Large Gradient Subsidence Monitoring in Mining Area Based on LuTan-1 SAR Images

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Abstract

Large gradient subsidence induced by coal mining generally results in limited applicability of interferometric synthetic aperture radar technique, and even fails to obtain complete and reliable deformation details for mining area. To solve this problem, the LuTan-1 SAR data with L-band and high spatial temporal resolution were employed for coal mining area deformation monitoring. In order to provide feasible technical solutions for monitoring large gradient deformation in mining areas, the research focus on the application capability analysis of LuTan-1 SAR data to monitor large gradient deformation in typical mining areas. Time series LuTan-1 SAR data of Shanxi Datong mining area from January to May 2023 were obtained. In combination with precise and high-timeliness DEM obtained from the Lutan-1 bistatic formation data, time-series deformation of the mining area was derived based on the InSAR technique. Through the qualitative and quantitative analysis and evaluation with the Sentinel-1 data monitoring results and leveling measurements, the following conclusions are obtained: (1) From January to May 2023, there are four obvious subsidence basins within the monitoring area, and the maximum subsidence reach to -4.1m within four months, which show a typical large gradient deformation feature; (2) The complete deformation details of the mining area was obtained based on the multi-temporal LuTan-1 SAR data. The monitoring results obtained by Sentinel-1 data in the same period presented obvious decoherence phenomenon, and only the subsidence basin margin deformation details was obtained. (3) Combined with the synchronous levelling measurements results of the mining area, the LuTan-1 time series deformation monitoring accuracy is better than 40mm, and the maximum relative error is better than 4%. For the large gradient deformation monitoring of mining area, the complete and reliable subsidence information can be obtained by using multi-temporal LuTan-1 SAR data, which provides effective technical support for the mining subsidence law research and the safety monitoring of mining area.

1. Introduction

Coal plays a significant role in numerous areas of human production, which is one of the most important energy sources in the world. China’s coal production constitutes 46% of the global total, positioning the country at the forefront of coal production worldwide.

Due to the mining activities in coal mine area, large gradient subsidence may be induced. Especially for coal mine areas with thick seams and shallow mining depth, quick and large magnitude subsidence may occurred, even meter levels subsidence per month. Thus serious damage can be induced by the ground subsidence, including ground fissure, equipment and building damage. Therefore, accurate and frequently deformation monitoring for mining area is significant for the safety management of mining activities. There are several methods for deformation monitoring, including levelling measurement, global positioning system (Ma et al, 2012) and remote sensing techniques. However, these traditional methods exhibit several limitations, including heavy workloads, high costs, and low efficiency (Casagli et al, 2023). Furthermore, the monitoring data generated by these technologies are often discrete point information, which pose challenges in comprehensively capturing surface deformation across large spatial and temporal scales (Cai et al, 2023). With advances in technology, interferometric synthetic aperture radar (InSAR) has gradually been adopted in the field of surface subsidence monitoring (Chen et al. 2020; Pawluszek et al. 2021). Due to the low cost and wide area monitoring advantages, remote sensing technique is the useful method for accurate and frequently deformation monitoring. Interferometric synthetic aperture radar is a typical approach for deformation monitoring, especially for slow and small magnitude subsidence. Therefore, different SAR data and InSAR technique were developed. D-InSAR is susceptible to time and space incoherent noise, atmospheric delay, terrain residual phase and other factors in the process of acquiring surface deformation, which seriously restricts the development and application of InSAR technology. In response to the many problems faced by D-InSAR, single-master image time-sequence InSAR technology represented by persistent scatterers InSAR (PS-InSAR) (Ferretti et al, 2000) and multi-master images InSAR technology represented by small baseline subset InSAR (SBAS-InSAR) (Berardino et al, 2002) have been proposed. These time-series InSAR technologies can effectively make up for the shortcomings of the current D-InSAR technology, and lay the foundation for large-scale and low-cost surface deformation monitoring. In addition, in order to solve the problem that time-series InSAR is difficult to obtain the required density of monitoring points in non-urban and less coherent field areas, distributed scatterers InSAR(DS-InSAR) has been proposed, which can improve the number of observation points in the field, and the DS-InSAR technology has gradually become one of the hotspots of domestic and international research in recent years (Ferretti et al, 2011). For mining area subsidence monitoring, the SBAS technique was employed for application.

