QUALITY INSPECTION OF SURFACE DEFORMATION MONITORING RESULTS BASED ON PS-INSAR TECHNOLOGY

Wenjuan Mao [1], Jixian Zhang [1], Chang Li [1,] *, Wenchao Gao [1], Jin Zhou [1], Wenjun Xie [1], Yongmin Xu [1]

[1] National Quality Inspection and Testing Center for Surveying and Mapping Products, Beijing, China - 67516521@qq.com

Commission III, ICWG III/IVb

KEY WORDS: Quality inspection, Test parameter, PS-InSAR, Surface deformation monitoring

ABSTRACT:

In view of the problems that the permanent scatterer synthetic aperture radar interferometry (PS-InSAR) technology was limited by the difference of processing algorithms and the professional level of data processing personnel, and its monitoring results were still difficult to fully achieve the theoretical accuracy, a new technical process suitable for the detection of PS-InSAR surface deformation monitoring results was proposed in this paper. Based on the analysis of the characteristics of monitoring results, the inspection work was carried out by means of overall inspection. The test parameters, test objects and test items to be tested, as well as the test methods of different test parameters were determined; The key links of PS-InSAR surface deformation monitoring data processing were analyzed in detail, and the technical flow of mathematical accuracy detection was given. Finally, the quality detection of surface deformation monitoring results based on PS-InSAR technology of 3000 square kilometres were carried out, the results showed that the proposed technical route was feasible and quality evaluation result was objective.

1. INTRODUCTION

Traditional surface deformation monitoring methods are based on precision levelling, GPS technology, and radioactive layered standard monitoring technology. These methods have the technical characteristics of high time resolution and high precision; however, traditional monitoring technologies only perform observations and coverage of discrete points. The low degree of monitoring, high monitoring results and long cycle restrict the improvement of service efficiency. As an emerging space geodetic measurement technology(FERRETTI, 2000), the permanent scatterer synthetic aperture radar interferometry (PS-InSAR) technology is a surface deformation monitoring method developed on the InSAR technology, which can obtain a larger range of monitoring data and reduce the monitoring workload and the acquired monitoring data can represent the overall deformation information of the monitoring area, which can effectively make up for the shortcomings of small levelling coverage, sparse GPS points and difficult access to ground investigation. Therefore, it is widely used in urban surface deformation monitoring, monitoring along high-speed railways, and mining subsidence monitoring. It has broad development potential and application prospects. For the PS-InSAR method, when the amount of data is greater than 25-30 scenes, the sedimentation rate can theoretically reach 0.1-0.5mm/a. However, in the actual work process, PS-InSAR technology is subject to the differences in processing algorithms and the professional level of data processing personnel, and the monitoring results are currently difficult to fully achieve theoretical accuracy; Whether the monitoring accuracy of this method can meet the basic needs of urban deformation monitoring is also an important factor restricting the popularization and use of this technology(Ge, 2013).
By analyzing the key links in the process of surface deformation monitoring data processing, based on the actual detection work, this paper puts forward a set of process and method suitable for the quality detection of PS-InSAR surface deformation monitoring results.

2. QUALITY INSPECTION CONTENTS AND METHODS

Referring to the Specifications for quality inspection and acceptance of surveying and mapping products (GB/T 24356-2009), based on the analysis of the characteristics of surface deformation monitoring results, an integrated inspection method is proposed to carry out the detection work; According to the Technical specification for ground subsidence Interferometric Radar Data Processing (DD 2014-11) of the geological survey of China Geological Survey, the quality detection of PS-InSAR surface deformation monitoring and processing results mainly includes 12 detection items of 3 detection parameters, such as the integrity of data, the conformity of data processing process and the reliability of mathematical accuracy.. The specific test contents and methods are shown in Table 1.

