Land surface displacement geohazards monitoring using multi−temporal InSAR techniques

LIU Guang[1], ZBIGNIEW Perski[2], STEFANO Salvi[3], BENNI Thiebes[4], WU Lixin[5], FAN Jinghui[6], BAI Shibiao[7], WEI Lianhuan[5], YAN Shiyong[8], SONG Rui[9], CHRISTIAN Bignami[3], CRISTIANO Tolomei[3], SCHNEIDERBAUER Stefan[10], JOAQUIM JoãoSousa[11,12]

1. Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing 100094, China;
2. Carpathian Branch, Polish Geological Institute − National Research Institute, 1 Skrzatow St., 31−560 Cracow, Poland;
3. National Institute of Geophysics and Volcanology, Via di Vigna Murata, 605 − 00143 Roma, Italy;
4. German Committee for Disaster Reduction, Kaiser−Friedrich−Str. 13, 53113 Bonn, Germany
5. School of Resources and Civil Engineering, Northeastern University, Shenyang 110819, China;
6. Division of Remote Sensing for Environment, China Aero Geophysical Survey & Remote Sensing Center for Natural Resources, Beijing 100083, China;
7. School of Marine Science and Ocean Engineering, Nanjing Normal University, Nanjing 210046, China;
8. School of Environment Science and Spatial Informatics, China University of Mining and Technology, Xuzhou 221116, China;
9. Mullard Space Science Laboratory Department of Space and Climate Physics, University College London Holmbury St. Mary Dorking Surrey RH5 6NT, UK
10. Eurac Research, Viale Druso, 1, Drususallee 1 39100 Bolzano, Bozen − Italy
11. School of Science and Technology, University of Trás−os−Montes e Alto Douro, 5000−801 Vila Real, Portugal
12. Centre for Robotics in Industry and Intelligent Systems (CRIIS), INESC Technology and Science (INESC−TEC), 4200−465 Porto, Portugal

Abstract: China has been affected by some of the world's most serious geological disasters and experiences high economic damage every year. Geohazards occur not only in remote areas but also in highly populated cities. In the framework of the DRAGON-4 32365 Project, this paper presents the main results and the major conclusions derived from an extensive exploitation of Sentinel-1, ALOS-2 (Advanced Land Observing Satellite 2), GF-3 (GaoFen Satellite 3), and latest launched SAR (Synthetic Aperture Radar), together with methods that allow the evaluation of their importance for various geohazards. Therefore, in the scope of this project, the great benefits of recent remote sensing data (wide spatial and temporal coverage) that allow a detailed reconstruction of past displacement events and to monitor currently occurring phenomena are exploited to study different areas and geohazards problems, including: surface deformation of mountain slopes; identification and monitoring of ground movements and subsidence; landslides; ground fissure; and building inclination studies. Suspicious movements detected in the different study areas were cross validated with different SAR sensors and truth data.

Key words: Dragon-4 project; Sentinel-1; GF-3; landslide; geohazards; InSAR

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1 INTRODUCTION

China has been affected by some of the world's most serious geological disasters and experiences high economic damage every year. Ground deformations are frequent and widely distributed for the Chinese territory (Kampes, et al. 2001; Fan, et al. 2011a; Perissin & Wang 2011; Yue, et al. 2011; Liao, et al. 2011; Liu, et al. 2013, 2016) and cause geohazards in mountainous and urban regions. These extreme events commonly cause casualties and property damages. Therefore, continuous monitoring of rapidly moving and detection of potential threats is essential. Traditional ways of ground deformation monitoring are based on ground measurement techniques, such as optical leveling and GNSS (Global Navigation Satellite System) monitoring (Gili, et al. 2000; Calcaterra, et al.

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First author biography: LIU Guang (1979—), male, Professor, E-mail: liuguang@radi.ac.cn

2010). However, those ground based approaches only retrieve deformation values on discrete measurement points (Nakagawa, et al. 2000; Khan, et al. 2010). In order to obtain the overall deformation distribution over large areas, a remote sensing-based approach is necessary. Current availability of numerous SAR (Synthetic Aperture Radar) sensors on board of satellites, and the corresponding large amount of image data, TS-InSAR (Time Series Interferometry SAR) has been demonstrated to be the only imaging remote sensing technology able to monitor deformation from space with millimeter accuracy (Ferretti, et al. 2001; Adam, et al. 2004; Hilley, et al. 2004). The combination of ground displacement (or velocity) estimates from ascending and descending satellite passes, imaging the same ground element from two widely different angles, allows to derive also the Up and East components of the deformation and can help to fill gaps in the occlusion and layover areas caused by the side-looking geometry of SAR sensors. Besides, the availability of a multi-sensor and multi-angle coverage can provide additional constraints for an optimal numerical modeling of the ground motions.

