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Yang Chen
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Accuracy verification and evaluation of Sentinel-1A repeat track differential interferometric synthetic aperture radar in monitoring mining subsidence

Yang Chen,^a Qiuxiang Tao,^{a,*} Anye Hou,^b Liujian Ding,^a
Guolin Liu,^a and Ke Wang^a

^aShandong University of Science and Technology, College of Geomatics, Qingdao, China

^bQingdao Geotechnical Investigation and Surveying Institute, Qingdao, China

Abstract. The accuracy of differential interferometric synthetic aperture radar (DInSAR) in monitoring the ground subsidence is a major challenge to be addressed urgently. Using the repeat track DInSAR and GIS spatial analysis tools, eight C-band Sentinel-1A SAR images of the Guotun coal mine (China) were processed to determine the mining subsidence from November 27, 2015 to July 24, 2016. The mining data of 13 working faces and the DInSAR- and leveling-monitored results were compared. A method was proposed to solve the problem of time inconsistency between DInSAR- and leveling-monitored results. The location, spatial distribution, scope, and variations of mining subsidence monitored by Sentinel-1A repeat track DInSAR were consistent with the mining progress of the working faces. The accuracy of the DInSAR-monitored subsidence values was directly related to the coherence of the subsidence zones, and the absolute difference from the leveling-monitored values was small at the subsidence edge but large at the subsidence center. © The Authors. Published by SPIE under a Creative Commons Attribution 4.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JRS.14.014501](https://doi.org/10.1117/1.JRS.14.014501)]

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1 Introduction

Differential interferometric synthetic aperture radar (DInSAR) is an emerging technique that has overcome the limitations of the conventional measurement methods and realized the continuous monitoring of ground subsidence at large scale and for long-time periods.¹⁻³ In early development stages, it became an effective tool to monitor the deformation caused by crustal motions, such as earthquakes and volcanoes.⁴⁻⁸ DInSAR technology can be used to detect surface subsidence at centimeter level or even millimeter level and has widely been used in the field of subsidence monitoring and post-treatment in mining areas.⁹ For example, for surface subsidence DInSAR-monitoring in the Appin, Westcliff, and Tower coal mines in the UK, the results achieved an accuracy of ± 1 cm; ground subsidence caused by groundwater extraction and mining activities in the Ayntaio coal mine in Greece have also successfully been detected by this technology; and further, combined with leveling, the dynamic law of surface in mining areas was explored.¹⁰⁻¹³

Numerous researchers have accomplished significant work on mining subsidence monitoring with DInSAR. These studies demonstrate recent advances in theory and data processing techniques since its development. However, its progress in practical engineering applications has not been ideal, due to its problem in accuracy. Therefore, in-depth analysis of DInSAR subsidence monitoring accuracy and exploration of its monitoring capabilities can be used as an important reference in practical engineering applications.

*Address all correspondence to Qiuxiang Tao, E-mail: qiuxiangtao@163.com

In this study, eight Sentinel-1A SAR images from November 27, 2015 to July 24, 2016 were selected and processed with repeat track DInSAR, and the ground subsidence of the Guotun coal mine (China) in seven imaging periods was obtained. The location data, the main overlying features on the surface, and the mining progress data of 13 mining faces were collected, and a qualitative comparative analysis with DInSAR-monitored results in each imaging period was conducted. The results show that the Sentinel-1A repeat track DInSAR can accurately determine the location and spatial distribution of ground subsidence in the mining region. Furthermore, the leveling-monitored subsidence values of 55 leveling points on the dip line and 124 leveling points on the strike line of 1305 working face were collected, and the piecewise linear interpolations were performed to obtain the fitted leveling-monitored subsidence results, which consist of the DInSAR-monitored subsidence results in time. The absolute difference in the DInSAR results was calculated to conduct a quantitative comparative analysis. The results show that, for the Sentinel-1A repeat track DInSAR, the accuracy of monitored ground subsidence values is directly related to the coherence of the subsidence zones. When the coherence coefficient is greater than or equal to 0.54, the spatial distribution and variations in the subsidence values monitored by DInSAR and leveling are consistent. However, the coincident degree of ground subsidence values monitored by the two techniques is higher at the edge and lower at the center of the subsidence basins. When the coherence coefficient is equal to 0.47 and 0.46, the results of DInSAR and leveling are not significantly different in the numerical value, but there has been a large deviation in the spatial distribution and the variations. When the coherence coefficient is equal to 0.43, the DInSAR-monitored subsidence values can no longer reflect the leveling-monitored subsidence values in the mining area.

2 Study Area and Data

The Guotun coal mine is located in the north-central part of Juye Coalfield in Yuncheng County, Heze, China. It extends 14 km in the north-south direction and 13 km in the east-west direction with a total area of 180 km². Figure 1 shows the specific location and the extent of the study area. The Guotun coal mine has the topographical features of the alluvial plain of the Yellow River, with the flat terrain and the deep soil layer. The elevation of the ground is generally +41.60 to +45.38 m, and the slope of the natural terrain is 0.02%. Transportation in this area is convenient. Specifically, the Beijing–Kowloon railway passes from the west of the mine field, and the national road called 220 and several motorways also pass through this area. Moreover, many rivers and canals crisscross each other, such as Yun-Juan River, Yun-Ju River, and Song-Jin River, which makes the area an important transportation hub. The overlying features of the Guotun coal mine are farmlands with the common crops of wheat, corn, and sweet potato and the economic crops of soybean and cotton. The mining area is densely populated and has many underdeveloped township and village enterprises and natural villages. The problem of ground subsidence is serious in the region owing to the continuous underground coal mining. Hence, to maintain the balance between the underground coal mining and ground protection with efficient

Fig. 1 Study area of this research marked in the red rectangle and overlaid on the administrative map of Shandong province. The blue rectangle is the coverage of the SAR images.

