Accuracy verification and evaluation of small baseline subset (SBAS) interferometric synthetic aperture radar (InSAR) for monitoring mining subsidence

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ABSTRACT
This study investigated the role of the number of differential interferograms and coherent threshold values on the accuracy of SBAS InSAR (small baseline subset interferometric synthetic aperture radar) results for specific applications in Jiyang Coal. Fifty-eight images were utilized to form four differential interferogram timeseries with different numbers of interferograms and coherence thresholds. The four SBAS InSAR-monitored results, mining information of 15 working faces, and levelling-monitored results of 260 levelling points were compared. The greater number of differential interferograms and lower coherent threshold values could better reflect the spatial distribution and variation trend of mining subsidence and demonstrate the advantages of SBAS InSAR. However, an excessive number of differential interferograms and excessively low coherent threshold values would increase the data processing difficulty and the differences between SBAS InSAR- and levelling-monitored results. Location, spatial distribution, and scope of SBAS InSAR-monitored mining subsidence were consistent with the mining progress of the working faces. The accuracy of SBAS InSAR-monitored subsidence values followed a certain spatial-temporal variation law. The variation trend of absolute differences between SBAS InSAR- and levelling-monitored subsidence values was similar to the shape of the levelling-monitored subsidence basin, which was helpful to study the correction method of SBAS InSAR-monitored results.

Introduction
Research on the small baseline subset (SBAS) interferometric synthetic aperture radar (InSAR) technique is currently receiving significant global attention (Berardino et al., 2002; Corsetti et al., 2018). This technique is widely utilized in monitoring different types of surface deformation with a large-scale and long timeseries, such as mining areas, cities, and seismic fault zones (Du et al., 2018; Xing et al., 2018; Yan et al., 2012). Since initial development, the theory and data processing methods of SBAS InSAR have relatively matured. However, the progress of SBAS InSAR in practical engineering applications is not ideal, as the uncertainty regarding the accuracy of monitoring ground subsidence has been a challenge for majority of the users, till date. Resolving this challenge has been a long-term concern for researchers worldwide, for example, Casu and Pepe (Casu et al., 2006; Pepe, 2021). Some other examples can be cited, the performances of persistent scatterers (PS) InSAR and SBAS InSAR were compared quantitatively and cross-validated in the San Francisco Bay Area using a set of ERS-1/2 SAR data acquired during 1995–2000 (Shanker et al., 2011). The advantages and limitations of SBAS InSAR for measuring surface deformation in active seismogenic areas have previously been investigated using a set of ERS-1/2 SAR data acquired during 1992–2006 (Manzo et al., 2012). The SBAS InSAR results have been validated in a recent study using relative and absolute global navigation satellite system (GNSS) techniques and a set of Sentinel 1A SAR data acquired during the 2014–2018 in medium- and high-grade deformation areas (Mexico City and Aguascalientes) (Yalvac, 2020). The existing studies have comprehensively demonstrated the accuracy and capabilities of SBAS InSAR for surface deformation monitoring; however, there are a few shortcomings: (1) Verification and evaluation of the monitoring accuracy and ability of SBAS InSAR using only one multi-temporal differential interferogram series without considering the effect of the number of multi-temporal differential interferograms and coherent threshold values in selecting highly coherent pixels. (2) Only one or two working faces and several or dozens of GPS points (or levelling points) are typically utilized to verify and evaluate the SBAS InSAR-monitored mining subsidence results, which cannot distinctly demonstrate the spatial-temporal variations between the SBAS InSAR-monitored and actual mining subsidence results. Moreover, the monitoring accuracy of SBAS InSAR is affected by various complicated factors, such as SAR data types,
methods and models of data processing, atmospheric delay, orbit error, and the characteristics of the deformation bodies (Zhu & Li, 2017).

This study systematically investigates the effects of the number of multi-temporal differential interferograms, along with coherent threshold values in selecting highly coherent pixels and accuracy of SBAS InSAR in practical engineering applications, particularly in monitoring mining subsidence. To do so, the following four steps were taken: (1) Jiyang Coal Mine, located in northern China, was selected as the research area for this study, as long-term levelling observations have previously been carried out in this region. Thus, we have access to the levelling-monitored results of its ground subsidence and are familiar with its geological and mining conditions. (2) A total of 58 C-band Sentinel-1A SAR images of Jiyang Coal Mine, acquired from 20 May 2017 to 15 June 2019, were initially utilized to generate 68 and 87 optimal multi-temporal differential interferogram series under different threshold conditions of spatio-temporal baselines. Subsequently, two different coherent threshold values of 0.15 and 0.25 were set to select highly coherent pixels and phase unwrap; finally, a 68–0.15, 87–0.15, 68–0.25, and 87–0.25 multi-temporal unwrapped differential interferogram series were formed. The 68–0.15, 87–0.15, 68–0.25, and 87–0.25 series were processed using the SBAS InSAR technique and the ground subsidence of Jiyang Coal Mine was obtained for the same study area and period. (3) The location, major overlying features on the surface, and mining progress of 15 mining faces were collected. In addition, a qualitative comparative analysis with the SBAS InSAR-monitored results was conducted. (4) The levelling-monitored subsidence values of 260 levelling points were collected, and piecewise linear interpolations were performed to obtain the fitted levelling-monitored subsidence results, which entirely comprised the SBAS InSAR-monitored subsidence results over time. Furthermore, the difference between these two results could be calculated to conduct a quantitative comparative analysis.

Study area and data

Study area

Jiyang Coal Mine is located on the southern edge of the North China Plain, extending from 116°59′00″–117°06′00″ E to 36°47′00″–36°50′00″ N, approximately 5 km in the north-south direction and 10 km in the east-west direction, with a total area of approximately 49 km². In Jiyang Coal Mine, the recoverable reserve and the designed production capacity are 58.885 mt (metric tonne) and 450,000 T/A (ton/age), respectively. A production capacity of 750,000 T/A with a service life of 62 years was approved on 17 June 2013. Figure 1 shows the specific location and extent of the study area.

Overlying features of Jiyang Coal Mine include mostly farmland with common crops such as wheat, corn, and sweet potato, along with economic crops such as soybean, cotton, and vegetables. Furthermore, the industrial, construction, animal husbandry, and tertiary industries are relatively developed. The mining area is densely populated and has multiple villages, resulting in significant ground subsidence problem. To protect villages, rivers, and power grids, to appropriately manage contrasting values between underground coal mining and ground protection, as well as to achieve efficient and civilised resource production, the effective monitoring of ground subsidence in this mining area is of utmost importance. Furthermore, studying the mechanism of

![Figure 1. The location and coverage of the SAR images and study area: (a) The location and coverage of the first SAR image acquired on 20 May 2017 and marked in the blue rectangle, (b) The location and coverage of study area marked in the blue polygon.](image-url)
movement along with deformation of surface and strata during the mining process, is highly recommended.

**Test data**

The Sentinel-1 satellite carrying the C-band SAR is an Earth observation satellite of the European Space Agency Copernicus Program (Global Monitoring for Environment and Security, GMES), which was successfully launched in April 2014 (Ouyang et al., 2017). 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 can operate at several different polarisation modes, such as single and double polarisation, providing continuous imagery and data services for various users through wide range, multi-mode, and multi-application modes (Y. Chen et al., 2020). The present study selected 58 C-band Sentinel-1A SAR images from 20 May 2017 to 15 June 2019, which were captured with ascending orbits in the VV polarisation mode. The orbits and dates are provided in Table 1 (image data: https://search.asf.alaska.edu/).