2. Study Area and Datasets

2.1 Study Area

The research area is located in Datong Coal field in northern Shanxi Province. It is one of the six coal fields in Shanxi Province and the second largest coal production base in China

(Ji et al., 2023) (Figure 1). Datong coal field is located in the northwest region of Datong City. The main landforms of Datong coal field are loess gully region, loess hill terrace region and loess hill gentle slope wind-blown sand region. Due to the shallow depth of the underground coal seam and the large thickness of the coal seam, mechanized mining by fully mechanized caving led to rapid subsidence of the surface, resulting in geological disasters such as ground cracks, landslides and steps, which caused serious damage to the cultivated land, buildings and infrastructure in the mining area (Figure 2).

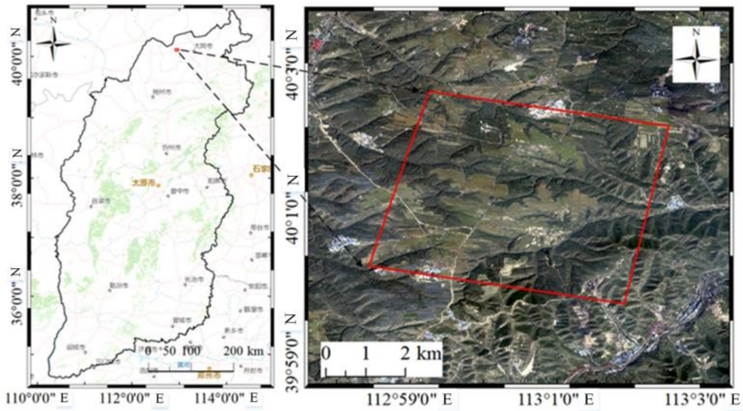

Figure 1. Study area

Figure 2. Land fissures caused by coal mining

The ground fissure was induced by the serious subsidence over the mining area, which damage the agricultural field. The soil moisture content may be also change significant, which may be result in the loss of farmland. Therefore, the subsidence over the mining area have serious damage for infrastructure and farmland.

2.2 Datasets

LuTan-1 SAR satellite is the first bistatic spaceborne SAR constellation for multiple applications in China, which consists of two identical multi-polarimetric L-band SAR satellites. The two satellites have been successfully launched from Jiuquan satellite launch center on 26 January and 27 February 2022, respectively. Due to the precise orbit control and two satellites operating in a common reference orbit with a 180-degree orbital phasing difference, the revisit cycle of LuTan-1 will be reduced from 8 days to 4 days with 350m orbital tube, which ensure the high temporal and spatial coherence for interferometric applications of LuTan-1 data.

In this study, the 22 LuTan-1 SAR images covering the study area are selected as the data source, and the imaging mode is stripmap 2, the images range are 100 km×100 km, and the distance and azimuthal resolution is 1.46 m×4.66 m. The range of the images incidence angle are 24.8°~25.4°, and the polarization mode is HH, and the date of the acquisition of the SAR data is shown in Table1.

In order to quantitatively evaluate the accuracy of surface deformation monitoring in InSAR mining area and provide accurate support for the accuracy of deformation monitoring accuracy in mining area and high-voltage transmission line, the second-class ground measurement was carried out simultaneously in the transit of LT-1 SAR satellite. The on-site measurement photos are shown in Figure 5. Two observation stations along the strike and tilt were deployed in the subsidence area, and the distribution of points is shown in Figure 3. It should be noted that, due to the fact that the surface movement deformation observation station was set up along the road, the line did not completely pass through the center of the hollowing area, but some of the measured points are located in the area of large gradient deformation.

Figure 3. Levelling measurement over the study area.