Table 1 The specific parameters of eight SAR images.

No.	Interferometric images		Temporal baseline (d)	Perpendicular baseline (m)
	Master (yyyy-mm-dd)	Slave (yyyy-mm-dd)		
1	2015-11-27	2015-12-21	24	−33
2	2015-12-21	2016-01-14	24	−12
3	2016-01-14	2016-03-02	48	−94
4	2016-03-02	2016-03-26	24	33
5	2016-03-26	2016-04-19	24	40
6	2016-04-19	2016-06-30	72	−50
7	2016-06-30	2016-07-24	24	51

and enhanced production, it is urgent to effectively monitor ground subsidence in mining areas and study the mechanism of movement and deformation of the surface and the strata in the mining process.

Sentinel-1 satellite carrying the C-band synthetic aperture radar is an Earth observation satellite of the European Space Agency Copernicus Program (the Global Monitoring for Environment and Security, GMES), which was successfully launched in April 2014. The satellite has an all-weather and all-time radar imaging system with an on-orbit altitude of 693 km and a data update period of 12 days; it realizes several different polarization modes, such as single and double polarization; it provides continuous images and data services for more users with its wide range, multimode, and multiapplication characteristics of. In this study, we selected eight C-band Sentinel-1A SAR images from November 27, 2015 to July 24, 2016, which were captured with ascending orbits, in VV polarization mode (The radar emits vertical electric field vector and receives vertical electric field vector of the echoes. The “V” is short for “vertical”), with a path number of 142, at the incidence angle of about 38.93 deg in the center of every image, and a pixel spacing of 5 m in the slant range and 20 m in the azimuth range. The specific parameters are presented in Table 1.

For the repeat track DInSAR, it is necessary to simulate the topographic phase by an external digital elevation model (DEM) and remove it from the SAR interferometric phase to extract the ground subsidence phases and values. Consequently, the Shuttle Radar Topography Mission-3 SRTM DEM, provided by the American National Aeronautics and Space Administration and National Imagery and Mapping Agency in 2000, was selected. It covers >80% of the world’s land surface and is comprehensive and accurate in China. Its ground resolution is 90 m with an average accuracy of 16 m.^{14,15}

3 Methodology

DInSAR can be divided into dual-, three-, and four-track differential interferometry according to the interferometric mode. The repeat track DInSAR is most widely used to monitor ground subsidence in mining areas. Its basic principle is to generate an interferogram by conjugate multiplication of two radar complex images before and after deformation, remove topographical factors using the difference from the external DEM to generate a differential interferogram, and then extract the deformation information of the ground targets from the differential interferogram.^{16–19}

Phase φ of the interferogram is closely related to the radar imaging parameters, antenna position, incident angle, and the elevation of the ground targets, which can be expressed as

$$\varphi = \varphi_{\text{flat}} + \varphi_{\text{topo}} + \varphi_{\text{def}} + \varphi_{\text{atm}} + \varphi_{\text{noise}}, \quad (1)$$

where φ_{flat} is the flat earth phase caused by the earth surface, φ_{topo} is the topographic phase caused by the surface fluctuation, φ_{def} is the deformation phase caused by the surface deformation, φ_{atm} is the atmospheric phase caused by the ionospheric and tropospheric delay, and φ_{noise} is the noisy phase.

The repeat track DInSAR eliminates the topographic phase by differential processing with external DEM, weakens the influence of flat-earth phase by flattening processing, restrains the influence of the atmospheric phase and the noisy phase by filtering and multilook processing, and finally obtains the deformation phase. In addition, φ_{def} of the differential interferogram is wrapped and should be unwrapped to obtain the true deformation phase. Then the surface deformation in the direction of radar line of sight (LOS) can be extracted and expressed as

$$\Delta R_{\text{tow}} = (\lambda/4\pi) \cdot \varphi_{\text{real}}, \quad (2)$$

where ΔR_{tow} is the deformation in the LOS direction, λ is the central wavelength of the transmitted signal, and φ_{real} is the unwrapped differential interferometric phase.

In this study, we performed differential interferometric processing on seven interferometric pairs presented in Table 1 by repeat track DInSAR and obtained the ground subsidence information in seven interferometric periods in the study area. Then the DInSAR results were qualitatively and quantitatively compared with the mining conditions of 13 working faces and 179 leveling results to verify the accuracy and reliability of the C-band Sentinel-1A repeat track DInSAR in monitoring mining subsidence. The main data processing workflow is shown in Fig. 2.

Fig. 2 Processing procedure of test data.

Fig. 3 Filtered and enhanced differential interferograms of the study area: (a) 2015-11-27 to 2015-12-21, (b) 2015-12-21 to 2016-01-14, (c) 2016-01-14 to 2016-03-02, (d) 2016-03-02 to 2016-03-26, (e) 2016-03-26 to 2016-04-19, (f) 2016-04-19 to 2016-06-30, and (g) 2016-06-30 to 2016-07-24.