From May 2017 to June 2019, mining in Jiyang Coal Mine was primarily concentrated in the third and fourth mining areas, and the target coal seams were the first and seventh coal seams. In June 2013, mining of the first coal seam in the third mining area was initiated, and 11 working faces have been mined till date. In December 2015, the mining of the first coal seam in the fourth mining area was initiated, and 4 working faces have been mined since then. In June 2015, the mining of the seventh coal seams in the fourth mining area was initiated; 10 working faces have been mined since then, and 2 additional working faces are currently being mined. According to the time span of the 58 Sentinel-1A SAR images, this study compiled the mining information of 15 working faces and the levelling-monitored results of 260 levelling points in the third and fourth mining areas to compare, analyse, and verify the accuracy and reliability of SBAS InSAR in monitoring mining ground subsidence. Figure 2 shows the distribution and extent of the 15 working faces and 260 levelling points, and Table 2 provides the basic mining information of the 15 working faces. The levelling points on the dip lines are numbered from south to north, and the levelling points on the strike lines are numbered according to the advancing direction of the working face.

Fifteen levelling survey data obtained between 10 May 2017 to 27 June 2019 were processed and analysed after combining the time span of the 58 SAR images and actual levelling surveys of 260 levelling points. Table 3 and 4 presents the levelling survey dates and the distribution intervals of cumulative ground subsidence relative to the reference date (10 May 2017), for each of the 260 levelling points.

**Methodology**

**Basic principles of SBAS InSAR**

Consider a set of \(N + 1\) SAR images from the study area, acquired at the ordered times \(t_0, t_1, \ldots, t_N\). The SAR images were combined into interferometric pairs characterized by small values of the spatial and temporal baselines, and \(M\) interferograms were generated (Berardino et al., 2002; Fan et al., 2018), where:

\[
(N + 1)/2 \leq M \leq N(N + 1)/2.
\]

The topographic phase was further removed from each of the \(M\) interferograms using an external digital elevation model (DEM).

The highly coherent pixels were selected after generating \(M\) multi-temporal differential interferogram series (Aobpaet et al., 2013; Pawluszek-Filipiak & Borkowski, 2020). The deformation phase \(\delta \phi_f(r, x)\)

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**Table 1. Orbits and dates of SAR images.**

| Number | Orbit | Date       | Number | Orbit | Date       | Number | Orbit | Date       |
|--------|-------|------------|--------|-------|------------|--------|-------|------------|
| 1      | 16,664| 2017/5/20  | 21     | 20,689| 2018/2/20  | 41     | 24,539| 2018/11/11|
| 2      | 17,014| 2017/6/13  | 22     | 20,864| 2018/3/4   | 42     | 24,714| 2018/11/23|
| 3      | 17,189| 2017/6/25  | 23     | 21,214| 2018/3/28  | 43     | 24,889| 2018/12/5 |
| 4      | 17,539| 2017/7/19  | 24     | 21,389| 2018/4/9   | 44     | 25,064| 2018/12/17|
| 5      | 17,714| 2017/7/31  | 25     | 21,564| 2018/4/21  | 45     | 25,239| 2018/12/29|
| 6      | 17,889| 2017/8/12  | 26     | 21,739| 2018/5/3   | 46     | 25,414| 2019/1/10 |
| 7      | 18,064| 2017/8/24  | 27     | 21,914| 2018/5/15  | 47     | 25,589| 2019/1/22 |
| 8      | 18,239| 2017/9/5   | 28     | 22,089| 2018/5/27  | 48     | 25,764| 2019/2/3  |
| 9      | 18,414| 2017/9/17  | 29     | 22,264| 2018/6/8   | 49     | 26,114| 2019/2/27 |
| 10     | 18,764| 2017/10/10 | 30     | 22,439| 2018/6/20  | 50     | 26,289| 2019/3/11 |
| 11     | 18,939| 2017/10/23 | 31     | 22,614| 2018/7/2   | 51     | 26,464| 2019/3/23 |
| 12     | 19,114| 2017/11/4  | 32     | 22,789| 2018/7/14  | 52     | 26,639| 2019/4/4  |
| 13     | 19,289| 2017/11/16 | 33     | 22,964| 2018/7/26  | 53     | 26,814| 2019/4/16 |
| 14     | 19,464| 2017/11/28 | 34     | 23,139| 2018/8/7   | 54     | 26,989| 2019/4/28 |
| 15     | 19,639| 2017/12/10 | 35     | 23,314| 2018/8/19  | 55     | 27,164| 2019/5/10 |
| 16     | 19,814| 2017/12/22 | 36     | 23,489| 2018/8/31  | 56     | 27,339| 2019/5/22 |
| 17     | 19,989| 2018/1/3   | 37     | 23,664| 2018/9/12  | 57     | 27,514| 2019/6/3  |
| 18     | 20,164| 2018/1/15  | 38     | 23,839| 2018/9/24  | 58     | 27,689| 2019/6/15 |
| 19     | 20,339| 2018/1/27  | 39     | 24,014| 2018/10/6  |        |        |            |
| 20     | 20,514| 2018/2/8   | 40     | 24,189| 2018/10/18 |        |        |            |
for a highly coherent pixel located at \((r, x)\) in the \(i\)th unwrapped differential interferogram can be expressed as follows:

\[
\delta \phi_i (r, x) = \phi (t_B, r, x) - \phi (t_A, r, x) = -\frac{4\pi}{\lambda} [d(t_B, r, x) - d(t_A, r, x)], i = 1, 2, \ldots, M
\]  

(2)

where \(d(t_A, r, x)\) and \(d(t_B, r, x)\) are the cumulative deformation at \(t_A\) and \(t_B\) \((t_A < t_B)\), respectively, \(\lambda\) is the central wavelength of the transmitted signal, and \(\phi (t_A, r, x)\) and \(\phi (t_B, r, x)\) represent the cumulative deformation phases at \(t_A\) and \(t_B\), respectively. The cumulative deformations and the cumulative deformation phases are along the line of sight (LOS) direction and calculated with respect to the first reference scene \(t_0\), assuming that \(d(t_0, r, x)\) and \(\phi (t_0, r, x)\) are zero (Berardino et al., 2002; Caro, 2012).

Let \(\phi^T = [\phi (t_1), \ldots, \phi (t_M)]\) be the vector of the \(N\) unknown LOS cumulative deformation phase values with respect to \(t_0\), \(\delta^T = [\delta (t_1), \ldots, \delta (t_M)]\) be the vector of the \(M\) known deformation phase values derived from the stack of unwrapped differential SAR interferograms. Furthermore, \(I_M^T = [I_{M_1}, \ldots, I_{M_M}]\) and \(I_S^T = [I_{S_1}, \ldots, I_{S_M}]\) correspond to the acquisition time index associated with the image pairs for the generation of differential interferograms. Note that we assume the master \((I_M)\) and slave \((I_S)\) images to be chronologically ordered, i.e., \(I_M < I_S\), where \(i = 1, 2, \ldots, M\); thus, we have

\[
\delta \hat{\phi} = \hat{\phi} (I_S) - \hat{\phi} (I_M), i = 1, 2, \ldots, M
\]  

(3)

Accordingly, we derive a system of \(M\) equations in \(N\) unknowns that may be organized in the following matrix equation (Berardino et al., 2002):

\[
\delta \hat{\phi} = B \phi
\]  

(4)

where \(\delta \hat{\phi}\) are the optimal estimates of the known phase of the \(M\) differential interferogram series, \(\phi\) are the optimal estimates of unknown parameters of the LOS cumulative deformation phase, and \(B\) is a known matrix comprising 0, 1, and −1. We have \(B(i, I_s) = 1\), if \(I_s \neq 0\), \(B(i, I_M) = -1\), and zero otherwise (Berardino et al., 2002). For instance, if \(\delta \hat{\phi}_1 = \hat{\phi} (t_2) - \hat{\phi} (t_0)\) and \(\delta \hat{\phi}_2 = \hat{\phi} (t_3) - \hat{\phi} (t_1)\), \(B\) can be expressed as follows:

\[
B_{M,N} = \begin{bmatrix}
0 & 1 & 0 & 0 & \ldots \\
-1 & 0 & 0 & 0 & \ldots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{bmatrix}
\]  