In order to obtain high-density monitoring points and high-precision large-gradient deformation as much as possible, the distributed point target was extracted by using a baseline combination based on the optimal time coherence, that is, the shortest time baseline. Its spatial and temporal baseline

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combinations are shown in Figure4. The comprehensive consideration of spatial and temporal baselines ultimately selects the eighth period image, which is relatively centered on the temporal and spatial baselines, as the main image, and forms a total of 21 interferometric pairs. The maximum vertical baseline is 913.8 m, and the minimum vertical baseline is -41.1 m. The maximum temporal baseline is 8 days and the minimum temporal baseline is 4 days. The average coherence of all interferometric pairs is up to 0.75, and the average coherence of the interferograms after adaptive filtering is 0.97. The high coherence of the LuTan-1 SAR satellite data is benefited from the longer wavelength of the satellite, the shorter regression period, and the shorter regression radius.

Acquisition time	Satellite	Acquisition time	Satellite
2023/1/16	LuTan-1 A	2023/4/2	LuTan-1 B
2023/1/24	LuTan-1 A	2023/4/6	LuTan-1 A
2023/1/28	LuTan-1 B	2023/4/10	LuTan-1 B
2023/2/1	LuTan-1 A	2023/4/14	LuTan-1 A
2023/2/9	LuTan-1 A	2023/4/18	LuTan-1 B
2023/2/17	LuTan-1 A	2023/4/22	LuTan-1 A
2023/2/25	LuTan-1 A	2023/4/26	LuTan-1 B
2023/3/5	LuTan-1 A	2023/4/30	LuTan-1 A
2023/3/13	LuTan-1 A	2023/5/4	LuTan-1 B
2023/3/21	LuTan-1 A	2023/5/8	LuTan-1 A
2023/3/29	LuTan-1 A	2023/5/12	LuTan-1 B

Table 1. Lutan-1 data for Datong coal mine subsidence monitoring

3. METHODOLOGY

The short baseline set technique (SBAS-InSAR) was first applied for time series deformation monitoring (Berardino et al, 2002) and further refined for multiple applications (Hooper, 2008). This technique is further developed on the basis of D-InSAR technique, which is to form an interferometric combination set of multi-scene SAR data according to a set spatial-temporal baseline, and the method overcomes the incoherence of SAR images due to the large spatial-temporal baseline by decreasing the spatial-temporal baseline threshold. Then the interferometric combination set is solved by least squares estimation to eliminate the error caused by entanglement and reduce the influence of atmospheric interference and other factors, so as to obtain the accurate time-sequence cumulative deformation value of the ground surface. The technical route is shown in Figure 3.