4 Main Results

4.1 Generation of Filtered and Enhanced Differential Interferograms

First, the slave image and the external DEM were co-registered and resampled into the master image space to ensure that they share exactly the same SAR coordinates. Second, differential processing was performed and the flat-earth effect was removed to obtain the differential interferogram. Then the Goldstein adaptive filter method was used to effectively reduce the phase noise of the differential interferogram. Owing to the small range and flat terrain of the study area, the orbital error and atmospheric delay error is often assumed to be negligible. The enhanced differential interferograms and coherence images were finally obtained. Figure 3 shows the filtered and enhanced differential interferograms of the study area. Figure 4 shows the corresponding coherence images.

In Fig. 3, each interferometric fringe represents the deformation of half wavelength of the SAR images. “AZ” and “LOS” represent the azimuth and LOS of the radar satellite, respectively.

4.2 Phase Unwrapping

The phase values are wrapped to modulo 2π as long as the phase change exceeds its period of 2π and need to be corrected by adding the appropriate number of 2π cycles, a step known as phase unwrapping, which provides the original phase difference of the pixels in differential interferograms. Therefore, the minimum cost flow phase unwrapping method was used to unwrap the filtered and enhanced differential interferometric phase. Figure 5 shows the unwrapped differential interferograms.

4.3 Transforming Phase to Deformation and Geocoding

Based on Eq. (2), the unwrapped differential phase can be converted to deformation in the LOS direction, and then the LOS deformation can be decomposed in the vertical direction. For

Fig. 4 Coherence images of the study area: (a) 2015-11-27 to 2015-12-21, (b) 2015-12-21 to 2016-01-14, (c) 2016-01-14 to 2016-03-02, (d) 2016-03-02 to 2016-03-26, (e) 2016-03-26 to 2016-04-19, (f) 2016-04-19 to 2016-06-30, and (g) 2016-06-30 to 2016-07-24.

Fig. 5 Unwrapped differential interferograms of the study area: (a) 2015-11-27 to 2015-12-21, (b) 2015-12-21 to 2016-01-14, (c) 2016-01-14 to 2016-03-02, (d) 2016-03-02 to 2016-03-26, (e) 2016-03-26 to 2016-04-19, (f) 2016-04-19 to 2016-06-30, and (g) 2016-06-30 to 2016-07-24.

Fig. 6 Subsidence maps of the Guotun coal mine: (a) 2015-11-27 to 2015-12-21, (b) 2015-12-21 to 2016-01-14, (c) 2016-01-14 to 2016-03-02, (d) 2016-03-02 to 2016-03-26, (e) 2016-03-26 to 2016-04-19, (f) 2016-04-19 to 2016-06-30, and (g) 2016-06-30 to 2016-07-24.

comparison, deformation in the SAR coordinate system should be geocoded back to the geographic coordinate system. Figure 6 shows the vertical ground subsidence of the mining area after geocoding.

5 Discussion

In this study, we collected the mining data of 13 working faces and the leveling-monitored results of 179 leveling points to compare, analyze, and verify the accuracy and reliability of the Sentinel-1A repeat track DInSAR in monitoring ground subsidence.

5.1 Comparative Analysis with Working Faces

There are 13 mining working faces in the Guotun coal mine. Figure 7 shows their distribution and the geographical extent, Table 2 presents the basic mining information, Fig. 8 shows the ground subsidence maps of the Guotun coal mine superimposed with the working faces, and Fig. 9 shows the changes of subsidence area in the coal mine.

Figures 3–9 and Table 2 demonstrate as follows.

Fig. 7 13 working faces in Guotun coal mine: (a) eight working faces in the north and (b) five working faces in the south.

Table 2 Mining information of 13 working faces in Guotun coal mine.

No.	Strike length (m)	Dip length (m)	Average buried depth (m)	Mining period	Remarks
1301	1800	200	890	2010-11 to 2013-01	Adjacent to villages in the east and its hydro geological conditions are simple
1302	400	190	775	2010-01 to 2010-06	About 2 km from county road called 067 in the east
1303	2070	210	845	2012-06 to 2015-08	Its surface is mostly farmland with sporadic buildings
1304	800	130	790	2010-09 to 2011-03	Its surface is mostly farmland with sporadic buildings and without perennial water
1305	1823	224	800	2013-09 to 2016-08	Its surface is mostly farmland without perennial water, and seasonal rivers pass through its south
1306	690	110	—	2015-02 to 2015-11	Adjacent to villages in the north and its surface is mostly farmland
1307	1150	240	—	2016-04 to present	Adjacent to the village in the west and it is densely populated
1308	573	223	800	2011-07 to 2012-03	There is no perennial water, and seasonal rivers pass through its northern part
1310	770	171	800	2012-12 to 2013-08	Its surface is mostly farmland with sporadic buildings on the ground, and without perennial water
1312	1800	102	—	2014-12 to 2015-06	Its surface is mostly farmland
1314	1350	143	—	2016-01 to 2016-10	Adjacent to the village in the west and about 1.5 km from the Song-Jin River in the northwest
1315	243	107	—	2016-04 to 2016-06	There is no perennial water, and its hydro geological conditions are simple
4301	185	380	—	2016-10 to 2017-01	Its surface is mostly farmland without perennial water, and seasonal rivers pass through its southern part

Fig. 8 Ground subsidence maps of Guotun coal mine superimposed with the working faces: (a) 2015-11-27 to 2015-12-21, (b) 2015-12-21 to 2016-01-14, (c) 2016-01-14 to 2016-03-02, (d) 2016-03-02 to 2016-03-26, (e) 2016-03-26 to 2016-04-19, (f) 2016-04-19 to 2016-06-30, and (g) 2016-06-30 to 2016-07-24.