Serial number	Detection parameters	Detection object	Detection item	Detection method
1	Integrity of data	SAR data quality	Consistency between SAR data and design requirements	Verification analysis
			Data integrity of repeat pass InSAR	
			Quality of amplitude image	

*Chang Li, National Quality Inspection and Testing Center for Surveying and Mapping Products, Beijing, China - 554895951@qq.com

Serial number	Detection parameters	Detection object	Detection item	Detection method
		Auxiliary data quality	Integrity of terrain data	Verification analysis Comparative analysis
			Consistency of terrain data	
			Completeness of ancillary data	
2	Compliance of data processing process	Spatial reference system	Consistency with design document	Verification analysis
		Data processing workflow	Consistency with design document	
			Integrity of data processing flow	
		statistical information	Integrity of settlement statistics	
		Analysis data	Integrity of settlement monitoring results analysis	
3	Reliability of mathematical accuracy	Data accuracy verification	Evaluate the accuracy of InSAR land subsidence monitoring results	Verification analysis Field investigation

Table 1. Contents and Test Methods of the Deformation Monitoring Result of PS-InSAR

2.1 Verification analysis

Verification analysis method is to detect the internal characteristics of the tested data, which detects SAR data, repeat pass InSAR data, amplitude image map, settlement statistical results, such as the quality of SAR data, the quality of auxiliary data, statistical data, accuracy verification, etc. For the reliability inspection of data accuracy, the key parameter test method is mainly used to verify the surface deformation trend of InSAR by using the first and second order levelling settlement observation data according to the requirements of Specifications for the first and second order levelling in China (GB/T 12897-2006) and the technical design document of the project.

2.2 Comparative analysis

In the production process, various reference data such as the type, quality, accuracy and quantity of auxiliary data are compared to determine whether the tested data is complete or to obtain the difference between the tested data and the reference data. ① Check the integrity and consistency of terrain data to determine whether there is data range and whether it meets the technical design requirements; ② Check the cloud coverage of optical remote sensing image data, whether the data is missing, whether the hue is consistent, etc. That is, human-computer interaction is used to check whether the data quality of optical remote sensing image meets the technical design requirements; ③ Confirm the accuracy of track data; ④ Confirm whether the accuracy grade of the level reference data meets the requirements of the design document.

2.3 Field investigation

Field investigation method refers to comparing the result data with the field measurement results through field measurement or investigation to determine whether the settlement trend of the tested data is consistent with the field measured data. This method is applicable to the inspection of actual measurement, such as whether there is topographic change through field inspection. The settlement characteristics of severe surface deformation area can usually be characterized by the dislocation and fracture of buildings and structures.

3. TECHNICAL PROCESS

In order to carry out the detection of surface deformation monitoring data processing results, the method of integrity inspection is adopted. Firstly, the data audit method is used to detect the SAR data quality and auxiliary data quality until it meets the design requirements; Secondly, check whether the operation process is consistent with the technical requirements from the technical point of the production process of data processing, and check whether the spatial reference system, statistical data and analysis data are consistent with the design requirements. Finally, the mathematical accuracy detection is carried out, and the surface deformation trend of InSAR is verified by using the first and second order levelling settlement observation data. The technical route for quality inspection of surface deformation monitoring and processing results is shown in Figure 1.

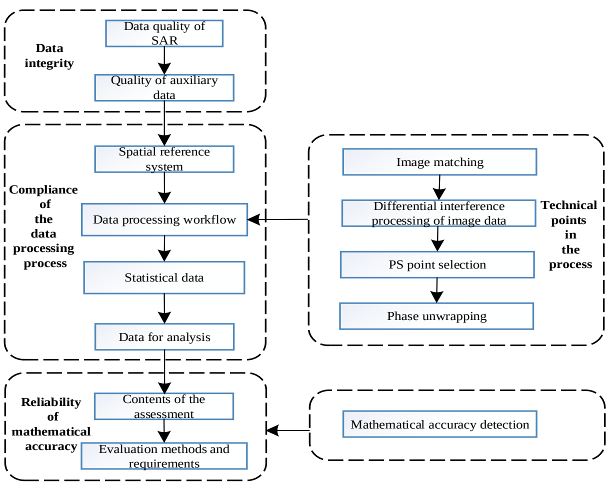

Figure 1. The Technical Route of Quality Inspection of the Deformation Monitoring Result of PS-InSAR