(5)

Equation (5) highlights that \(B\) is an incidence-like matrix, directly depending on the set of \(M\) multitemporal differential interferogram series generated from the available SAR images. If all the acquisitions belong to a single small baseline (SB) subset, \(B\) is a column rank-full matrix and the system of Equation (4) can be solved by the least squares (LS) method (Berardino et al., 2002; Jiang et al., 2014; Liu et al., 2012), as follows:
\[
\phi = (B^T B)^{-1} B^T \delta \phi
\]  

(6)

If the \( M \) differential interferograms does not belong to one single SB subset, \( B \) exhibits a rank deficiency. For instance, if we assume to face \( L \) different SB subsets, the rank of \( B \) will be \( N - L + 1 \) and the system of Equation (4) can be solved by the general singular value decomposition (SVD) method (Berardino et al., 2002; J. Chen et al., 2018; Nie, 2016; Yin et al., 2011), as follows:

\[
\hat{\phi} = V S^+ U^T \delta \phi
\]  

(7)

where \( U \) and \( V \) are the left-singular and right-singular matrix of \( B \), respectively. \( S^+ = \begin{bmatrix} \Sigma^{-1} & 0 \\ 0 & 0 \end{bmatrix} \) and \( \Sigma = \text{diag}(\sigma_1, \cdots, \sigma_{N-L+1}) \), \( \sigma_1, \cdots, \sigma_{N-L+1} \) are the non-zero singular values of \( B \).

Using the LS or SVD method, we can obtain \( \hat{\phi} = [\phi(t_1), \cdots, \phi(t_N)] \). Further, the deformation \( \delta \delta \) and deformation velocity \( \delta \hat{v} \) along the LOS direction between time-adjacent acquisitions can be estimated as follows:

\[
\delta \delta_{\text{LOS}} = \left[ -\frac{1}{4 \pi} (\phi(t_1) - \phi(t_0)), -\frac{1}{4 \pi} (\phi(t_2) - \phi(t_1)), \cdots \right]
\]  

(8)

\[
\delta \hat{v}_{\text{LOS}} = \left[ -\frac{1}{4 \pi} \frac{\phi(t_1)}{t_1 - t_0}, -\frac{1}{4 \pi} \frac{\phi(t_2) - \phi(t_1)}{t_2 - t_1}, \cdots \right]
\]  

(9)

**SAR data processing method**

The major steps involved in the surface deformation time-series retrieval, implemented via the SBAS InSAR technique, are as follows:

1. The generation of a stack of differential interferograms: The image acquired on 12 August 2017 was selected as a super master image, where 68 interferometric pairs were selected by constraining 24 days of temporal baseline and 136 m of spatial baseline. Subsequently, 87 interferometric pairs were selected by constraining 24 days of temporal baseline and 151 m of spatial baseline. This was followed by coregistration, interferogram generation, removal of flat-Earth phase component due to Earth’s curvature, and Goldstein filtering of interferogram noise. Subsequently, 68 and 87 multi-temporal differential interferogram series were generated, which were utilized to study the effect of different qualities of multi-temporal differential interferogram series on the SBAS InSAR-monitored surface deformation results. Figure 3 shows an example of the filtered and enhanced differential interferogram and the corresponding coherence image.

2. The selection of highly coherent pixels: The coherent coefficient of every pixel in the 68 and 87 differential interferograms were calculated, and the coherent threshold values were set to 0.15 and 0.25. This yielded a total of 2,704,749 (for the first set) and 4,310,090 (second set) highly coherent pixels for the 68 differential interferogram series. In addition,
3,025,724 (first set) and 5,140,752 (second set) highly coherent pixels were yielded for the 87 differential interferogram series. Setting different coherent threshold values for selecting highly coherent pixels enabled studying the effect of coherence on the SBAS InSAR-monitored surface deformation results.

(3) Phase unwrapping: The phase values could be wrapped to modulo 2π provided that the phase change exceeded its period of 2π and the values had to be corrected by adding an appropriate number of 2π cycles. This process is known as phase unwrapping, and this provides the original phase difference of the highly coherent pixels in the differential interferograms (Cuenca et al., 2011). Figure 4 shows an unwrapped example of the 68 and 87 multi-temporal differential interferogram series.

(4) Inversion of deformation information on highly coherent pixels: The deformation models were established and solved based on Equations (2)–(6) to obtain the deformation magnitude, velocity, and other deformation information regarding the highly coherent pixels (Tao et al., 2020). Figures 5 and 6 show the SBAS InSAR-monitored ground subsidence information of the mining area after geocoding.

The primary data processing procedure is shown in Figure 7.

Figure 3. The filtered and enhanced differential interferogram and corresponding coherence image under Range-Doppler coordinate system of 2017/12/22-2018/01/03, and the location and coverage of study area marked in the blue polygon: (a) Differential interferogram and (b) Coherence image.
Mining subsidence analysis

Figures 5 and 6 show that the ground subsidence was primarily concentrated in the third and fourth mining areas, which were analysed emphatically. Figure 8 shows the subsidence velocity of the third and fourth mining areas in Jiyang Coal Mine. Figures 9 and 10 show the cumulative ground subsidence values of the third and fourth mining areas of 12 imaging moments relative to 20 May 2017, monitored by the 68–0.15 series and 87–0.15 series.

The following observations can be inferred from Figures 2, 5, 6, and 8-10.

The maximum subsidence position, subsidence velocity, and cumulative subsidence monitored by SBAS InSAR with 68–0.15, 68–0.25, 87–0.15, and 87–0.25 differential interferogram series differed from each other. For the 68–0.15 series, the maximum subsidence position was located in the "A" pixel (Figures 8a, 117°0'48" E, 36°49'25" N). In addition, the subsidence velocity was −359 mm/yr, and maximum final cumulative subsidence was −982 mm. Similarly, for the 87–0.15 series, the maximum subsidence position was located in 'B' pixel (Figures 8b, 117°0'49" E, 36°49'29" N); the velocity was −363 mm/yr with the maximum final cumulative subsidence value of −997 mm. For the 68–0.25 series, the maximum subsidence position was located in the 'C' pixel (Figures 8c, 117°0'46" E, 36°49'25" N); the velocity was −311 mm/yr, and the final subsidence was −900 mm. For the 87–0.25 series, the maximum subsidence position was...
located in the ‘D’ pixel (Figure 8d), 117°0′47″ E, 36° 49′26″ N); the velocity was $-332$ mm/yr with the maximum final cumulative subsidence value of $-926$ mm.

When the number of differential interferograms of the multi-temporal differential interferogram series were identical, the coherent threshold values for selecting highly coherent pixels increased, and the number of highly selected coherent pixels decreased (as shown in Figures 8a and 8c). When the coherent threshold values for selecting highly coherent pixels were identical, the number of differential interferograms increased, and the number of selected highly coherent pixels increased (as shown in Figures 8a and 8b). In this study, the coherent threshold value was set to 0.25, and the highly coherent pixels selected in the mining area were less (as shown in Figures 8c and 8d). Thus, SBAS InSAR could not effectively or comprehensively reflect the spatial distribution and variance of ground subsidence, nor could its advantages be well demonstrated.