Fig. 9 Change chart of subsidence area in mining area during each monitoring period.

- (1) From November 27, 2015 to July 24, 2016, DInSAR detected two subsidence basins. The upper basin was in Shangai and Weimiao villages, whereas the lower basin was located in Qinzhuang and Chelou villages, and they all coincided with the locations of the working faces. With continuous mining, the subsidence area gradually expanded and indirectly caused the loss of groundwater. It then resulted in the small subsidence of large-scale around the mining area and finally affected the surrounding natural villages, rivers, and roads in different degrees.
- (2) From November 27, 2015 to December 21, 2015, referring to Fig. 8(a), in the north of the mining area, a subsidence basin appeared near working face 1306, which had just finished mining, and the overlying surface had not yet reached a stable state and was still slowly sinking. In addition, there were old mine goafs formed by working faces 1302, 1304, 1308, and 1310, which had been mined, and the mining activities of 1306 disturbed the overlying strata of these goafs. As a result, the aquifer in their thick surface soil lost water and the overlying stratum was compacted, resulting in ground subsidence with the maximum subsidence value of 5.32 cm. In the south of the mining area, the mining activities of working face 1303 were completed in August 2015, and the surface

- was still slowly sinking. The mining activities of working face 1305 were continuing and a subsidence basin appeared above it with the maximum subsidence value of 4.77 cm.
- (3) From December 21, 2015 to January 14, 2016, referring to Fig. 8(b), in the north of the mining area, the mining activities of working face 1314 had not yet started. The mining activities of 1306 had finished for about 40 days, and the ground subsidence caused by it was still continuing, but the subsidence area and subsidence value decreased; the maximum subsidence value was 3.59 cm. However, in the south of the mining area, the subsidence degree increased significantly with the mining advance of working face 1305, and the maximum subsidence value reached 8.33 cm.
 - (4) From 14 January 2016 to 2 March 2016, referring to Fig. 8(c), in the north of the mining area, the mining activities of working face 1314 began. Working face 1314 is only 1.5 km away from the Song-Jin River in the northwest and its water abundance was stronger. The adjacent working faces 1310 and 1312 had been mined, the overlying strata near 1314 working face was disturbed, and the strata were continuously compressed with the mining activities of working face 1314. As a result, water and sediment in the aquifer lost and subsidence increased. The subsidence basin appeared on working faces 1314 and 1312, and the maximum subsidence value was 8.11 cm. At the same time, the overlying surface of working face 1306 still continuously and slowly subsided and caused the expansion of the subsidence area. In the south of the mining area, the rock layer caved with continuous mining and increased mining intensity of working face 1305. Moreover, working face 1305 was adjacent to the north-south fault zone in the west, and there were seasonal rivers passing through its south. Groundwater loss caused by mining also accelerated the ground subsidence, and the maximum subsidence value reached 11.8 cm.
 - (5) From 2 March 2016 to 26 March 2016, referring to Fig. 8(d), in the north of the mining area, the mining activities of working face 1306 had been completed for about 110 days and the overlying surface gradually tended to be stable. There was no obvious subsidence above it and the subsidence area was apparently reduced. Meanwhile, the continual exploration of working face 1314 led to the continuous ground subsidence above it, and the maximum subsidence value reached 8.05 cm. In the south of the mining area, the mining intensity of working face 1305 was weakened, and the maximum subsidence value reached 5.73 cm. The groundwater loss resulted in large-scale small subsidence around the working face.
 - (6) From 26 March 2016 to 19 April 2016, referring to Fig. 8(e), in the north of the mining area, the subsidence center was located above working face 1314 and the maximum subsidence value decreased to 6.05 cm. The mining activities of working face 1315 started, but the ground subsidence was not obvious due to the short recovery time. In the south of the mining area, the mining activities of working face 1305 were still in progress, and the maximum subsidence value reached 6.85 cm.
 - (7) From 19 April 2016 to 30 June 2016, referring to Fig. 8(f), in the north of the mining area, the subsidence center moved to the southeast with the mining advance of working face 1315, and the maximum subsidence value was 3.27 cm. In the south of the mining area, the mining activities of working face 1307 started, and mining of working face 1305 was still in progress. The overlying strata above the two working faces were disturbed, and the groundwater loss continually expanded the subsidence area with the maximum subsidence value of 5.75 cm.
 - (8) From June 30, 2016 to July 24, 2016, referring to Fig. 8(g), in the north of the mining area, the mining activities of working face 1314 continued, a subsidence basin appeared above it, and the maximum subsidence value reached 5.18 cm. Although the mining activities of working face 1315 had finished, its surface was not yet stable, and it was still continually and slowly sinking. Moreover, the distribution of working faces was relatively dense; thus the interaction of the overlying strata and the loss of groundwater led to the enlargement of the subsidence area. In the south of the mining area, the mining activities of working face 1305 were close to the end, and the mining intensity of 1307 working face increased. The subsidence center moved to the southwest and located in working face 1307 with the maximum subsidence value of 6.71 cm.