3.1 Integrity of data

The integrity inspection of data mainly adopts the methods of verification analysis and comparative analysis. Check whether

https://doi.org/10.5194/isprs-annals-V-3-2022-597-2022 |

the quality of SAR data is consistent with the requirements of the design document, whether the quantity of repeat pass InSAR data is missing, and whether the quality of amplitude image meets the design requirements; Check whether the topographic data is complete during the project, whether the topographic data is consistent with the sample area, and whether the auxiliary data are complete (DD2014-11, 2014).

3.2 Compliance of data processing process

The compliance inspection of data processing process mainly adopts the method of on-site verification and analysis, Check the consistency between the operation flow of SAR data processing and the requirements of the design document, and check the integrity of statistical data and analysis data.

PS technology was proposed by Ferretti in 1999. The technical principle of this method is as follows: firstly, select one of all SAR images as the main image and the rest as the sub image. The sub image is registered with the main image to obtain the registered SAR image and interference pair. Secondly, based on the known DEM data, the differential interference processing is carried out on the interference pair to obtain the differential interference phase of each PS point in the study area. Thirdly, according to the surface deformation in the study area, combined with the physical and statistical characteristics of each component of interference phase, a phase composition model based on differential interference phase, elevation error and surface deformation is established. Finally, the relevant algorithm is used to solve the model, so as to obtain the elevation error and surface deformation information of each PS point (FERRETTI, 2000).

3.2.1 Image registration: Image registration is the basis of surface subsidence analysis. It is to register the main image and sub image covering the same monitoring area, that is, to obtain the displacement between different pixels in the process of main and sub image registration. After coordinate conversion and re sampling, a small number of feature points are selected from the main and sub images to match the pixels with the same name in the image. With the help of the matching algorithm, enough pixels with the same name in the research area can be obtained, so as to realize the image registration and lay a foundation for the subsequent extraction of surface subsidence information. The flow chart of image registration is shown in Figure 2.

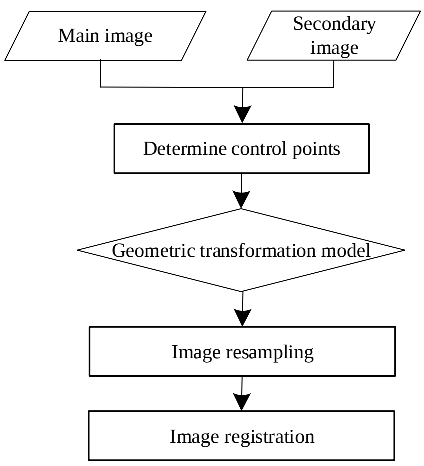

Figure 2. The image registration flow diagram

All images register the main image; During the main image registration, the azimuth and distance errors are required to be less than 0.25 pixels, and the homonymous points of the registration polynomial shall be evenly distributed on the whole image.

3.2.2 Selection of PS points: The selection of PS points is the key link of PS-InSAR technology. The technical flow chart of PS point target selection is shown in Figure 3. PS interference phase model is suitable for pixels with stable phase in time sequence. It is necessary to select relatively stable scattering points in SAR image before PS interference processing, Such as PS point targets with strong stability and good coherence. When selecting PS point targets, amplitude dispersion method, signal-to-noise ratio and other methods can be used. Combined with the types of surface features in the monitoring area, one or more methods should be selected to establish corresponding mathematical models to phase unwrapping the selected PS points with strong stability and high coherence, so as to obtain the contribution of different factors to surface settlement, which can be converted into the deformation information of each pixel point.