Indeed, TS-InSAR analysis approach mainly including PS-InSAR (Persistent Scatter InSAR), SBAS-InSAR (Small BAselines Subset InSAR) and DS-InSAR (Distributed Scatter InSAR) ich have been widely used in the earth surface deformation extraction (Ferretti, et al. 2000, 2011; Berardino, et al. 2002) and presented an efficient approach for various geohazards, with emphasis to landslide hazard, risk management and disaster prevention (Fan, et al. 2011b; Perissin and Wang 2011; Zhao, et al. 2012; Yan, et al. 2013, 2015; Guo, et al. 2014; Liu, et al. 2015, 2016; Novellino, et al. 2017; Dong, et al. 2018; Zhang, et al. 2018). For the mapping of landslides and other geohazards and the evaluation of their activity, SAR data and multi temporal SAR interferometry and SAR tomography are good techniques. However, high-resolution image matching, data modeling and assimilation technology are extensively used as well.

This study, carried out on the scope of Dragon-4 32365 project, draws on the exploration of the vast amount of remote sensing SAR data to better characterize different geohazards phenomena. Landslide hazard and land subsidence will deserve the main focus. There are four study areas (Fig. 1), including (1) Beijing South research area, covering Beijing and south region of Beijing. The Sentinel-1 TOPS (Terrain Observation by Progressive Scans) IW (Interferometric Wide Swath) full resolution full swath SAR data was processed with SBAS method, and the GF-3 (GaoFen Satellite 3) SAR time series results were used for cross-validation; (2) Liaoning Province research area, located in a quadrangular area linking four traditional heavy industrial cities (Benxi, Anshan, Shenyang, Fushun - BASF district) in the Liaoning Province, Northeast China. The COSMO-SkyMed stripmap images covering Shenyang city were processed using the SBAS approach; (3) Danba County landslide, located in Sichuan province with complex weather and large undulation topography. The C band ENVISAT ASAR and L-band ALOS PALSAR were studied with PS+DS method, and compared with results provided by ALOS-2 PALSAR-2 data; and (4) Maoxian County, located in the northwest of Sichuan Province and southeast of Aba Tibetan and Qiang Autonomous Prefecture on the southeastern edge of the Qinghai-Tibet Plateau. In 2017 a collapse occurred on high mountain slope, resulting in river blockage of 2 km and burial of more than 100 people. The Sentinel-1 data were used in this particular study.

The latest SAR sensor including the X, C and L bands data from DLR (Deutsches Zentrum für Luft- und Raumfahrt), JAXA (Japan Aerospace Exploration Agency), ESA (European Space Agency) and CNSA (China National Space Administration) were exploited. The ESA Sentinel-1, in the TOPS IW mode time series InSAR, is able to simultaneously monitor areas bigger than of 5×10^5 square kilometers which is five times the area of traditional C band SAR data, and its high resolution SAR image can effectively obtain the overall movement information of landslide. The results provided by different SAR sensors interferometry measurements were cross-validated and the results demonstrated the powerful capability of time series InSAR technique for landslide and subsidence monitoring.

Fig.1 Location of the four key study areas used in this project

2 DATASETS AND METHODOLOGY

2.1 Datasets

Copernicus Sentinel-1 TOPS IW mode images, acquired in 2017, were used for monitoring the subsidence due to underground water extraction in Huabei plain around the Beijing City. A stack of 17 images covering Beijing city and its southern region of about 250 km×200 km was explored by the SBAS technique (Berardino, et al., 2002), and in the meanwhile 5 GF-3 images, covering Beijing city, were acquired and also processed with SBAS technique. Finally, the two sets of results were compared.

Two descending stacks of COSMO-SkyMed stripmap SAR images, covering Shenyang city, were processed using the SBAS technique. A stack of 18 images, from March 2016 to April 2017, covering eastern Shenyang, and a stack of 15 images, from March 2016 to April 2017, covering western Shenyang, were processed.