Fig. 10 Distribution of leveling points laid on 1305 working face and overlaid on the ground subsidence map of 2016-01-14 to 2016-03-02: (a) the overall distribution of leveling points, (b) the most serious subsidence leveling points on the dip line and strike line.

5.2 Comparison with Leveling Results

The mining period of working face 1305 (September 2013 to August 2016) completely covered the time span of eight Sentinel-1A SAR images (November 27, 2015 to July 24, 2016) (Table 2). Therefore, we collected the mining information and the leveling data of working face 1305, which is located 600 m east of Chelou Village. The average thickness of coal seam was 3.35 m, and the mining area was 400,000 m². The surface of the working face was covered by farmland, and the ancient Zhao-Wang River passed to the south. The dip line of working face 1305 was 2800 m and a total of 55 leveling monitoring points were arranged, H1 to H55 from west to east. The strike line of working face 1305 is 4800 m with 124 leveling monitoring points, Z1 to Z124 from south to north. Figure 10 shows the distribution of these leveling points. For these leveling points, 22 fourth-grade leveling surveys were carried out from October 7, 2013 to September 20, 2017. Combining the imaging dates of eight SAR images, we only selected six leveling surveys from October 20, 2015 to October 24, 2016 to verify the accuracy of the DInSAR-monitored results. Table 3 shows the dates of six leveling surveys and two examples of the subsidence at H43 and Z79 leveling points (Fig. 10).

In Table 3, the “mining ×××× m” refers to the mining progress of working face 1305 at the beginning of each leveling survey. H43 and Z79 are the most serious subsidence leveling points on the dip line and strike line, respectively.

Tables 1 and 3 show that although the monitoring period of the leveling surveys (October 20, 2015 to October 24, 2016) covered that of the seven interferometric pairs acquired by DInSAR (November 27, 2015 to July 24, 2016), the two are not completely consistent. In order to solve this problem, we performed a piecewise linear fitting process for 179 leveling points. We first assumed that no subsidence occurred on October 12, 2015, then performed a piecewise linear interpolation using the leveling-monitored subsidence values of six leveling surveys, and finally obtained the subsidence curves of each leveling point in five leveling monitoring periods and

Table 3 The observation date of 6 leveling surveys for 179 leveling points and two examples of leveling-measured subsidence.

	1	2	3	4	5	6
No.	Mining 1023 m	Mining 1110 m	Mining 1192 m	Mining 1284 m	Mining 1620 m	Finished
Date (yyyy-mm-dd)	2015-10-20	2015-12-04	2016-01-18	2016-03-12	2016-07-10	2016-10-24
H43 [subsidence (cm)]	0	−14	−34	−56	−88	−94
Z79 [subsidence (cm)]	0	0.19	−3	−4	−27	−76

Fig. 11 Two examples of fitted subsidence curves of leveling points.

seven DInSAR interferometric periods. Figure 11 shows the fitted subsidence curves of the two leveling points of H43 and Z79.

In Fig. 11, “0” represents the beginning date of subsidence (December 12, 2015), “subsidence days” represents the number of the cumulative subsidence days that the dates of six leveling surveys and eight SAR images minus the beginning date (October 12, 2015); e.g., the second date of the leveling surveys is December 4, 2015 and the number of cumulative subsidence days is 45 days. Similarly, the imaging date of the first SAR image is November 27, 2015, and the number of cumulative subsidence days is 38 days. The “subsidence magnitude” of the vertical axis is the cumulative subsidence value of each leveling point on the leveling and DInSAR monitoring dates.

Figure 11 shows that the fitted subsidence curve of eight radar imaging dates fits well with the fitted curve of six leveling surveying dates with only slight differences between the seventh and eighth dates. This indicates that piecewise linear interpolation can accurately predict the subsidence of each leveling point on the SAR imaging dates and solve the problem of inconsistency between leveling and DInSAR monitoring periods. We also performed the experiment using polynomial fitting, nearest neighbor interpolation, cubic spline interpolation, and cubic interpolation, but the results were not as good as linear interpolation.

The interpolated leveling-measured subsidence of 179 leveling points was analyzed, and the results are shown in Table 4.

Table 4 Distributions of 179 leveling points in the subsidence intervals of seven interferometric periods.

Subsidence intervals (cm)	Interferometric pairs						
	1	2	3	4	5	6	7
[22, 20]	0	0	0	0	0	4	0
(20, 15]	0	0	11	0	0	16	0
(15, 10]	4	12	15	0	0	17	0
(10, 5]	24	22	24	11	20	40	39
(5, 2]	37	58	25	61	46	57	43
(2, 1]	57	46	42	42	53	9	43
(1, 0.1]	39	19	36	40	37	17	39
(0.1, 0]	16	13	13	16	13	9	6
No subsidence	8	9	13	9	10	10	9
Sum	179	179	179	179	179	179	179
Maximum subsidence (cm)	11.3	14.5	19.8	7.8	7.3	21.8	8.4

Table 5 Distributions of 179 leveling points in the subsidence intervals of seven interferometric periods.