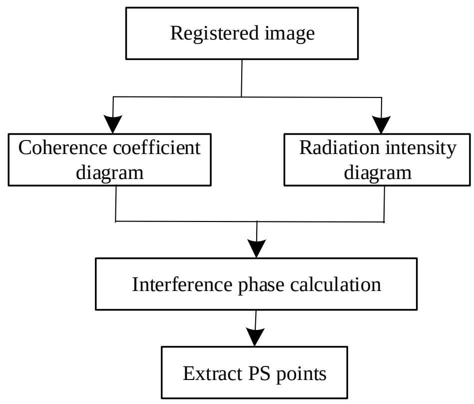

Figure 3. Technical flow chart of PS point selection

3.2.3 Differential interference calculation: The image data differential interference processing of PS-InSAR technology is to perform time series interference processing on the registered image to obtain the interference atlas based on time series. Then, the terrain phase is proposed by using the external high-precision DEM data to generate the differential interferogram in time sequence. Use visual inspection to check whether each scene differential interferogram contains residual interference fringes more than half a wavelength. The technical flow of differential interference processing of image data of PS-InSAR is shown in Figure 4.

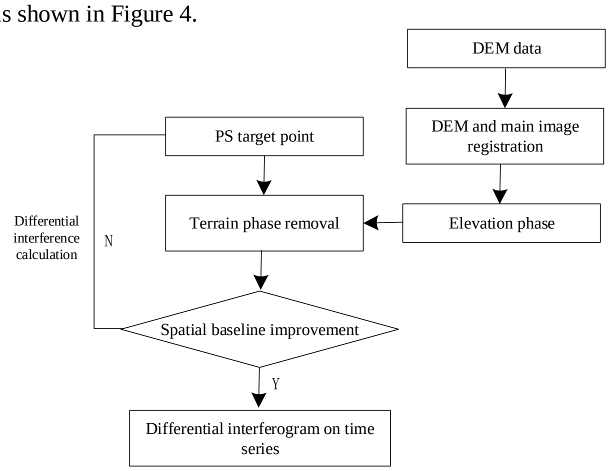

Figure 4. Flow chart of differential interference processing

3.2.4 Phase unwrapping: The phase unwrapping of PS-InSAR technology is based on the matrix grid established by PS points. Its object is mainly the sparsely distributed and independent PS point targets on the matrix. The phase unwrapping method of PS-InSAR generally adopts two-dimensional unwrapping method for phase unwrapping. The process is as follows: calculate the phase difference between adjacent pixels and carry out low-pass filtering in the time domain to weaken the influence of atmospheric delay between image time series; The phase principal value of the filtered phase difference is calculated and integrated to unwrap the phase difference in time dimension.

Generally, the quality of InSAR phase unwrapping results can be evaluated by a simple visual discrimination method, and the overall effect can be seen from the unwrapping diagram[16]. The flow chart of phase unwrapping is shown in Figure 5.

