: 463-467. doi: http://dx.doi.org/10.1016/j.mstc.2011.06.001.

Wang X.F., Wang Y.J., Huang T. (2008) - Extracting mining subsidence land from remote sensing images based on domain knowledge. Journal of China University of Mining and Technology, 18: 168-171. doi: http://dx.doi.org/10.1016/S1006-1266(08)60036-X.

Werner C., Strozzi T., Wiesmann A., Wegmüller U., Murray T., Prittchard H., Luckman A. (2001) - Complimentary measurement of geophysical deformation using repeat-pass SAR. In: IEEE International Geoscience and Remote Sensing Symposium, 9-13 July 2001, Sydney, pp. 3255-3258. doi: http://dx.doi.org/10.1109/igarss.2001.978320.

Yan Y., Trouvé E., Pinel V., Mauris G., Pathier E. (2012) - Fusion of D-InSAR and sub-pixel image correlation measurements for coseismic displacement field estimation: Application to the Kashmir earthquake. International Journal of Image and Data Fusion, 3 (1): 71-92. doi: http://dx.doi.org/10.1080/19479832.2011.577563.

Yan Y., Pinel V., Trouvé E., Pathier E., Perrin J., Bascou P., Jouanne F. (2013) - Coseismic displacement field and slip distribution of the 2005 Kashmir earthquake from SAR amplitude image correlation and differential interferometry. Geophysical Journal International, 193 (1): 29-46. doi: http://dx.doi.org/10.1093/gji/ggs102.

Yan Q., Wu J., Zhang L. (2014) - Land surface deformation monitoring of mining area based on PS-InSAR. Advances in Earth and Environmental Sciences, 189: 95. doi: http://dx.doi.org/10.2495/ICESEP130141.

Yang C., Zhang Q., Zhao C., Ji L., Zhu W. (2010) - Monitoring mine collapse by D-InSAR. Mining Science and Technology, 20: 696-700. doi: http://dx.doi.org/10.1016/S1674-5264(09)60265-9.

Yun S.H., Zebker H., Segall P., Hooper A., Poland M. (2007) - Interferogram formation in the presence of complex and large deformation. Geophysical Research Letters, 34 (12). doi: http://dx.doi.org/10.1029/2007GL029745.

Zhao C., Lu Z., Zhang Q. (2013) - Time-series deformation monitoring over mining regions with SAR intensity-based offset measurements. Remote Sensing Letters, 4: 436-445. doi:
Zhao C., Lu Z., Zhang Q., Yang C., Zhu W. (2014) - Mining collapse monitoring with SAR imagery data: a case study of Datong mine, China. Journal of Applied Remote Sensing, 8: 083574. doi: http://dx.doi.org/10.1117/1.JRS.8.083574.

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