Ground deformation of Dongsheng mining area revealed by multi-temporal InSAR

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Abstract. Coal is one of the most important mineral resources in the industrial development of China. In order to minimize the losses directly or indirectly caused by the ground subsidence, it is necessary to accurately retrieve the information of the ground subsidence distribution during the mining process and make the accurate impact assessment of changes in the ecological environment. In this paper, we selected Sentinel-1A data of 22 scenes from July 2018 to March 2019, which covers Dongsheng coalfield of Ordos, Inner Mongolia. Then, PS-InSAR is used to obtain the ground deformation information. The results show that the PSs with high deformation rate and large accumulation are mainly located in the centre of the focused area, where the velocity along line of sight (LOS) mainly ranges from -17 mm/year to -5 mm/year with the extreme value reaching -33.5 mm/year. Meanwhile the deformation rate of the majority of the PSs ranges from -5 mm/year to 5 mm/year. It is highly recommended to reduce the ground deformation and mitigate the impact of land subsidence on the ecological environment caused by mining through programming logical mining schemes.

1. Introduction

Mineral resources are one of the material bases of national economic construction and social development. With the development of economy and society, the need for all kinds of mineral resources is increasing in China, the largest energy producer and consumer all over the world. The investment in exploration and the annual mining volume are increasing. While producing huge economic and social benefits, long-term and large-scale mining of minerals will form underground mined out areas, which will lead to geological disasters such as landslides, ground subsidence and cracks, which will damage not only roads and buildings, but also infrastructure, and reduce the value of land. In short, it brings a series of problems of production and living safety to the infrastructure and local residents, which threatens the sustainability of local environment and economy [1]. On December 25, 2015, a goaf collapse occurred in the Wanzhuang Yurong gypsum mine area in Baotai Town, Linyi, Shandong Province, resulting in trapping 29 miners working under the mine belonging to Pingyi Yurong commercial trade Co. Ltd. that failed to detect and control the local collapse of the goaf during the long-term shutdown. To put it another way, Yurong commercial trade Co. Ltd. did not
fully perform the monitoring and treatment of the goaf, who was mainly responsible for the accident that causing 1 death and 13 missing, and direct economic loss of 41 million yuan at least.

Therefore, it is urgent to use effective monitoring methods to comprehensively investigate the movement law of mining area for mastering the subsidence situation. It cannot only provide theoretical basis and reference data for the evaluation and effective treatment of mining area settlement, but also bring convenience for ecological management, which is of great significance to the sustainable development of environment and economy of mining area.

In view of the limitations of temporal and spatial decorrelation and atmospheric effect in the application of Differential Interferometric Synthetic Aperture Radar (D-InSAR) technology, people have been trying to optimize the imperfection. At the end of the 20th century, Ferretti, Rocca et al proposed a revolutionary method named permanent scatterers interferometric synthetic aperture radar (PS-InSAR) based on point targets [2], which uses long time series of SAR images covering the same area. Through the analysis of the phase sequence of ground target echo signal, it identifies and extracts the point targets that remain stable for a long time, as well as the permanent scatterers (or PSs). After eliminating the influence of atmospheric phase based on the sparse grid formed by these PSs, it separates the deformation phase sequence in the end.

In 2006, C.Meisina et al used the permanent scatterers technique to detect and monitor the ground deformation in Oltrepo Pavese territory (Northern Italy, southern Lombardia) from 1992 to 2001. The PS-InSAR technique overcomes most of the limitation of conventional interferometric approaches by identifying a set of “radar benchmarks” (PS), where very precise displacement measurements can be carried out [3]. In 2012, P.Daniele et al revealed ground subsidence caused by subway tunnels and highways by analyzing new high resolution SAR data, which had been acquired by the Italian X-band sensor Cosmo-SkyMed, and detecting 1.2 million of individual and independent targets in the Shanghai urban area [4]. In 2018, R.Shamshiri et al used Sentinel-1 data and integrated distributed scatterers (DS) with persistent scatterers to effectively monitor surface displacement [5].

This paper aims to reduce the damage to the ground infrastructure and the natural environment as much as possible by monitoring and analyzing the subsidence of the Dongsheng mining area.