During the time span of the 58 Sentinel-1A SAR images (20 May 2017–15 June 2019), the area and severity of the SBAS InSAR-monitored ground subsidence in the mining areas with a $68–0.15$ and $87–0.15$ series were gradually increasing, while the spatial and temporal distribution along with variation trends were consistent. Although fewer highly coherent pixels were selected by the SBAS InSAR of the $68–0.25$ and $87–0.25$ series, the ground subsidence situation reflected by these highly coherent pixels was consistent with that of the $68–0.15$ and $87–0.15$ series. In addition, the subsidence velocity and cumulative subsidence values, at the same time for the same highly coherent pixels, monitored by SBAS InSAR for the $68–0.15$, $68–0.25$, $87–0.15$, and $87–0.25$ series differed from each other (as shown in Table 5 and Figure 11 and 14).

### Accuracy verification and evaluation

#### Comparative analysis with working faces

The SBAS InSAR-monitored ground subsidence results of the mining area with the $68–0.15$, $68–0.25$, $87–0.15$, and $87–0.25$ series exhibited consistent spatial and temporal distribution and variation trends. SBAS InSAR with the $87–0.15$ series selected the most highly coherent pixels, so a qualitative and comparative analysis between the monitored results of SBAS InSAR with the $87–0.15$ series and the mining progress of 15 mining faces was conducted. Figure 11 shows the overlaying map of 15 working faces and the final cumulative subsidence map of the $87–0.15$ series.

Figures 10 and 11 show that during the period from May 2017 to September 2019, the ground subsidence zones in the third and fourth mining areas can be divided into four subsidence basins, namely, A, B, C, and D, coinciding with the locations of the working faces. The severity of mining ground subsidence gradually increased with continuous mining, until it finally affected the surrounding villages indirectly. The following observations could be ascertained regarding the subsidence of each basin (A–D).
The subsidence of basin A primarily includes the two working faces of I and II. Working face I has been mined since February 2019, while working face II has been mined from March to October 2018.

During the period from July 2017 to January 2018 (Figures 10a–d), the mining activities of working faces I and II had not yet started, and thus, no evident ground subsidence above the faces was observed. During the period from March 2018 to January 2019 (10e–10 j), the mining activities of working face II started, and the ground subsidence degree above the northeast portion of working face II started increasing accordingly. Moreover, the ground subsidence area gradually expanded from east to west in accordance with the progress of mining from east to west of working face II. Neither the subsidence area nor the subsidence values above working face I exhibited a conspicuous increase. During the period from March to June of 2019 (Figures 10k and 10l), the mining activities of working face I was initiated, and the ground subsidence degree above it gradually increased with the progress of mining. In addition, the mining activities of working face II had finished; however, the overlying surface had not reached a stable state and continued to sink. Finally, the subsidence basin appeared above working faces I and II.
Subsidence basin B primarily includes five working faces of III, IV, V, VI, and VII with the following mining timeframes: Working face III, August 2018 to February 2019; working face IV, March to June 2017; working face V, July to November 2017; working face VI, September 2017 to June 2018; working face VII, January to September 2018.

According to Figures 2 and 11 along with Tables 2 and 3, the five working faces in subsidence basin B were relatively concentrated, that is, closely adjacent to each other or overlapping (e.g., working faces III and IV were overlapped, and working faces VII and VI were overlapped). During the period from May 2017 to February 2019, mining activities continued. Therefore, the ground subsidence in basin B was complex. In addition, the ground subsidence in this area was extremely severe compared to other basins (i.e., the maximum cumulative ground subsidence of Q52 was 1817 mm), and the basin itself belonged to the serious low coherent zone. Thus, SBAS InSAR of the 87–0.15 series could not detect the highly coherent pixels above the “blank” zones in basin B, particularly those above working faces VI and VII. Therefore, we could not analyse the ground subsidence of the blank zones.

During the period from July to November 2017 (Figures 10a–c), the subsidence basin initially appeared above working faces IV and V, which had been mined (Figures 10a and 10b). Furthermore, the ground subsidence degree increased with the progress of mining from east to west for working face V, until November 2017 (Figure 10c). For working face III, although the mining activities had not yet started, ground subsidence was present above this face at the time, likely caused by the continuous ground subsidence of the overlying working face IV. During the period from January to September 2018 (Figures 10d–10h), the mining activities of working face V were completed; however, the mining activities of the adjacent working faces VI and VII were continuing. Thus, although the surface subsided, the velocities did not slow down considerably. During the period from November 2018 to May 2019 (Figures 10i–10j), the mining activities of working face III initiated, and the strata above working faces V, IV, and III were disturbed, leading to the continuous and rapid ground subsidence above them. Generally, the spatial and temporal variations in ground subsidence monitored by the SBAS InSAR could reflect the progress of coal mining in this subsidence basin.

Subsidence basin C primarily includes the three working faces of VIII, IX, and XIII; working face VIII was mined from October 2018 to January 2019, working face IX was mined from May to December 2017, and working face XIII was mined from December 2017 to May 2018.

For working faces IX and XIII, the ground subsidence basin first appeared on the left side, and further gradually spread toward the right. The ground subsidence values also increased as the two working faces were mined until May 2018. After the completion of mining activities of working face XIII, the overlying surface gradually stabilised, and the cumulative ground subsidence values exhibited no further evident changes. For working face VIII, although the mining

![Figure 8. The subsidence velocity of the third and fourth mining areas of Jiyang Coal Mine from 20 May 2017 to 15 June 2019: (a)68–0.15; (b)87–0.15; (c)68–0.25 and (d) 87–0.25.](image-url)
activities initiated in October 2018, ground subsidence was observed above the face due to the influence of the mining activities of its upper and lower adjacent working faces, thereby gradually increasing the subsidence (Figures 10a–10h). Moreover, when the mining activities started, the subsidence became increasingly serious, as shown in Figures 10i–10l. This was consistent with the progress of mining from west to east of working face XIII.

Subsidence basin D primarily included the five working faces X, XI, XII, XIV, and XV. Working face X was overlapped by working faces XI and XIV and
was mined from April to December 2018. Working faces XI and XIV were mined from April 2017 to March 2018, and working faces XII and XV were mined from July 2016 to October 2017.

During the period from July 2017 to March 2018 (Figures 10a–10e), ground subsidence primarily occurred above working faces XI, XIV, and X, gradually increasing and ultimately forming a preliminary subsidence basin, which coincided with the mining time and progress of the working faces XI and XIV. The overlying surface above working faces XII and XV gradually stabilised, and the ground subsidence did not increase evidently because mining activities were completed by October 2017. During

Figure 10. The cumulative subsidence values of the third and fourth mining of 12 imaging dates relative to 20 May 2017 monitored by SBAS InSAR with 87–0.15 series: (a)2017/07/19; (b)2017/09/17; (c)2017/11/16; (d)2018/01/15; (e)2018/03/28; (f) 2018/05/27; (g)2018/07/14; (h)2018/09/24; (i)2018/11/23; (j)2019/01/22; (k)2019/03/23; (l)2019/06/15.
the period from April 2018 to January 2019 (Figures 10f–10j), mining was active at working face X, and thus, the subsidence areas and values increased evidently, ultimately forming the larger subsidence basin D. During the period from January to May 2019 (Figures 10j–10l), although the mining activities of the five working faces were completed, the overlying surface did not reach a stable state and was still sinking at a slow rate.

Comparison and analysis with levelling results

The SBAS InSAR technique required the selection of highly coherent pixels to monitor ground subsidence. If the pixels on the multi-temporal SAR images corresponding to the 260 levelling points could not conform to the thresholds for selecting highly coherent pixels, their ground subsidence information could not be monitored by SBAS InSAR. Table 4 provides the number of levelling points with SBAS InSAR-monitored ground subsidence values, and Figure 12 shows their distribution. The “common levelling points” in Table 4 indicate that only 23 out of 260 levelling points had the SBAS InSAR-monitored ground subsidence values of 68–0.15, 68–0.25, 87–0.15, and 87–0.25 series, at the same time.