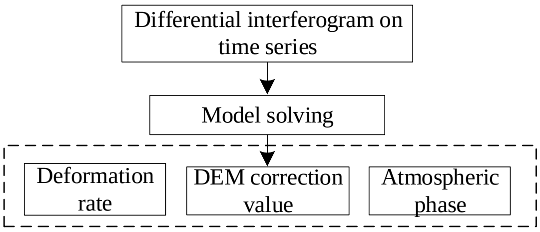

Figure 5. Flow chart of phase unwrapping

3.3 Accuracy verification

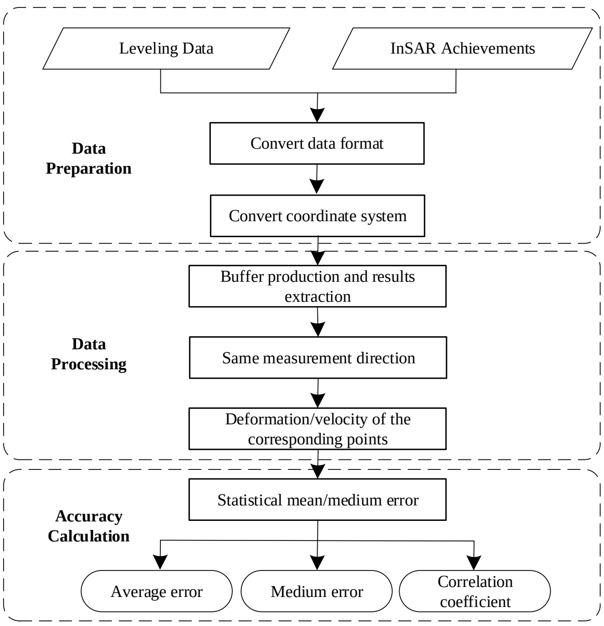

Figure 6. The Technical Route of Quality Inspection of the Mathematic Precision

For the surface deformation monitoring results obtained by PS-InSAR technology, the accuracy is generally evaluated by fixed-point comparison with the high-level measurement data obtained in the same period. Because PS-InSAR technology obtains the deformation information on the pixels of highly coherent targets in the image coverage area, the spatial positions of these targets and benchmarks are generally not completely consistent (Cai, 2020). In order to ensure the objectivity and accuracy of the evaluation results, the representative values within a certain range of PS-InSAR results are compared with the high-level measurement results, that is, find the stable high coherence target (PS point) within a certain buffer, and evaluate the accuracy of the representative values of all the stable high coherence target InSAR results found with the high-level measurement points, The accuracy of InSAR land subsidence monitoring results is evaluated according to the difference between them (Zhang, 2014). The flow chart of mathematical accuracy detection technology is shown in Figure 6.

In the data preparation stage, the number of surface deformation measurement points (pairs) that meet the accuracy detection requirements shall not be less than 15 groups. Firstly, the InSAR results in the same period which are basically consistent with the leveling observation date are extracted, and the InSAR and leveling measurement results are uniformly projected to the accurate WGS-84 coordinate system to realize the unification of spatial datum; Secondly, in the data processing stage, considering that the deformation results obtained by PS-InSAR technology are the changes of the target along the radar line of sight, when comparing and analyzing them with the level monitoring results, it is necessary to convert them into vertical land subsidence according to a certain projection relationship and unify the measurement directions of the two; Finally, the inverse range weighted interpolation method is used to interpolate the InSAR measurement results to obtain the distribution map of land subsidence rate. The difference between the leveling subsidence rate in each period and the InSAR subsidence rate in the corresponding period is obtained for accuracy evaluation. The main index algorithms are as follows:

3.3.1 Mean square: Using the mean square error as the index, assuming that the precision leveling result is the true value and the settlement measured by PS-InSAR is the observed value, the unbiased estimation of the mean square error of the difference between the leveling observation value and PS-InSAR measurement value is the index to test the PS-InSAR measurement accuracy. The calculation formula of mean square error is:

$$m_0 = \pm\sqrt{\frac{[\nu\nu]}{n-1}} \tag{1}$$

$$[\nu\nu] = \sum_{i=1}^{n}(dI_i - dL_i)^2 \tag{2}$$

Where: n -- number of samples;

dL_i and dI_i are the leveling observation value corresponding to the sample point and the InSAR observation value respectively.

3.3.2 Correlation coefficient: The correlation coefficient is used to test the correlation between PS-InSAR and levelling results. The calculation formula of correlation coefficient ρ is:

$$\rho = \frac{n\sum_{i=1}^{n} dL_i dI_i - \sum_{i=1}^{n} dL_i \bullet \sum_{i=1}^{n} dI_i}{\sqrt{n\sum_{i=1}^{n} dL_i^2 - \left(\sum_{i=1}^{n} dL_i\right)^2} \bullet \sqrt{n\sum_{i=1}^{n} dI_i^2 - \left(\sum_{i=1}^{n} dI_i\right)^2}} \tag{3}$$

Where: n -- number of samples;

dL_i and dI_i are the levelling observation value corresponding to the sample point and the InSAR observation value respectively.

3.3.3 Precision index: The correlation coefficient is greater than 0.7, and the evaluation shows that the accuracy of InSAR results is reliable and the data is credible. The mean square error limit is 5mm/y (DD2014-11, 2014).