Regarding the monitoring of Danba landslide, a total of 9 C-band ENVISAT ASAR images, from August 2007 to June 2008, and 16 L-band ALOS PALSAR, from February 2007 to January 2011, were processed. Moreover, 35 scenes of IW ascending sentinel 1 SAR images, from November 2015 to September 2017, were also used.

For MaoXian landslide monitoring, a total of 17 Sentinel-1 IW images, from July 2016 to June 2017, were acquired and processed with SBAS technique.

2.2 Methodology

Time Series (TS)-InSAR techniques are gaining popularity as tools for deformation measurements due to its ability to overcome the limitations of conventional Differential SAR interferometry (DInSAR): temporal and geometric decorrelation, and atmospheric inhomogeneities (Ferretti, et al. 1999, 2001). Temporal decorrelation in our area of interest is caused by physical terrain changes between the images taken at different acquisition times. These changes affect the scattering characteristics of the surface, which results in a loss of coherence (Hanssen 2001). Geometric decorrelation is the introduction of noise due to an increase of the effective distance between two sensors or acquisitions (spatial baseline). Atmospheric phase delay is mainly caused by the water vapor in the troposphere and can introduce an error of several centimeters, depending on atmospheric conditions (Hanssen 2001). Therefore, TS- InSAR techniques can be seen as an extension of the conventional InSAR techniques. Therefore, in order to overcome the limitations of traditional InSAR time series analysis techniques, Distributed Scatterers (DS) -InSAR along with Permanent Scatterers (PS) -InSAR (Ferretti, et al. 2001) have to be extracted and used. Its similar statistical characteristic could be potentially employed in maximizing the spatial sampling of deformation signal over rural regions. Therefore, both PS and DS targets can be combined and be useful in the comprehensive investigation of the deformation. The selection of both DS targets and PS points, are jointly processed without the need for significant changes in traditional InSAR time series analysis processing chain.

In this study we employed the descripted DS-InSAR and PS-InSAR combination method and the traditional InSAR time series technique (SBAS-InSAR) to PALSAR and ASAR imagery in order to increase the number of measurements (DS + PS points). The topographic phase was simulated and removed from the interferograms using the SRTM (Shuttle Rader Topography Mission) DEM (Rosen, et al. 2001) of 1-arc-second resolution. The SBAS approach has been proposed to overcome the limitation of decorrelation with reduced amount of SAR images by making full use of all possible interferograms with small spatial and temporal baselines.

The Sentinel-1 full swath IW mode SAR time series processing presents a huge challenge, due to its much larger coverage when compared with ENVISAT and ERS SAR data. For that reason and in order to ensure the temporal continuity in the processing, in this study, we modified the SBAS approach implemented in StaMPS (Hooper, et al. 2007; Hooper 2008) and used SSDS (SAR Subsidence Demonstration System) (Perski, et al. 2014). The displacements acquired in the line of sight direction was translated to vertical direction based on a simple assumption that no horizontal ground motion occurred for subsidence monitoring applications (Galloway, et al. 1998; Amelung, et al. 1999).

In the case of Fushun pit mine processing, and because of the large deformations expected, the SARScape software (http://www.sarmap.ch), using 50 km^2 subareas for each single reference point with a 30% overlapping zone among adjacent patches, was used. The Goldstein adaptive filtering algorithm sensitive to the local phase noise and fringe rate (Goldstein and Werner 1998) were also considered in the processing. Finally, it was included a double filtering step using an 800 meters' low pass filter and 365 days as high pass filter for the estimation of the atmospheric contribution in the inversion step.

3 RESULTS AND DISCUSSION

3.1 Beijing South area subsidence monitoring with full resolution Sentinel-1 full swath IW SAR data

Huabei Plain is a serious land subsidence area in China, affecting a mega-city group, including the area around Beijing and Tianjin (Kampes, et al. 2001; Liu, et al. 2011; Luo, et al. 2011; Perissin and Wang 2011; Ng, et al. 2012b). Land subsidence has a serious impact on infrastructure and people's production and life (Yue, et al. 2011). In 2017, there were 21 million permanent residents in Beijing and 15 million permanent residents in Tianjin, and a floating population beyond 10 million. The groundwater overexploitation for residential water consumption has caused series of land subsidence events (Ng, et al. 2012). This phenomena happens in other big cities as well (Abidin, et al. 2011; Marshall, et al. 2018), making the monitoring of the dynamic change of the land subsidence a mandatory task. A single Sentinel-1 SAR image has a coverage of about 250 km×200 km, about 5 times bigger than the previous C-band ERS and ENVISAT ASAR data, making it suitable for large scale land subsidence monitoring.