Tables 1 and 3 reveal that although the monitoring period of the levelling surveys (10 May 2017 to 27 June 2019) covered the same period as that of the 58 SAR images (20 May 2017 to 15 June 2019), the two periods were not entirely consistent. To solve this problem, we performed a piecewise linear fitting process for the ground subsidence values of the levelling points, corresponding to the highly coherent pixels (Y. Chen et al., 2020). Subsequently, the difference between SBAS InSAR- and levelling-monitored results was calculated for quantitative and comparative analysis.

![Figure 11. The overlying map of 15 working faces and the final cumulative subsidence map of 87–0.15 series.](image)

Table 4. Number of the levelling points that have SBAS InSAR-monitored ground subsidence values.

| Series | 68–0.15 | 68–0.25 | 87–0.15 | 87–0.25 | Common levelling points |
|--------|---------|---------|---------|---------|------------------------|
| Number of levelling points with SBAS InSAR-monitored ground subsidence values | 134 | 204 | 31 | 49 | 23 |

Table 5. Number of common levelling points in each absolute difference intervals.

| Absolute difference intervals/mm | 68–0.15 | 68–0.25 | 87–0.15 | 87–0.25 | Sum |
|----------------------------------|---------|---------|---------|---------|-----|
| [0, 100]                         | 17      | 16      | 16      | 18      | 63  |
| [100, 200]                       | 2       | 3       | 3       | 2       | 10  |
| [200, 300]                       | 2       | 2       | 2       | 1       | 7   |
| [300, 400]                       | 0       | 0       | 0       | 0       | 0   |
| [400, 500]                       | 1       | 1       | 0       | 1       | 3   |
| [500, 600]                       | 0       | 0       | 2       | 0       | 2   |
| [600, 700]                       | 0       | 1       | 0       | 1       | 2   |
| [700, 800]                       | 1       | 0       | 0       | 0       | 1   |
| Sum                              | 23      | 23      | 23      | 23      | 92  |
Figure 13 shows the scatter plots of the cumulative ground subsidence values on 15 June 2019, which can be used to compare the ground values monitored by SBAS InSAR using four time series and the fitted levelling-monitored ground subsidence values. Table 5 provides the number of common levelling points in each absolute difference intervals.

From Tables 4 and 5 and Figures 12 and 13, the following observations could be deduced.

For the SBAS InSAR-monitored ground subsidence values of the 68–0.15 series, five observations were concluded: (1) Only 134 out of 260 levelling points demonstrated SBAS InSAR-monitored ground subsidence values. (2) The levelling-monitored cumulative subsidence values of 36 out of 134 levelling points were $< -100 \text{ mm}$ (the maximum levelling-monitored subsidence was $-72 \text{ mm}$, and maximum SBAS InSAR-monitored subsidence was $-220 \text{ mm}$). Twenty-seven
levelling points (~75%) displayed absolute differences of 0–100 mm, and nine points (~25%) displayed absolute differences of 100–150 mm. For these 36 levelling points, all SBAS InSAR-monitored subsidence values were greater than those obtained by levelling monitoring, exhibiting relatively severe ground subsidence. (3) The levelling-monitored cumulative subsidence values of 68 out of 134 levelling points were (~100 mm, −600 mm) with a maximum levelling-monitored subsidence of −584 mm and maximum SBAS InSAR-monitored subsidence of −623 mm. The absolute differences were as follows: 37 levelling points (~54%), 15 points (~22%), and 16 points (~24%) demonstrated absolute differences of 0–100 mm, 100–200 mm, and

Figure 13. The scatter plots of the cumulative ground subsidence values on 15 June 2019: (a) 68–0.15; (b) 87–0.15; (c) 68–0.25; (d) 87–0.25 and (e) the common levelling points.
200–300 mm, respectively. For these 68 levelling points, the SBAS InSAR-monitored subsidence values of 25 points were greater than those obtained by levelling monitoring, exhibiting relatively severe ground subsidence. However, the subsidence values of 43 points were less than those obtained by levelling monitoring, exhibiting comparatively mild ground subsidence. (4) The levelling-monitored cumulative subsidence values of 30 out of 134 levelling points were $>\text{−600 mm}$ (the maximum levelling-monitored subsidence was $\text{−1567 mm}$, and maximum SBAS InSAR-monitored subsidence was $\text{−881 mm}$). The absolute differences were as follows: one levelling point (~3%), 10 points (~33%), 12 points (~41%), and 7 points (~23%) exhibited an absolute difference of 0–100 mm, 100–400 mm, 400–600 mm, and 600–800 mm, respectively. For these 30 levelling points, all SBAS InSAR-monitored subsidence values were less than those obtained by levelling monitoring. (5) For 23 common levelling points, the maximum levelling-monitored subsidence was $\text{−1447 mm}$, and maximum SBAS InSAR-monitored subsidence was $\text{−743 mm}$, which appeared at point Q104. The absolute differences were as follows: 17 points (~74%), 4 points (~18%), and 1 point (~4%) demonstrated an absolute difference of 0–100 mm, 100–300 mm, and 400–500 mm, respectively. In addition, another single point (~4%) displayed an absolute difference of 700–800 mm. For these 23 levelling points, the SBAS InSAR-monitored subsidence values of 14 points were greater than those obtained by levelling monitoring, whereas those recorded for the 9 points were less.

For the SBAS InSAR-monitored ground subsidence values of the 87–0.15 series, five observations were made: (1) 204 out of 260 levelling points demonstrated SBAS InSAR-monitored ground subsidence values. (2) Levelling-monitored cumulative subsidence values of 31 out of 204 levelling points were $<\text{−100 mm}$ (the maximum levelling-monitored subsidence was $\text{−98 mm}$, and maximum SBAS InSAR-monitored subsidence was $\text{−117 mm}$). The absolute difference of all the points was in the range of 0–100 mm. Out of the 31 levelling points, the SBAS InSAR-monitored subsidence values of 21 points were greater than those obtained by levelling monitoring, whereas the subsidence values of 10 points were less. (3) The levelling-monitored cumulative subsidence values of 115 out of 204 levelling points ($\text{−100 mm}$, $\text{−600 mm}$) demonstrated a maximum levelling-monitored subsidence of $\text{−589 mm}$ and a maximum SBAS InSAR-

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**Figure 14.** The line charts of SBAS InSAR-monitored and levelling-monitored ground subsidence values on 12 monitoring dates of Table 6.
monitored subsidence of −597 mm. The absolute differences were as follows: 58 levelling points (−50%), 32 points (−28%), 18 points (−16%), and 7 points (−6%) demonstrated an absolute difference of 0–100 mm, 100–200 mm, 200–300 mm, and 300–450 mm, respectively. For these 115 levelling points, the SBAS InSAR-monitored subsidence values of 32 points were greater than those obtained by levelling monitoring, whereas those obtained from the 83 points were less. (4) The levelling-monitored cumulative subsidence values of 58 out of 204 levelling points were > −600 mm (the maximum levelling-monitored subsidence was −1609 mm, and maximum SBAS InSAR-monitored subsidence was −860 mm). The absolute differences were as follows: 4 points (~7%), 14 points (~24%), 26 points (~45%), and 14 points (~24%) exhibited an absolute difference of 0–100 mm, 100–400 mm, 400–600 mm, and 600–800 mm, respectively. Among these 58 levelling points, the SBAS InSAR-monitored subsidence values of 2 points were greater than those obtained by levelling monitoring, whereas those of 56 points were less. (5) For 23 common levelling points, the maximum levelling-monitored subsidence was −1447 mm, and maximum SBAS InSAR-monitored subsidence was −797 mm, which appeared at point Q104. The absolute differences were as follows: 16 points (~70%), 5 points (~22%), and 1 point (~4%) exhibited an absolute difference of 0–100 mm, 100–300 mm, and 400–500 mm, respectively. Among these 23 levelling points, the SBAS InSAR-monitored subsidence values of 6 points were greater than those obtained by levelling monitoring, whereas those obtained from the 17 points were less.