4. CASE ANALYSIS

The study area is located in the settlement area of a large city, with an area of about 3000 square kilometers. It is an important business center; The above ground road facilities are advanced, the high-rise buildings are dense, and the underground loop traffic roads extend in all directions. At the same time, 5 leveling lines are covered in the area, and the leveling network is re measured and monitored regularly every year.

4.1 Overview of inspected results

In this experiment, 53COSMO-SkyMed satellite images covering the area were used, with a time span of October 2015 to August 2019. The image was obtained by the satellite constellation jointly developed by the Italian Space Agency and the Ministry of defense. The imaging mode is HIMADE strip mode, and the ground resolution is 3M × 3M, the planned mode is HH, and the incident angle is 20.06 °. After processing and analysis of InSAR image technology, PS point position and settlement information are formed, including 53 phases (from October 2015 to August 2019) of original SAR image data, InSAR surface deformation monitoring vector results in the monitoring area and analysis report results.

4.2 Test contents and methods

The project results in the test area are tested from the integrity of data, the consistency of data processing process, the reliability of mathematical accuracy and so on.
For the integrity inspection of data, the data audit method is mainly used. For the compliance inspection of data processing process, the methods of on-site verification and data audit are mainly used. For the reliability inspection of data accuracy, the method of key parameter test is mainly used. According to the requirements of China's national code for first and second order leveling (GB/T 12897-2006), the surface deformation trend of InSAR is verified by using two second-order leveling settlement observation data in the East (from August 2019 to September 2020) and the West (from September 2019 to August 2020).

4.3 Quality test results

After testing the project results in the test area, the data in the sample area are complete, the data processing process meets the technical design requirements, and the surface deformation trend of InSAR is basically consistent with that of the two second-class levels. The inspection results of data integrity and data processing process compliance are shown in Table 2 and Table 3.

Serial number	Detection object	Detection item	Detection result
1	SAR data quality	Consistency between SAR data and design requirements	Conformity
		Data integrity of repeat pass InSAR	Conformity
		Quality of amplitude image	Conformity
2	Auxiliary data quality	Integrity of terrain data	Conformity
		Consistency of terrain data	Conformity
		Completeness of ancillary data	Conformity

Table 2. The inspection results of data integrity

Serial number	Detection object	Detection item	Detection result
1	Spatial reference system	Consistency with design document	Conformity
2	Data processing workflow	Consistency with design document	Conformity
3		Integrity of data processing flow	Conformity
4	statistical information	Integrity of settlement statistics	Conformity
5	Analysis data	Integrity of settlement monitoring results analysis	Conformity

Table 3. The inspection results of data processing process compliance

For the reliability inspection of data accuracy, there are 71 benchmark points in the monitoring area from 2015 to 2019, excluding 1 gross error, and there are 70 points for accuracy evaluation. The accuracy evaluation results of the monitoring area are as follows: from October 2015 to August 2019, the average error is ±2.60mm/yr, the mean error is ±3.76mm/yr, and the correlation coefficient is 0.994. The interval rate verification in the monitoring area is shown in Figure 7. From this figure, it can be seen that the trend of PS point deformation rate and horizontal verification deformation rate in the study area is basically the same.

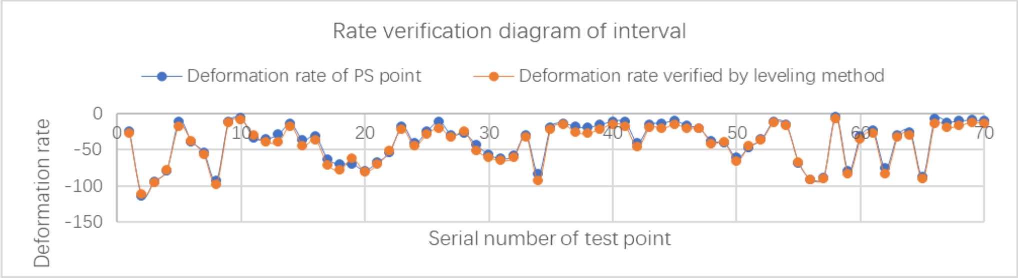

Fig.7 The Interval Rate Verification

5. CONCLUSION

Based on the analysis of the characteristics of surface deformation monitoring results, this paper puts forward an overall inspection method to carry out the quality detection of PS-InSAR surface deformation monitoring results from three aspects: the integrity of data, the consistency of data processing process and the reliability of mathematical accuracy. Through the detection of PS-InSAR surface deformation monitoring results in the study area, the data in the sample area are complete, the data processing process meets the technical design requirements, and the InSAR surface deformation trend is basically consistent with that of a second-class level. The results show that the technical route proposed in this paper is feasible and the quality evaluation results are objective.