2. Methodology
The basic principle of PS-InSAR is to statistically analyze the stability of the amplitude and phase information of the image with multi scene SAR images in the same area. The target that has the characteristics with strong emissivity and stable scattering is regarded as the PS, such as artificial buildings, roads, exposed rock, artificial angle reflector and other targets that have the superiority of reflective and scattering. Although the geometric size of PS points is much smaller than the spatial resolution unit of SAR image, their backscattering coefficient plays a dominant role in the echo signal of the whole unit, which cannot be affected by the spatial baseline, thus showing satisfactory coherence. Hence, the PS point can be taken as the analysis target, and the phase function model can be established on the high signal-to-noise ratio of time series differential interference [6]. Then, the subsidence circumstance of the target area can be inversed since the deformation information of PS point was obtained.

3. Study area and dataset

3.1. Description of the study area
The study area selected in this paper is the Ordos Basin, which contains more than 50 kinds of mineral resources, such as coal, oil and natural gas. Taking coal as an example, about 87000 km² that is 70% of area of the city contains coal. Shenfu-Dongsheng coalfield, also known as Dongsheng coalfield, is the largest coal field with proven reserves in China, covering an area of 22860 km². The coal storage capacity has reached 230 billion tons, accounting for one sixth of the whole country. The mining area is located in 109°45′0″E-110°40′0″E, 38°50′0″N-39°50′0″N, the northwest of Shaanxi Province and the south of Inner Mongolia, where had been taking shape in a hilly terrain that higher in the middle
and gradually decreasing from south to north. Furthermore, this area is on the Loess Plateau that began to form during the Jurassic century, which has simple structure, stable seam, complete coal types with low gas content, shallow burial that is suitable for the construction of large or super large mines. Besides, the study area has a dry climate and sparse vegetation, which is very suitable for InSAR monitoring of surface deformations.

The long-term and large-scale mineral mining has formed a large-scale mined out area, which has caused the most prominent geological disasters in the city, such as subsidence and subsidence. By the end of 2010, the goaf area caused by coal mining has reached 307 km², and the subsidence area has reached 741 km².

3.2. Dataset
In this paper, a total of 22 scenes of C-band Sentinel-1A Interferometric Wide (IW) swath and VV polarization mode data are adopted to implement to PS-InSAR method. The images are captured along the ascending track No.11 with a 250 km swath at a 5 m × 20 m spatial resolution from July 2018 to March 2019. Preview of the study area is shown in the Figure 1 (the red rectangle indicates the study area), and detailed information is shown in Table 1.

| No. | Date      | Orbit  | No. | Date      | Orbit  |
|-----|-----------|--------|-----|-----------|--------|
| 1   | 20180705  | 022658 | 12  | 20181126  | 024758 |
| 2   | 20180729  | 023008 | 13  | 20181208  | 024933 |
| 3   | 20180810  | 023183 | 14  | 20181220  | 025108 |
| 4   | 20180822  | 023358 | 15  | 20190101  | 025283 |
| 5   | 20180903  | 023533 | 16  | 20190113  | 025458 |
| 6   | 20180915  | 023708 | 17  | 20190125  | 025633 |
| 7   | 20180927  | 023883 | 18  | 20190206  | 025808 |
| 8   | 20181009  | 024058 | 19  | 20190218  | 025983 |
| 9   | 20181021  | 024233 | 20  | 20190302  | 026158 |
| 10  | 20181102  | 024408 | 21  | 20190314  | 026333 |
| 11  | 20181114  | 024583 | 22  | 20190326  | 026508 |

![Figure 1. Preview of the study area.](image-url)
Besides, the three arc-second shuttle radar topography mission (SRTM) digital elevation models (DEM) result from a collaborative effort by the National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA - previously known as the National Imagery and Mapping Agency, NIMA), as well as the participation of the German and Italian space agencies (Figure 2) that contains pixel size of 90 m is adopted.

Moreover, the Google Earth optical image is also used to show the final results and perform the analysis in the area of interest.