Interferometric pairs	1	2	3	4	5	6	7
Coherence coefficient of A	0.47	0.59	0.54	0.47	0.46	0.43	0.47
Coherence coefficient of B	0.47	0.59	0.55	0.45	0.47	0.44	0.45

In order to study the influence of coherence on the accuracy of DInSAR-monitored subsidence, the coherence of two main subsidence zones called A and B in seven interferometric pairs (shown in Fig. 6) is also calculated. The results are shown in Table 5.

According to the number of leveling points and the maximum subsidence value of each subsidence interval in Table 4, we can deduce that the severity of subsidence decreased in the following order: the sixth, third, second, seventh, first, fifth, and fourth interferometric pair.

Because working face 1305 is in subsidence zone A, according to the coherence coefficient of subsidence zone A in Table 5, the coherence decreased in the following order: the second, third, fourth, first, seventh, fifth, and sixth interferometric pair.

We analyzed the DInSAR- and leveling-monitored results one by one according to the order of coherence from high to low.

1. Comparative analysis of the results of the second and third interferometric pairs.

Tables 4 and 5 show that the coherence coefficients of the subsidence zone A in the second and third interferometric pairs are relatively high, 0.59 and 0.54, respectively. In addition, the maximum subsidence detected by leveling surveys is 14.5 and 19.8 cm, respectively. The subsidence is more serious in these two periods. Figure 12 shows the comparison of the DInSAR- and leveling-monitored subsidence values and their absolute differences at 55 leveling points on the dip line and 124 leveling points on the strike line of the two interferometric pairs.

2. Comparative analysis of the results of the first, fourth, fifth, and seventh interferometric pairs.

The coherence coefficients of subsidence zone A in the first, fourth, fifth, and seventh interferometric pairs are 0.47, 0.47, 0.46, and 0.47, respectively (Tables 4 and 5). The maximum

Fig. 12 Comparative analysis of the DInSAR- and leveling-monitored subsidence results of the second and third interferometric pair on (a) the dip line of the second interferometric pair, (b) the strike line of the second interferometric pair, (c) the dip line of the third interferometric pair, and (d) the strike line of the third interferometric pair.

Fig. 13 Comparative analysis of the DInSAR- and leveling-monitored subsidence results of the first, fourth, fifth, and seventh interferometric pair on (a) the dip line of the first interferometric pair, (b) the strike line of the first interferometric pair, (c) the dip line of the fourth interferometric pair, (d) the strike line of the fourth interferometric pair, (e) the dip line of the fifth interferometric pair, (f) the strike line of the fifth interferometric pair, (g) the dip line of the seventh interferometric pair, and (h) the strike line of the seventh interferometric pair.

subsidence detected by leveling is 11.3, 7.8, 7.3, and 8.4 cm, respectively. The degree of subsidence of these pairs is smaller than that of the second and third interferometric pairs. Figure 13 shows the comparison of the DInSAR- and leveling-monitored subsidence values and their absolute differences at 55 leveling points on the dip line and 124 leveling points on the strike line of the four interferometric pairs.

3. Comparative analysis of the results of the sixth interferometric pair.

The coherence coefficient of the subsidence zone A in the sixth interferometric pair is 0.43, and the maximum subsidence detected by leveling is 21.8 cm (Tables 4 and 5). The coherence is the lowest and the degree of subsidence is the highest in this interferometric pair. Figure 14 shows the comparison of the DInSAR- and leveling-monitored subsidence values and their absolute differences at 55 leveling points on the dip line and 124 leveling points on the strike line of the sixth interferometric pair.

4. Comparative analysis of the final results of the cumulative subsidence.

We calculated the leveling-measured cumulative subsidence value of each leveling point from November 27, 2015 to July 24, 2016 using the fitted subsidence results after piecewise linear interpolation, and compared them with those of DInSAR (Fig. 15).

Fig. 14 Comparative analysis of the DInSAR- and leveling-monitored subsidence results of the sixth interferometric pair on (a) the dip line and (b) the strike line.

Fig. 15 Comparative analysis of the DInSAR- and leveling-monitored cumulative subsidence results from November 27, 2015 to July 24, 2016 on (a) the dip line and (b) the strike line.

In addition, we counted the maximum DInSAR- and leveling-monitored subsidence values, the maximum difference between the two results, and the root-mean-square errors (RMSE) of seven interferometric pairs from November 27, 2015 to July 25, 2016 (Table 6).

For the second and third interferometric pairs, Fig. 12 and Table 6 show as follows.