REFERENCES

Cai, T.L., Gong, X.L., Lu, Yi, et al. Accuracy Assessment and Multi-source Data Validation of In-SAR in Jiangsu Coastal Area[J]. *Remote Sensing Technology and Application*, 2020, 35(6): 1426-1435.

China Aero Geophysical Survey and Remote Sensing Centre for Land and Resources. DD2014-11 Technical Specification for Data Processing of Land Subsidence Interference Radar[S]. *Beijing: China Geological Survey*, 2014.

FERRETTI A, Prati C. Rocca F. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry[J]. *IEEE Transactions on Geoscience and Remote Sensing*, 2000, 38(5): 2202-2212.

Ge, D.Q. Research on the Key Techniques of SAR Interferometry for Regional Land Subsidence Monitoring[D]. *Beijing: China University of Geosciences*, 2013.

General Administration of Quality Supervision, Inspection and Quarantine of P.R.C., Standardization Administration of P.R.C.. GB/T 24356-2009, Specifications for inspection and acceptance of surveying and mapping achievements[S]. *Beijing: Standards Press of China*, 2009.

He, Ping. Error Analysis and Surface Deformation Application of Time Series InSAR[D]. Wuhan: Wuhan University, 2014.

Lei, K.C., Jia, S.M., Chen, B.B., et al. Land Subsidence Detection based on PS-InSAR in Langfang[J]. *Remote Sensing Technology and Application*, 2013, 28(6): 1114-1119.

Li, G.Y., Zhang Rui., Liu G.X., et al. Land subsidence and analysis over Beijing-Tianjin-Hebei area based on Sentinel-1A TS-DInSAR[J]. *Journal of Remote Sensing*, 2018, 22(4): 633-646.

Li, Lu, Hong, Y.T, Study on ground subsidence monitoring based on PS-InSAR technique in Taiyuan City[J]. *Mine surveying*,2020, 48(4) : 51-56.

Li, Xing, Chen, X.T. Deformation monitoring of reclamation area based on PS-InSAR in Caofeidian[J]. *Mine Surveying*. 2020, 4848(4): 42-46.

Sun, Y.Z., Ding, Dong, LI, G.X., W, Rui, Liang, Z.H. Monitoring methods of seawall deformation based on multisource observation technology[J]. *Marine Sciences*. Vol.45, No.3 2021.

Zhang, Jian, He, B.G., Liu, T.M., et al. Surface subsidence monitoring of Lanzhou downtown area based on time series InSAR technology[J]. *Science of Surveying and Mapping*, 2021, 46(1): 99-107,161.

Zhang, Y.H., Li, M.J., Wu, H.A., et al. Ground subsidence monitoring over full territory of Jiangsu province with InSAR[J]. *Science of Surveying and Mapping*, 2019, 44(6): 114-120.

Zhao, Feng, Wang, Y.J., Yan, S.Y. Analysis of the Reliability and Subsidence Gradient for the Subsidence Monitoring Result of Time-series InSAR[J]. *Remote Sensing Technology and Application*, 2015, 30(5): 969-979.

Zhu, J.J., Li, Z.W., Hu, Jun. Research progress and methods of InSAR for deformation monitoring[J]. *Acta Geodaetica et Cartographica Sinica*, 2017, 46(10): 1717-1733.

Zhang, Jing. Study of Quality Control on InSAR Time Series Monitoring and Application[D]. *Xi'an：Chang'an University*, 2014.