The P-SBAS results has shown very good prospect of Sentinel-A SAR data (De Luca, et al. 2016) for land subsidence monitoring in Italy, however there is few demonstration of large scale application in other places. Up to date there are only small crop areas monitored around Beijing with Sentinel-1 SAR data (Guo, et al. 2017), covering about 5×10 km^2, only one-tenth of the full swath.

Sentinel-1 data in TOPS IW mode, acquired in 2017, were used for monitoring the land subsidence with SBAS method. The linear subsidence velocity map is showed in Fig. 2. The result show that the largest subsidence happened at Wangqingtuo and Shengfang Town, around Tianjin City and GaoYang town in the Hebei province, which is larger than 1 m/year. Some obvious subsidence evidences areas also presented in Tongzhou County of Beijing. The underground water extraction should be controlled in the future in order to stop these strong deformations.

To give more detailed information, the subsidence map around Tianjin west is enlarged and shown in Fig.3. A clear border of subsidence is visible in this area, and the subsidence gradient is quite large in Wangqingtuo Town (2017). Fig. 4 presents the subsidence map of Beijing as obtained from SBAS processing of C-band GF-3 data. The subsidence pattern and the magnitude match quite well the Sentinel-1 results: both show a clear subsidence in JinZhan area of ChaoYan district. These results allowed to conclude that the groundwater level, changing due to overexploitation, is highly correlated with the spatial and temporal distribution of land subsidence in the Huabei plain area. Therefore, TS-InSAR techniques applied to Sentinel-1 and GF-3 data are excellent tools for monitoring these subsidence mechanisms. The same area has been studied using similar techniques for a long time (Kampes, et al. 2001; Chen, et al. 2011, 2016; Fan, et al. 2011a; Ng, et al. 2012b). However, only ENVISAT SAR data, from 2003 to 2009, and ALOS PALSAR data, from 2007 to 2008, were used and it was found that the vertical rates were in the range of −115 mm/yr to 6 mm/yr. Guo, et al. (2017) applied SBAS techniques to Sentinel-1 IW mode data, acquired between 2015 to 2016 in Tianjin and their results shown a maximum subsidence of about 126mm/yr in Tianjin area. These results are well in agreement with our results.

2.2 Liaoning Province subsidence monitoring with Cosmo-Skymed SAR data

The ground subsidence map retrieved from CSK imagery in Shenyang area by means of SBAS technique is shown in Fig.5. As overall result it can be concluded that most parts of Shenyang area are relatively stable. However, there is a large area in Tiexi district showing serious subsidence, highlighted in the magenta box. This area is located between two major faults (marked as black lines). The newly built railway lines near the Shenyang south railway station are also subsiding, and are highlighted in a dark blue box.

In Fig. 6, the CSK retrieved velocity map using the PSI technique for the Fushun pit mine and some examples of displacement time series, are presented.

These results show that the upper edges of the mine slopes are subject to gravitational deformation with very high velocity, up to over 25 mm/yr. Such strong velocities might evolve in catastrophic collapse of the upper slopes (which can affect nearby buildings and infrastructures) and continuous monitoring of the sites using remote sensing and in situ methods are ongoing in the scope of this project.