For the SBAS InSAR-monitored ground subsidence values of the 68–0.25 series, the following five observations were inferred: (1) Only 31 out of 260 levelling points exhibited SBAS InSAR-monitored ground subsidence values. (2) The levelling-monitored cumulative subsidence values of 16 out of 31 levelling points were < −100 mm (the maximum levelling-monitored subsidence value was −72 mm, and maximum SBAS InSAR-monitored subsidence was −115 mm). All levelling points (100%) demonstrated an absolute difference of 0–100 mm. In addition, all SBAS InSAR-monitored subsidence values were greater than those obtained by levelling monitoring. (3) The levelling-monitored cumulative subsidence values of 6 out of 31 levelling points (−100 mm, −300 mm) displayed a maximum levelling-monitored subsidence of −300 mm and a maximum SBAS InSAR-monitored subsidence of −299 mm. All levelling points (100%) demonstrated an absolute difference of 0–100 mm. For these six levelling points, the SBAS InSAR-monitored subsidence values of 3 points were greater than those obtained by levelling monitoring, whereas those obtained from the 3 points were less. (4) The levelling-monitored cumulative subsidence values of 9 out of 31 levelling points were > −300 mm (the maximum levelling-monitored subsidence was −1447 mm, and maximum SBAS InSAR-monitored subsidence was −888 mm). The absolute differences were as follows: 1 point (~10%), 3 points (~33%), and 5 points (~57%) displayed an absolute difference of 0–100 mm, 100–200 mm, and 200–600 mm, respectively. Among these nine levelling points, all SBAS InSAR-monitored subsidence values were less than those obtained by levelling monitoring. (5) For 23 common levelling points, the maximum levelling-monitored subsidence and the maximum SBAS InSAR-monitored subsidence was −1447 mm and −888 mm, respectively, which appeared at point Q104. The absolute differences were as follows: 16 points (~70%), 5 points (~21%), and 2 points (~9%) displayed an absolute difference of 0–100 mm, 100–300 mm, and 500–600 mm, respectively. For these 23 levelling points, the SBAS InSAR-monitored subsidence values of 12 points were greater than those obtained by levelling monitoring, whereas those of 11 points were less.

For the SBAS InSAR-monitored ground subsidence values of the 87–0.25 series, five observations were concluded: (1) Only 49 out of 260 levelling points exhibited SBAS InSAR-monitored ground subsidence values. (2) The levelling-monitored cumulative subsidence values of 23 out of 49 levelling points were < −100 mm (the maximum levelling-monitored subsidence was −72 mm, and the maximum SBAS InSAR-monitored subsidence was −165 mm). The absolute differences were as follows: 20 points (~87%) exhibited an absolute difference of 0–100 mm, and 3 points (~13%) exhibited an absolute difference of 100–200 mm. Among these 23 levelling points, all SBAS InSAR-monitored subsidence values were greater than those obtained by levelling monitoring. (3) The levelling-monitored cumulative subsidence values of 13 out of 49 levelling points (<−100 mm, −400 mm) displayed a maximum levelling-monitored subsidence of −392 mm and a maximum SBAS InSAR-monitored subsidence of −357 mm. All levelling points (100%) demonstrated an absolute difference of 0–100 mm. Among these 13 levelling points, the SBAS InSAR-monitored subsidence values of 4 points were greater than those obtained by levelling monitoring, whereas those obtained from the 9 points were less. (4) The levelling-monitored cumulative subsidence values of 13 out of 49 levelling points were > −400 mm (the maximum levelling-monitored subsidence was −1567 mm, and maximum SBAS InSAR-monitored subsidence was −848 mm). The absolute differences were as follows: 3 points (~23%), 1 point (~8%), 5 points (~38%), and 4 points (~31%) demonstrated an absolute difference of 0–100 mm, 100–200 mm, 200–400 mm and 400–800 mm, respectively. Among these 13 levelling points, the SBAS InSAR-monitored
subidence value of 1 point was greater than that obtained by levelling monitoring, whereas those of 12 points were less. (5) For 23 common levelling points, the maximum levelling-monitored subidence was −1447 mm, and maximum SBAS InSAR-monitored subidence was −799 mm, which appeared at point Q104. The absolute differences were as follows: 18 points (~78%) had an absolute difference of 0–100 mm, 3 points (~14%) had 100–300 mm, 1 point (~4%) had 400–500 mm, and 1 point (~4%) had 600–700 mm. Among these 23 levelling points, the SBAS InSAR-monitored subidence values of 13 points were greater than those obtained by levelling monitoring, whereas those obtained from the 10 points were less.

In addition, the SBAS InSAR- and levelling-monitored results of 23 common levelling points were systematically compared and analysed. Table 6 and Figure 14 present the comparison results of 9 common levelling points on the 12 monitoring dates (as shown in Figures 9 and 10 and Table 6).

From the comparison results of SBAS InSAR- and levelling-monitored ground subidence of 23 common levelling points presented in Table 6 and Figure 14, seven observations can be deduced as described in the subsequent paragraphs.

For levelling point Q104 (the levelling-monitored vertical average ground subidence velocity was −679 mm/yr), the SBAS InSAR with the 68–0.15, 68–0.25, 87–0.15, and 87–0.25 series could successfully monitor the continuous ground subidence during the monitoring period, and the SBAS InSAR-monitored subidence trend was consistent with the levelling results. However, the SBAS InSAR-monitored subidence values were substantially less than those of levelling monitoring, and the differences were relatively high for the 12 monitoring dates.

For levelling points G12 (~383 mm/yr), G4 (~253 mm/yr), G5 (~224 mm/yr), G20 (~198 mm/yr), G6 (~190 mm/yr), and G23 (~371 mm/yr), the SBAS InSAR with 68–0.15 series successfully