4. Results and analysis
Figure 3 shows the distribution map of PSs extracted for the 0.87 coherence threshold. It can be inferred that most of PS points are distributed near the urban area, and most of the point targets are selected as ground markers with strong echo signals, including buildings, roads and exposed rocks in mountainous areas, which are accurate and reliable. As shown in Figure 4, two typical areas are chosen for verification. The ground objects are represented by the point targets in the existing area, but some houses are not recognized.
Combined with the annual deformation rate (Figure 5) and distribution (Figure 6) of PSs, the high-speed moving region is basically located in the middle of the area, and the maximum rate is -33.5 mm/year. The average value of total is -6.81 mm/year while the median is -6.56 mm/year, and the standard deviation is about 6.85 mm/year. Among them, nearly half of the point values are between -5 mm/year and 5 mm/year, and most of PS points are between -17 mm/year and 7 mm/year. In macroscopic analysis, it can be assumed that the point value around 0 is very small and can be ignored.

Figure 5. Annual deformation rate of PSs.  
Figure 6. Histogram of annual deformation rate.

Here, all PSs are taken as the research object, while their longitude and latitude are set as the horizontal and vertical coordinate axes, and the beginning is July 5, 2018. Meanwhile, the cumulative deformation map of the corresponding area in different interval is drawn as Figure 7, in which the coordinates range from 109.9° E - 110.1° E, 39.4° N-39.5° N. It evidences that the accumulation is increasing progressively with the extension of time lag which represents graphically as the colour gradually changes from orange to yellow, green, and indigo blue finally. The maximum subsidence is up to -491.58 mm in the whole monitoring period.

Table 2. Information of selected typical PSs.

| No.   | Longitude (E) | Latitude (N) | Annual deformation rate (mm/year) |
|-------|---------------|--------------|-----------------------------------|
| 83630 | 109.69°       | 39.38°       | -12.24                            |
| 91925 | 109.97°       | 39.43°       | -30.85                            |
| 97268 | 109.98°       | 39.43°       | -30.14                            |
| 105752| 109.98°       | 39.23°       | -18.27                            |
| 113296| 109.71°       | 39.32°       | -13.35                            |
| 114453| 110.09°       | 39.38°       | -17.47                            |

Combined with Google Earth, six typical PSs near mining areas are selected as shown in Table 2. Their cumulative deformation and variation tendency are shown in Figure 8. Obviously, exception of the slight uplift with point 91925 from July 5 to July 29, 2018 and point 113296 from July 5 to July 29, 2018, August 22 to September 3, 2018, in which the annual deformation rate of these PSs is negative, and the accumulation derives a downward trend, that is, the subsidence occurred in the period. Among them, point 91925 has the largest movement reaching -400.07 mm, point 83630 has the slowest change with the rate of -12.24 mm/year and the accumulation amount of -240.18 mm.
5. Summary and conclusions

Traditional measurement methods include geodetic leveling, photoelectric rangefinder measurement and global positioning system measurement. Although they have the advantage of providing accurate deformation information of monitoring points, they also have low density of monitoring points, which is difficult to reflect the overall sliding and settlement laws of the monitoring area. They cannot meet the needs of rapid and time-sensitive monitoring and have high operating costs, long monitoring cycle, low degree of automation and other defects. Compared with the traditional measurement methods, the InSAR shows distinct advantages and unlimited application potential.

Through the PS-InSAR processing, we have retrieved the ground subsidence covering nearly half of the study area, which ranges from -5 mm/year to 5 mm/year. The rate deformation of remaining PSs is relatively high, ranges mainly from -17 mm/year to -5 mm/year, with the extreme value reaching -33.5 mm/year. Among them, the PSs with high deformation rate and large accumulation are mainly concentrated in the central area with the geographic coordinates of 109°54′0″ E - 110°4′21″ E, 39°22′48″ N - 39°29′0″ N.

Combined with the local physical and geographical conditions, we can draw the following conclusions:
(1) According to the division of mining area, layout of roadway and different seam in the mining process, different mining schemes should be formulated reasonably, so as to reduce or eliminate the ground deformation and reduce the impact of land subsidence on the ecological environment caused by mining;

(2) In the view of the features of each mining area, it would be necessary to strengthen the investigation work in every period and prevent potential risks. In order to form an effective prevention and control system, the measures of soil and water conservation, ground subsidence and ecological environment protection should be combined.

(3) Due to the limitations of collecting the field investigation data, the result we obtained has not been verified and it need to be improved in further study.

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