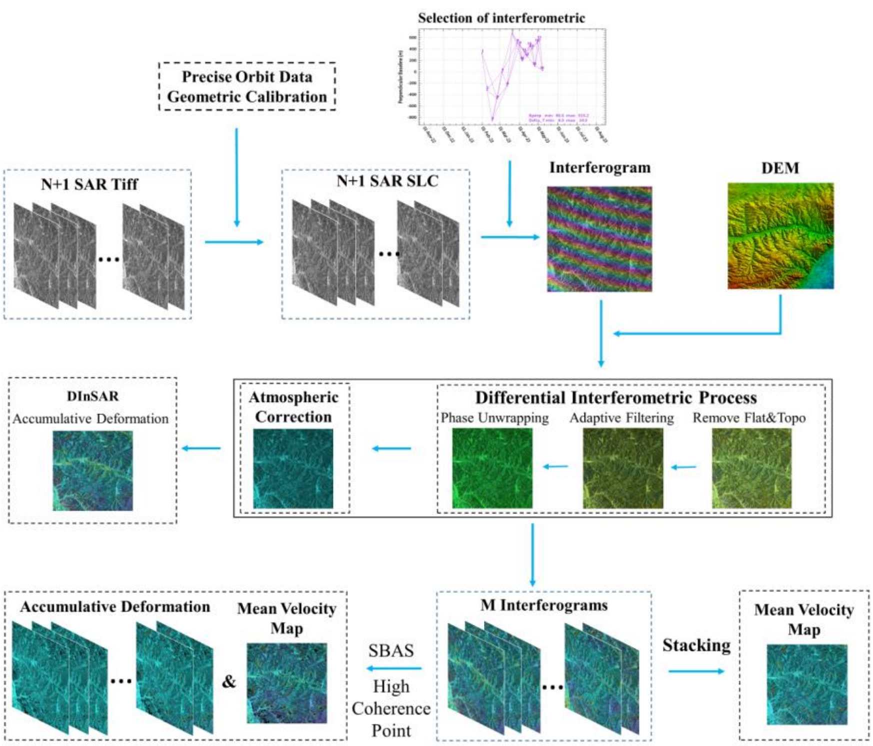

Figure 4. The flow chart of SBAS-InSAR technology

4. Results and Analysis

In order to monitor the deformation information of the transmission line, this study mainly adopts the SBAS-InSAR method to acquire the cumulative subsidence to the study area from January 16, 2023 to May 12, 2023.The cumulative subsidence results are shown in Figure 4. The results show that: (1) There are four obvious subsidence basins in the study area, which are elliptical in shape, in line with the mining subsidence characteristics of the mining area; (2) The density of the acquired monitoring points is high, which is able to reflect the information of the mining subsidence basins better; (3) The maximum cumulative subsidence value of the study area is 3.80 m for four months interval, and the average monthly subsidence is more than 0.96 m, which indicated that serious subsidence was induced over Datong coal mine with thick seams and shallow mining depth; (4) One of the mining subsidence basin B is affected by topographic relief, and partial information in the center of the basin are missing. The whole deformation field was characterised by time serious Lutan-1 SAR data.

In addition, time serious Sentinel-1 SAR data was applied for deformation monitoring over Datong coal mine area, the results were shown as figure 6. There are obvious decoherence phenomenon over the mining area, and the deformation details cannot be obtain in the center of settling funnel. The results may be attributed to the low spatial resolution, C-band SAR signal and long revisit time for the study area. Therefore, the long wavelength SAR data with short revisit time and high spatial resolution is benefit for deformation monitoring, especially for large gradient deformation scenes.

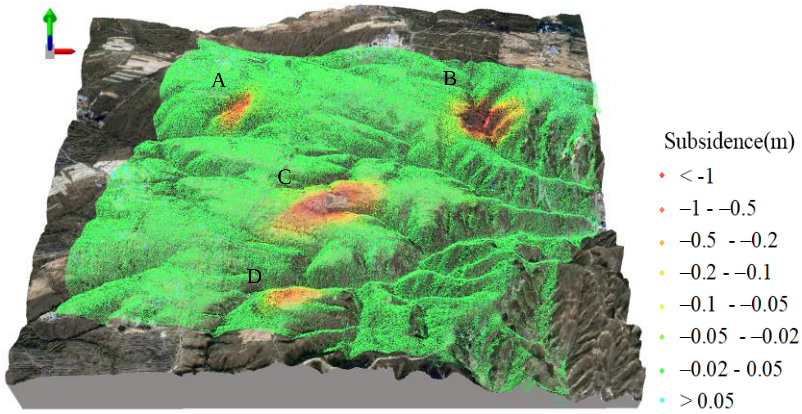

Figure 5. SBAS-InSAR cumulative subsidence monitoring result using Lutan-1 data.

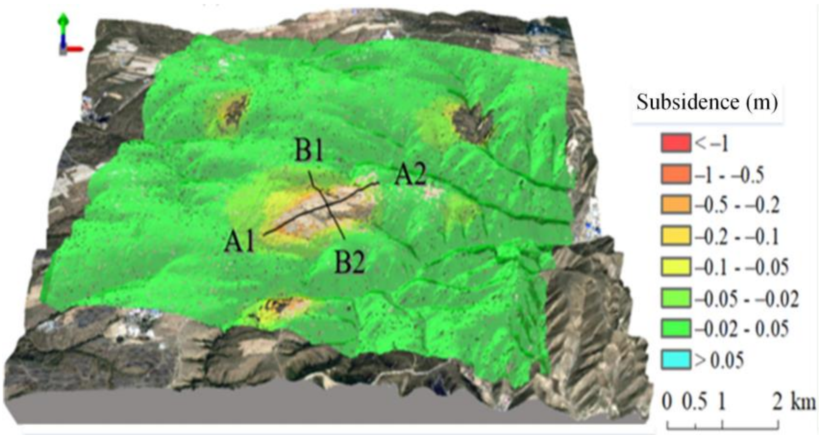

Figure 6. SBAS-InSAR cumulative subsidence monitoring result using Sentinel-1 data.