| Table 6. Nine examples of the comparison results of SBAS InSAR- and levelling-monitored ground subidence values (units: mm). |
| Levelling points and monitoring methods | Monitoring dates |
|------------------------------------------|-----------------|
| Q104 levelling                           | 2017/7/15 2017/9/15 2017/11/16 2018/1/15 2018/3/1 2018/5/1 2018/7/15 2018/9/1 2019/1/15 2019/3/15 |
| 68–0.15                                  | −286 −546 −748 −901 −968 −1024 −1069 −1089 −1166 −1264 −1385 −1447 |
| 87–0.15                                  | −65 −87 −161 −239 −338 −386 −421 −464 −519 −600 −666 −743 |
| G4 levelling                             | −2017/7/6 2017/9/8 2017/11/16 2018/1/15 2018/3/1 2018/5/1 2018/7/15 2018/9/1 2019/1/15 2019/3/15 |
| 68–0.15                                  | −50 −109 −208 −286 −383 −433 −464 −503 −573 −662 −727 −799 |
| G23 levelling                            | 2017/7/6 2017/9/8 2017/11/16 2018/1/15 2018/3/1 2018/5/1 2018/7/15 2018/9/1 2019/1/15 2019/3/15 |
| 68–0.15                                  | −9 −21 −40 −101 −240 −355 −448 −494 −531 −528 −530 |
| L84 levelling                            | 2017/7/6 2017/9/8 2017/11/16 2018/1/15 2018/3/1 2018/5/1 2018/7/15 2018/9/1 2019/1/15 2019/3/15 |
| 68–0.15                                  | −54 −53 −60 −79 −105 −129 −153 −180 −202 −235 −264 −305 |
| 87–0.15                                  | −35 −31 −18 −28 −54 −77 −96 −124 −145 −175 −203 −247 |
| G23 levelling                            | 2017/7/6 2017/9/8 2017/11/16 2018/1/15 2018/3/1 2018/5/1 2018/7/15 2018/9/1 2019/1/15 2019/3/15 |
| 68–0.15                                  | −3 −16 −33 −84 −103 −168 −188 −213 −235 −289 −316 −351 |
| G119 levelling                           | 2017/7/6 2017/9/8 2017/11/16 2018/1/15 2018/3/1 2018/5/1 2018/7/15 2018/9/1 2019/1/15 2019/3/15 |
| 68–0.15                                  | −10 −20 −43 −76 −87 −71 −65 −68 −153 −191 −213 −234 |
| 87–0.15                                  | −10 −20 −43 −76 −87 −71 −65 −68 −153 −191 −213 −234 |
| 87–0.25                                  | −10 −20 −43 −76 −87 −71 −65 −68 −153 −191 −213 −234 |
| Q117 levelling                           | 2017/7/6 2017/9/8 2017/11/16 2018/1/15 2018/3/1 2018/5/1 2018/7/15 2018/9/1 2019/1/15 2019/3/15 |
| 68–0.15                                  | −81 −116 −144 −159 −168 −175 −181 −186 −193 −197 −203 −215 |
| 87–0.15                                  | −32 −52 −63 −74 −87 −97 −107 −119 −130 −136 −144 −156 |
| 68–0.25                                  | −35 −69 −80 −90 −102 −108 −114 −123 −130 −133 −139 −153 |
| 87–0.25                                  | −15 −37 −59 −81 −88 −105 −112 −120 −127 −133 −139 −153 |
| H130 levelling                           | 2017/7/6 2017/9/8 2017/11/16 2018/1/15 2018/3/1 2018/5/1 2018/7/15 2018/9/1 2019/1/15 2019/3/15 |
| 68–0.15                                  | −24 −51 −57 −65 −76 −95 −89 −93 −99 −102 −108 −117 |
| 87–0.15                                  | −14 −36 −17 −30 −46 −80 −46 −66 −49 −72 −87 |
| 68–0.25                                  | −24 −51 −57 −65 −76 −95 −89 −93 −99 −102 −108 −117 |
| 87–0.25                                  | −8 −42 −49 −58 −68 −84 −87 −86 −99 −99 −99 −99 |
| H131 levelling                           | 2017/7/6 2017/9/8 2017/11/16 2018/1/15 2018/3/1 2018/5/1 2018/7/15 2018/9/1 2019/1/15 2019/3/15 |
| 68–0.15                                  | −1 −10 −17 −19 −20 −21 −24 −26 −26 −26 −25 −29 |
| 87–0.15                                  | −21 −40 −43 −51 −61 −72 −76 −84 −92 −94 −99 −104 |
| 68–0.25                                  | −19 −61 −85 −94 −72 −86 −85 −94 −94 −94 −94 −102 |
| 87–0.25                                  | −5 −31 −38 −48 −55 −67 −69 −74 −85 −86 −91 −92 |
monitored the continuous ground subsidence during the monitoring period. The SBAS InSAR with the 68–0.25, 87–0.15, and 87–0.25 series monitored the ground uplift on the first, second, or third monitoring dates when the ground subsidence was minute, contrasting with the levelling-monitored results. The SBAS InSAR-monitored subsidence trends among the points were relatively consistent with each other. The SBAS InSAR- and levelling-monitored ground subsidence values were not substantially different during the first four periods when the ground subsidence was mild; however, when the severity of ground subsidence increased, the SBAS InSAR-monitored subsidence values became less than those of the levelling monitoring, and the differences between the two increased. In comparison, the SBAS InSAR-monitored results with the 68–0.15 and 87–0.25 series exhibited higher accuracy, whereas those with 87–0.15 displayed low accuracy.

For levelling points L82 (−155 mm/yr), L83 (−141 mm/yr), and L84 (−130 mm/yr), the SBAS InSAR-monitored subsidence trends of the four time series were relatively consistent with that of the levelling results. The SBAS InSAR- and levelling-monitored ground subsidence values were not substantially different, and overall accuracy was improved. The SBAS InSAR-monitored subsidence values of the 87–0.15 series were less than those of the levelling monitoring, and the SBAS InSAR-monitored subsidence values of the other three series were either less or greater than those of the levelling monitoring. In comparison, the SBAS InSAR-monitored results of the 68–0.15 and 68–0.25 series exhibited higher accuracy, whereas those of 87–0.15 exhibited the lowest accuracy.

For levelling point Q117 (−101 mm/yr), the SBAS InSAR of the four time series successfully monitored the continuous ground subsidence during the monitoring period, and the SBAS InSAR-monitored subsidence trend was consistent with that of the levelling results. However, the SBAS InSAR-monitored subsidence values were substantially less than those of the levelling monitoring, and the differences were relatively high for the 12 monitoring dates.

For levelling points Q118 (−68 mm/yr), Q119 (−60 mm/yr), and Q120 (−47 mm/yr), the SBAS InSAR-monitored subsidence trends of the 68–0.15, 68–0.25, and 87–0.25 series were relatively consistent with those of the levelling monitoring and exhibited higher accuracy. However, the SBAS InSAR-monitored subsidence values of the 87–0.15 series were less than those of the levelling monitoring and exhibited the lowest accuracy.

For levelling points H129 (−34 mm/yr), H130 (−23 mm/yr), H131 (−14 mm/yr), H132 (−8 mm/yr), Q15 (−7 mm/yr), and H133 (−5 mm/yr), the levelling-monitored values exhibited continuous and slow subsidence. The SBAS InSAR-monitored subsidence values of the 87–0.15 series were closest to that of the levelling monitoring with the highest accuracy; however, the subsidence trend was not consistent with that of the levelling results and could not reflect the actual circumstances of ground subsidence at these levelling points. The SBAS InSAR of the 68–0.15, 68–0.25, and 87–0.25 time series successfully monitored the continuous and slow ground subsidence during the monitoring period; however, the SBAS InSAR-monitored subsidence values were substantially greater than those of the levelling monitoring, and the differences were evident.

For levelling points Q122 (−19 mm/yr), Q123 (−11 mm/yr), and Q124 (−6 mm/yr), the levelling-monitored values exhibited continuous and slow subsidence. The SBAS InSAR of the 68–0.15, 68–0.25, and 87–0.25 time series successfully monitored the continuous and slow ground subsidence during the monitoring period; however, the SBAS InSAR-monitored subsidence values were greater than those of the levelling monitoring, and the differences were evident. In comparison, the SBAS InSAR-monitored subsidence values of the 87–0.25 series were closest to those of the levelling monitoring and had the highest accuracy, followed by 68–0.15. The SBAS InSAR-monitored subsidence values of the 87–0.15 series could not accurately detect the trend of the three levelling points.

Figure 15 demonstrates the spatio-temporal variations between the levelling- and SBAS InSAR-monitored mining subsidence results.

In addition, the root mean square errors (RMSEs) of 23 common levelling points on the 12 monitoring dates were calculated and presented in Table 7 to clearly demonstrate the measurement accuracy.