- (1) From December 21, 2015 to January 14, 2016, ground subsidence around working face 1305 increased with the continuous mining activity. As can be seen from Fig. 12(a), the maximum leveling-monitored subsidence value of 10.5 cm appeared at the leveling point H39 on the dip line and the subsidence basin occurred. The DInSAR-monitored subsidence value at H39 was 7.2 cm with the absolute difference of 3.3 cm. The maximum DInSAR-monitored subsidence value of 7.8 cm appeared at the leveling point H42. The comparison of these two subsidence curves in Fig. 12(a) suggested that they were identical in shape with the same distribution and changing ground subsidence trend and that the absolute difference between them was small at the edge and large at the subsidence center.
- (2) The comparison of the two subsidence curves in Fig. 12(b) showed that the DInSAR- and leveling-monitored results and their differences have the same features as those on the dip line. The shapes of the two curves were similar unlike the maximum subsidence points detected by the two methods. The absolute difference gradually increased from the edge to the center of the subsidence basin.
- (3) Similarly, from January 14, 2016 to March 2, 2016, on the dip line, the maximum leveling-monitored subsidence value reached 19.8 cm at H41, and the maximum DInSAR-monitored subsidence value was 11.0 cm at H42. On the strike line, the maximum subsidence values were 17.1 cm at Z65 and 11.4 cm at Z69, respectively. The maximum subsidence points were still inconsistent.
- (4) The comparison of the subsidence curves in Figs. 12(c) and 12(d) showed the consistency of the subsidence centers and the subsidence curves of the two methods on the dip and strike lines, but the maximum subsidence points were slightly different. In addition, the absolute difference was small at the edge and large at the center.

For the first, fourth, fifth, and seventh interferometric pairs, Fig. 13 and Table 6 demonstrate as follows.

Table 6 The counted results of DInSAR- and leveling-monitored subsidence.

Interferometric pairs		The maximum DInSAR-monitored subsidence (cm)	The maximum leveling-monitored subsidence (cm)	The maximum difference (cm)	RMSE (cm)
2	Dip line	−7.8	−10.5	4.0	2.1
	Strike line	−7.0	−14.5	9.1	2.2
3	Dip line	−11.0	−19.8	9.1	3.9
	Strike line	−11.4	−17.1	6.8	1.4
1	Dip line	−3.8	−9.6	6.3	2.6
	Strike line	−3.7	−11.3	9.1	2.3
4	Dip line	−5.0	−7.8	6.5	2.0
	Strike line	−5.0	−4.7	4.7	1.4
5	Dip line	−5.7	−6.4	2.1	0.9
	Strike line	−6.9	−7.3	6.2	2.4
7	Dip line	−3.6	−3.5	3.2	1.4
	Strike line	−5.0	−8.4	5.0	1.7
6	Dip line	−3.8	−19.2	16.1	7.5
	Strike line	−4.2	−21.8	19.5	6.4
Cumulative	Dip line	−34.5	−76.3	42.4	18.7
	Strike line	−34.4	−49.6	34.4	12.5

- (1) From November 27, 2015 to December 21, 2015, referring to Figs. 13(a) and 13(b), it can be seen that on the dip line, the maximum leveling-monitored subsidence value of 9.6 cm appeared at the leveling point H39 with a visible subsidence basin, but the DInSAR-monitored subsidence at H39 was 3.4 cm with a smaller subsidence basin and the absolute difference of 6.2 cm. In addition, the maximum DInSAR-monitored subsidence value of 3.8 cm appeared at H44, which was not consistent with that obtained by the leveling surveys. The comparison of the two subsidence curves in Fig. 13(a) showed that their shapes and trends were similar to the small absolute difference at the edge of the subsidence basin. However, at the center, the difference between the two curves was large, the coincidence was poor, the DInSAR-monitored subsidence results were not consistent with the leveling-monitored subsidence results, and the absolute difference increased. Similarly, the comparison of the two subsidence curves on the strike line in Fig. 13(b) showed that the DInSAR- and leveling-monitored results were not consistent at the center.
- (2) Figures 13(c)–13(h) showed that at the edge of the subsidence basin, DInSAR-monitored results were in relatively good agreement with the leveling data. However, the DInSAR results can reflect the leveling-monitored subsidence to a lesser extent as we get closer to the basin center. For example, DInSAR-monitored subsidence trends were opposite to the leveling-monitored results at the center of the subsidence basin in Fig. 13(c).

For the sixth interferometric pair, Fig. 14 and Table 6 demonstrate as follows.

- (1) From April 19, 2016 to June 30, 2016, referring to Figs. 14(a) and 14(b), it can be seen that the maximum leveling-monitored subsidence value was 19.2 cm at the leveling point H42 on the dip line, and the DInSAR-monitored subsidence value at this point was only 3.1 cm. The absolute difference between the two also reached the peak value at this point,

which was 16.1 cm. The comparison of the two subsidence curves in Fig. 14(a) showed that the two curves are in good agreement at the edge of the subsidence basin. At the subsidence center, the leveling-monitored subsidence curve showed an obvious subsidence basin, whereas the DInSAR-monitored subsidence curve showed a very gentle changing trend with almost no fluctuations, and there was no obvious subsidence basin.

- (2) The comparison of the two subsidence curves in Fig. 14(b) showed that on the strike line, the morphological features of the two curves were consistent with those on the dip line, and their shapes and changing trends were consistent at the edge with small absolute differences. The DInSAR technique did not detect obvious subsidence basins in the subsidence center with large absolute differences.

The cumulative subsidence results from November 27, 2015 to July 24, 2016 in Fig. 15 and Table 6 demonstrate as follows.