The time series subsidence results were shown as Figure 7. The dynamic subsidence of mining area was characterised by the multi-temporal Lutan-1 SAR data. The result is consistent with the mining activities. In addition, the maximum deformation can reach to more than 4 meters, which is a typical large gradient deformation scence. With the application of high spatial resolution and temporal resolution Lutan-1 SAR images, the whole subsidence feature was obtained over mining area, which provided an effective approach for large gradient deformation monitoring.

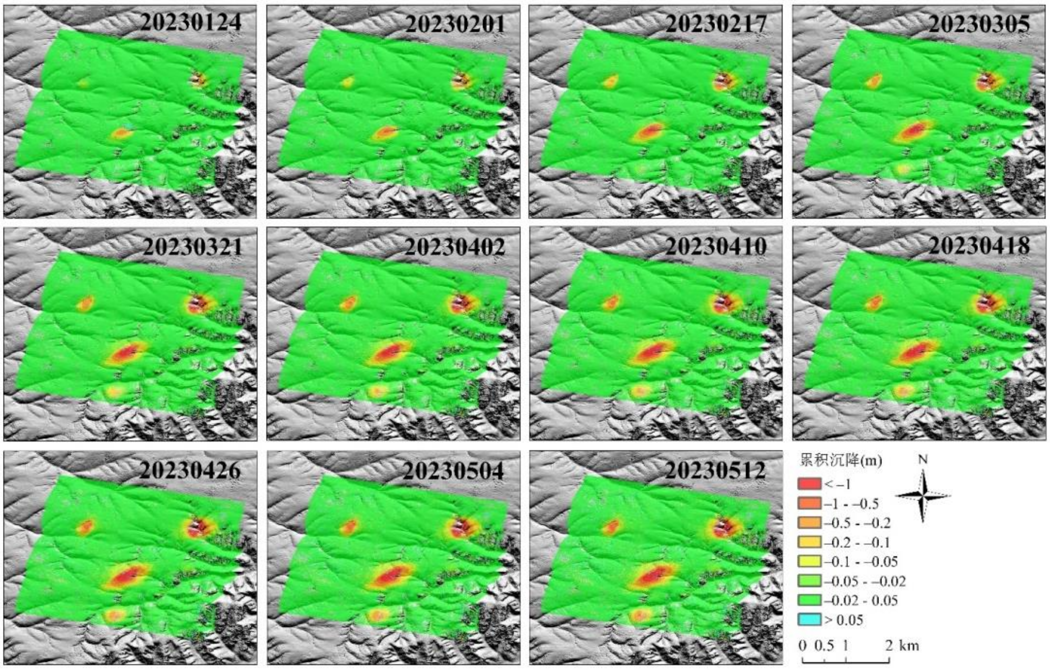

Figure 7. Time series cumulative subsidence of the study area

5. Conclusions

Time series Lutan-1 SAR data was acquired over Datong mining area. Serious subsidence was monitored, which induce ground fissures and farmland damage. Owing to the L-band characteristics and frequently SAR data acquisitions, the entire deformation field was characterised even for large gradient deformation. In comparison with the results obtained by time serious Sentinel-1 SAR data, the long wavelength SAR data with short revisit time and high spatial resolution is benefit for deformation monitoring, especially for large gradient deformation scenes. Through the qualitative and quantitative analysis and evaluation with the Sentinel-1 data monitoring results and levelling measurements, the following conclusions are obtained:

(1) From January to May 2023, there are four obvious subsidence basins within the monitoring area, and the maximum subsidence reach to -4.1m within four months, which show a typical large gradient deformation feature;

(2) The complete deformation details of the mining area was obtained based on the multi-temporal LuTan-1 SAR data. The monitoring results obtained by Sentinel-1 data in the same period presented obvious decoherence phenomenon, and only the subsidence basin margin deformation details was obtained.

(3) Combined with the synchronous levelling measurements results of the mining area, the LuTan-1 time series deformation monitoring accuracy is better than 40mm, and the maximum relative error is better than 4%.

For the large gradient deformation monitoring of mining area, the complete and reliable subsidence information can be obtained by using multi-temporal LuTan-1 SAR data, which provides effective technical support for the mining subsidence law research and the safety monitoring of mining area.

Acknowledgements

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