As shown in Table 7, the RMSEs of the 87–0.15 time series were mostly greater than those of the 68–0.15, 68–0.25, and 87–0.25 time series, that is, the SBAS InSAR-monitored results of the 87–0.15 time series displayed the lowest accuracy. From 20 May 2017 to 28 March 2018, the RMSEs of the 68–0.25 time series were less than those of the 68–0.15, 87–0.15, and 87–0.25 time series, and the SBAS InSAR-monitored results of the 68–0.25 time series exhibited the highest accuracy. From 27 May 2018 to 15 June 2019, the RMSEs of the 87–0.25 time series were less than those of the 68–0.15, 68–0.25, and 87–0.15 time series, and the SBAS InSAR-monitored results of the 87–0.25 time series exhibited the highest accuracy.

Discussion

The experimental results show that the ground subsidence of the mining area monitored by SBAS-InSAR varies significantly corresponding to different number of multi-temporal differential interferograms and
coherent threshold values. The greater the number of differential interferograms, the lower the coherence threshold, and the greater the number of highly coherent pixels will be selected, the more effectively the SBAS InSAR-monitored results can reflect the spatial distribution and variation trend of ground subsidence. However, an excessive number of differential interferograms and excessively low coherent threshold values not only increases the difficulty in data processing, but also increases the differences between SBAS InSAR- and levelling-monitored results, particularly in the serious or mild subsidence zones. For example, the SBAS InSAR-monitored ground subsidence results of the 87–0.15 series can best reflect the spatial distribution and variation trend of ground subsidence in mining areas; however, data processing consumes the most time in SBAS InSAR and the accuracy of the monitoring results was the lowest, with SBAS InSAR-monitored ground subsidence or uplift being inconsistent with the actual situation in the mild subsidence zones. Therefore, the reasonable and correct selection of the number of differential interferograms and coherent threshold values should be further explored for SBAS InSAR technique for improving monitoring of land subsidence in mining areas.

In comparison, the SBAS InSAR-monitored results of the four multi-temporal differential interferogram time series better reflect the size of subsidence values at the edge of the subsidence basin in the mining area; however, highly coherent pixels cannot be obtained or SBAS InSAR-monitored subsidence values were less than those obtained by levelling monitoring in the centre of the subsidence basin. As shown in Figure 15, the variation trend of absolute differences of the SBAS InSAR- and levelling-monitored subsidence values has a certain spatio-temporal variation law and is very similar to the shape of the subsidence basin monitored by levelling. The construction of a difference correction model and method of the SBAS InSAR-monitored subsidence (for a point, line, and surface) based on the variation trend of difference between SBAS InSAR-monitored subsidence values and the actual values of ground subsidence are key challenges to be addressed by future research.

Based on the existing literature, this study more comprehensively and vividly studies the accuracy of SBAS InSAR-monitored ground subsidence in mining area, investigates the role of the number of differential SAR interferograms and coherent threshold values, and gives the spatio-temporal variation law of the difference between SBAS InSAR-monitored subsidence values and the actual values of ground

**Table 7.** Root mean square errors of the 23 common levelling points of SBAS InSAR- and levelling-monitored ground subsidence values (units: mm).

| Monitoring dates | Monitoring methods |
|------------------|--------------------|
| 87–0.15          | 87–0.25            |
| 2017/7/19        | 68–0.15            |
| 2017/9/17        | 52.2               |
| 2017/11/16       | 100.2              |
| 2018/7/15        | 125.2              |
| 2018/3/28        | 141.4              |
| 2018/5/27        | 148.0              |
| 2018/7/14        | 168.1              |
| 2018/9/24        | 192.7              |
| 2018/11/23       | 185.9              |
| 2019/1/22        | 188.2              |
| 2019/3/23        | 187.6              |
| 2019/6/15        | 195.2              |
| Mean             | 197.2              |
| 87–0.025         | 68–0.025           |
| 2017/7/19        | 49.0               |
| 2017/9/17        | 98.5               |
| 2017/11/16       | 125.2              |
| 2018/7/15        | 141.4              |
| 2018/3/28        | 148.0              |
| 2018/5/27        | 168.1              |
| 2018/7/14        | 192.7              |
| 2018/9/24        | 185.9              |
| 2018/11/23       | 188.2              |
| 2019/1/22        | 187.6              |
| 2019/3/23        | 195.2              |
| 2019/6/15        | 197.2              |
| Mean             | 156.4              |
subidence. These results will contribute to the study of subsequent correction methods of SBAS InSAR-monitored mining ground subsidence.

Conclusions

This study presents the first comprehensive evaluation of the application of SBAS InSAR technique in mining subsidence, utilising four multi-temporal differential interferogram series and ground subsidence data from 15 working faces and 260 levelling points at the active Jiyang Coal Mine from May 2017 to June 2019. The major conclusions are as follows:

The number of differential interferograms of multi-temporal differential interferogram series and the coherent threshold values for selecting highly coherent pixels affected the SBAS InSAR-monitored ground subsidence results. When the coherent threshold values were identical, the number of differential interferograms increased, and the number of selected highly coherent pixels increased; thus, SBAS InSAR efficiently reflected the spatial distribution and variation trend of ground subsidence, and its advantages were better demonstrated. However, an excessive number of differential interferograms not only increased the difficulty in data processing, but also introduced more differential interferograms and highly coherent pixels with poor quality, thereby increasing the differences between SBAS InSAR- and levelling-monitored results. When the number of differential interferograms of the multi-temporal differential interferogram series were identical to each other, the coherent threshold values for selecting highly coherent pixels increased, and the number of selected highly coherent pixels decreased; thus, SBAS InSAR could not effectively or comprehensively reflect the spatial distribution and variation trend of ground subsidence, and its advantages were not well demonstrated. However, excessively low coherent threshold values caused SBAS InSAR-monitored ground subsidence or uplift to be inconsistent with the actual situation, particularly in the mild subsidence zones.

The SBAS InSAR could accurately trace the location and spatial distribution of ground subsidence in the mining area. The spatial and temporal variation trends of ground subsidence monitored by Sentinel-1A SBAS InSAR were consistent with the mining information of working faces and successfully reflected the progress of mining. However, for the working faces with relatively severe subsidence and low coherence, the SBAS InSAR technique could not detect sufficient highly coherent pixels to obtain ground subsidence above those faces.

The accuracy of the SBAS InSAR-monitored ground subsidence values was directly related to the severity of ground subsidence and had a certain spatio-temporal variation law. In the relatively severe subsidence zones with low coherence, either the SBAS InSAR technique could not detect sufficient highly coherent pixels to effectively monitor ground subsidence or the SBAS InSAR-monitored subsidence values were substantially less than those of the levelling monitoring, and large differences were evident. In less severe subsidence zones with higher coherence coefficients than the coherent threshold values for selecting highly coherent pixels, the results of SBAS InSAR and levelling monitoring were not significantly different in terms of spatial distribution, variation trend, and numerical values. In the relatively mild subsidence zones, the SBAS InSAR-monitored subsidence values were greater than the levelling-monitored subsidence values, with evident differences, and in some cases SBAS InSAR-monitored subsidence trend was inconsistent with the actual ground subsidence trend.

Our results will help users and researchers to select the number of interferometric pairs and the coherent threshold values for selecting highly coherent pixels when using SBAS InSAR to monitor mining subsidence, and provide a reference for further research on the correction method of SBAS InSAR-monitored mining subsidence results.

Acknowledgments

The authors wish to thank the European Space Agency (ESA) for supplying the free Sentinel-1A SAR images.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research was supported by the National Natural Science Foundation of China under grant nos. 42974009; the Shandong Natural Science Foundation under grant no. ZR2020MD043; no. ZR2020MD044; Natural Science Foundation of Shandong Province [ZR2020MD043, ZR2020MD044].

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