- (1) From November 27, 2015 to July 24, 2016, referring to Figs. 15(a) and 15(b), it can be seen that on the dip line, the maximum leveling-monitored subsidence value of 76.3 cm appeared at the leveling point H43. At this point, the DInSAR-monitored subsidence value was 34.5 cm with an absolute difference of 41.8 cm. The comparison of the two subsidence curves in Fig. 15(a) showed that the DInSAR- and leveling-monitored subsidence trends were consistent, but the DInSAR-monitored subsidence values were smaller than the leveling-monitored values.
- (2) Figure 15(b) showed the two subsidence basins on the strike line, consistent with the actual mining situation; the mining activities of working face 1305 were nearing the end, whereas the mining activities of working face 1307 began in the late stage of the subsidence monitoring period, causing the center of the subsidence basin to move to the southwest. The first subsidence center was located at Z27, and the DInSAR- and leveling-monitored subsidence values were 6.9 and 39.6 cm with the absolute difference of 32.7 cm. The second subsidence center was located at Z74, and the DInSAR- and leveling-monitored subsidence values were 49.6 and 34.4 cm with the absolute difference of 15.2 cm.

From Figs. 12–15, it can also be obtained that DInSAR- and leveling-monitored values were significantly different and DInSAR results were generally lower than leveling monitored values at the leveling points with large subsidence. This is mainly due to the two following reasons.

- (1) The leveling-monitored subsidence values can only reflect the subsidence of a “point,” whereas the DInSAR-monitored results reflect the deformation velocity of a “surface,” which is 20 m × 20 m in this case.
- (2) C-band Sentinel-1A SAR images have shorter wavelength (5.6 cm) and lower ground resolution (20 m × 20 m after 1:4 multilook). Theoretically, it is difficult to detect the subsidence of more than half wavelength occurring in a pixel of the differential interferogram by DInSAR technology based on C-band Sentinel-1A SAR images. If we want to detect these subsidence information, we should use the SAR images with longer wavelength and higher resolution (such as L-band POLSAR data).

6 Conclusion

Based on the mining information of 13 working faces and the leveling-monitored ground subsidence values of 179 leveling points in six periods, we validated the accuracy of mining subsidence monitored by repeat track DInSAR with seven interferometric pairs from November 11, 2015 to July 24, 2016. The following conclusions can be drawn from the results.

- (1) The DInSAR-monitored results showed that there were mainly two subsidence zones in the Guotun coal mine from November 27, 2015 to July 24, 2016. The location of these two subsidence zones was consistent with that of the Guotun coal mine working faces. The changes in subsidence in seven DInSAR monitoring periods were also consistent with the mining progress, interactions, and surrounding environment of the working

faces. The Sentinel-1A repeat track DInSAR technique can accurately identify the location, the main distribution, and the scope of mining subsidence.

- (2) When the coherence coefficients of the subsidence zones are 0.54 and 0.59, the subsidence curves detected by leveling surveys and Sentinel-1A repeat track DInSAR are consistent on the dip and strike lines, respectively. The location of the subsidence basin detected by the two techniques is the same, but the maximum subsidence point is slightly different. The absolute difference is small at the edge of the subsidence basin and large at the center.
- (3) When the coherence coefficients of the subsidence zones are 0.46 and 0.47, the Sentinel-1A repeat track DInSAR can still detect the fluctuations in ground subsidence in the mining area, and the morphology of the DInSAR-monitored subsidence curves is consistent with that obtained by leveling surveys on the dip and strike lines. However, the location of the subsidence center and the maximum subsidence point detected by DInSAR is different from those detected by the leveling surveys.
- (4) When the coherence coefficient of the subsidence zones is 0.43, the subsidence curve monitored by Sentinel-1A repeat track DInSAR changes very gently on the dip and strike lines, almost without any fluctuations and thus cannot reflect the real ground subsidence fluctuation characteristics. DInSAR-monitored results are different from those obtained by leveling surveys and thus are less accurate.
- (5) The accuracy of DInSAR-monitored mining subsidence is closely related to the coherence. The higher the coherence is, the smaller the difference from the leveling-monitored results and the greater the accuracy.

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Yang Chen is currently pursuing her MS degree in geodesy and surveying engineering at Shandong University of Science and Technology, Qingdao, China. She now mainly engages in the research of InSAR data processing and analysis.

Qiuxiang Tao received her MS degree in geodesy and surveying engineering and her PhD in photogrammetry and remote sensing from Shandong University of Science and Technology, Qingdao, China. She is an associate professor at the College of Geomatics of Shandong University of Science and Technology. She is currently working on the research of theory, methods, and key technologies in InSAR.

Anye Hou has received his MS degree in surveying engineering from Shandong University of Science and Technology, Qingdao, China. He is currently a registered surveyor and engineer at Qingdao Geotechnical Investigation and Surveying Institute, Qingdao, China. His current research interests include InSAR and national geoinformation survey.

Liu Jian Ding is currently pursuing his MS degree in surveying engineering at Shandong University of Science and Technology, Qingdao, China. He is currently engaged in the geometric calibration of SAR images.

Guolin Liu received his MS and PhD degrees in surveying engineering from Shandong University of Science and Technology and China University of Mining and Technology in 1992 and 1999, respectively. He is a professor at the College of Geomatics, Shandong University of Science and Technology, Qingdao, China. His current research interests include the theories and applications of modern surveying data processing, InSAR technology, and its application.

Ke Wang received her MS degree in geographic information science from Guilin University of Technology, Guilin, China, in 2016. She is currently pursuing her PhD in geodesy and surveying engineering at Shandong University of Science and Technology, Qingdao, China. She now mainly engages in the theories and applications of modern surveying data processing.