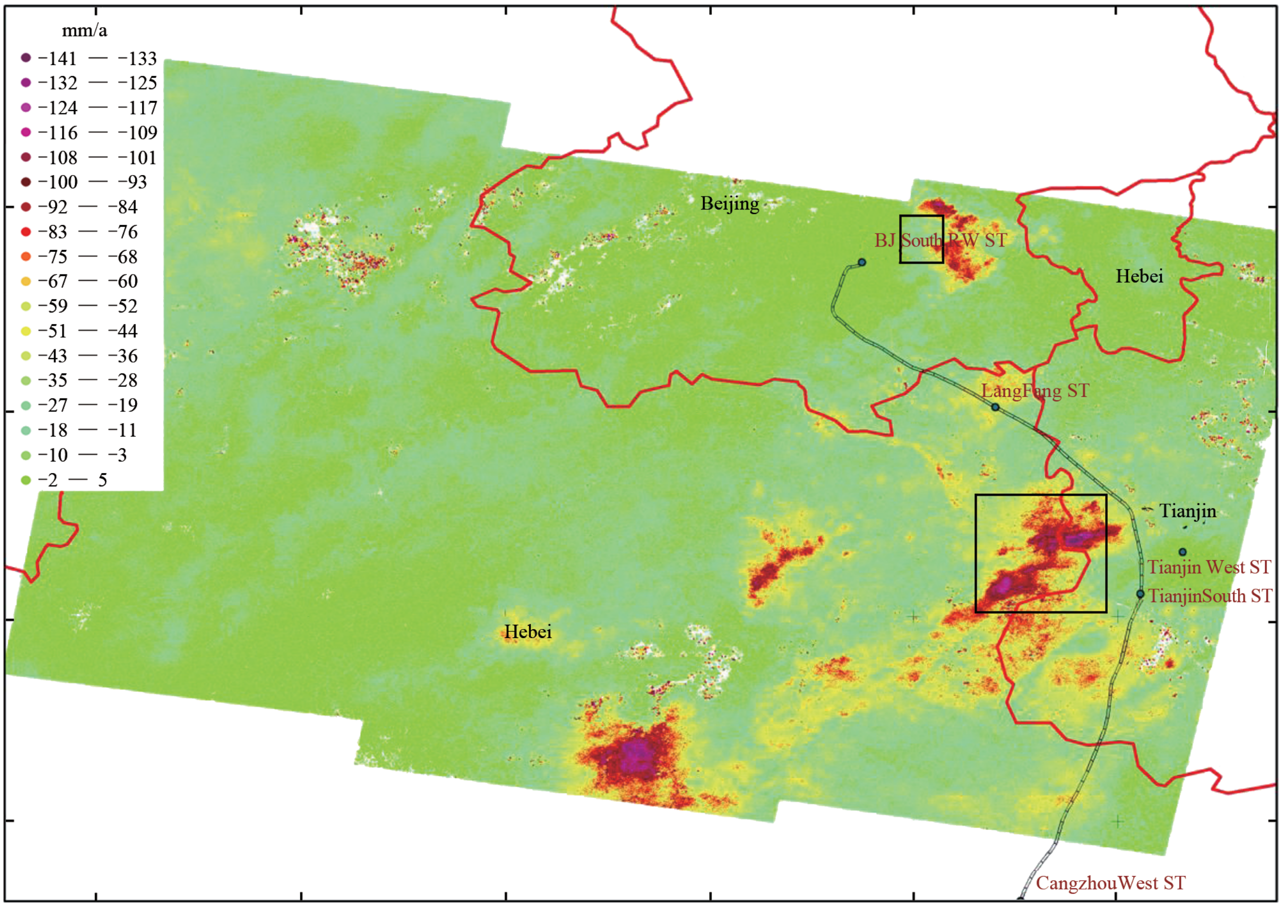


Fig.2 Sentinel−1 TOPS IW mode SBAS subsidence map of Beijing South

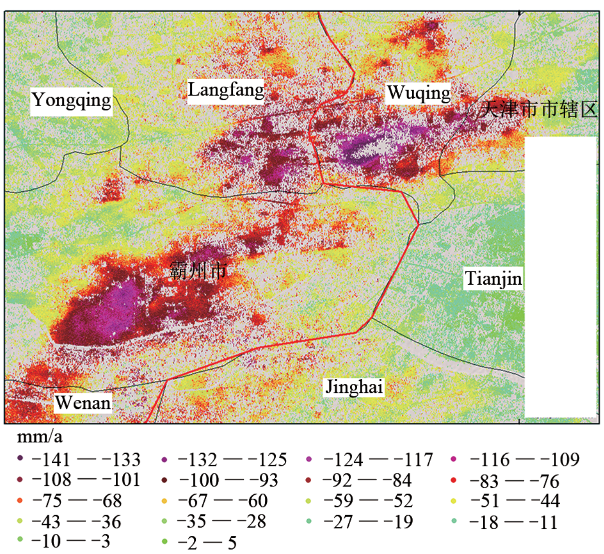


Fig.3 Enlarge subsidence map around Tianjin West

2.3 Danba County landslide monitoring with PS+DS method

Xiaojin, Jinchuan and Danba Counties are located in the west of Sichuan Province. The elevation of this area has changed largely, and the tributaries of Jinsha River are concentrated in this area. Donggu River, Xiaojin River, Dajinchuan River and Geshiza River meet near Danba County Town. The landslides are mainly distributed on the slopes of middle elevation, middle slopes and in both sides of the valley. Two ALOS-2 PLASAR-2 images, acquired in 2018, were processed and the results show clear slope movement evidence (Fig. 7). After delineating the border of the deformation patterns, we could see that the GaoDing and Zhezou landslides present the largest area (<7 km^2). Regarding GaoDing landslide, two other landslides were found in the same side of the end of this slope.

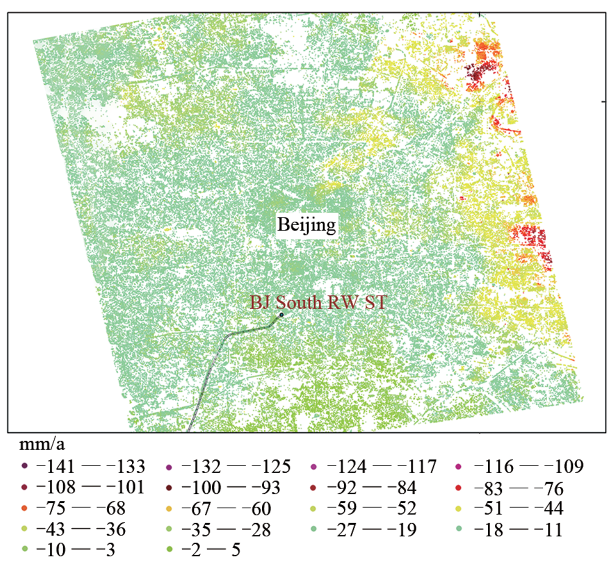


Fig.4 GF−3 SBAS subsidence map of Beijing

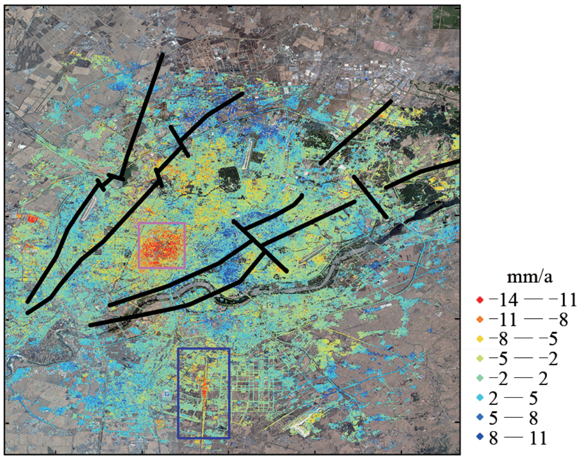


Fig.5 Ground subsidence map retrieved from the CSK images in Shenyang

The GaoDing landslide, located in the Danba country close to the offside of Dajinchuan River and the provincial road S211, is a type of large-scale stacked soil landslide. The Jiaju Landslide is located in the southern part and is characterized by a slow movement pattern. NieLa landslide, located in the northern part, presents a much fast movement. Affected by the erosion and cutting of the Dajinchuan River, the front edge of the slope body forms a steep ridge, ranging from 15 m to 25m, and a steep slope of 7~19 m was generated at the trailing edge. Its average slope is of about 25° and the maximum slope can reach up to 32°, and covers about 1.2 km^2, with length of 1200 m in EW direction and a width of 1000 m in the SN direction. In the past years, many geological disasters occurred in the Danba County, therefore, this region is attracting more and more attention due to its special geographic conditions and landslide mechanism. To get more information about these three landslides, a total of 9 C-band ENVISAT ASAR images and 16 L-band ALOS PALSAR images were used to map the displacement map of the landslides areas. The ALOS PALSAR dataset was acquired between February 2007 and January 2011, and the ENVISAT ASAR dataset was acquired between August 2007 and June 2008.

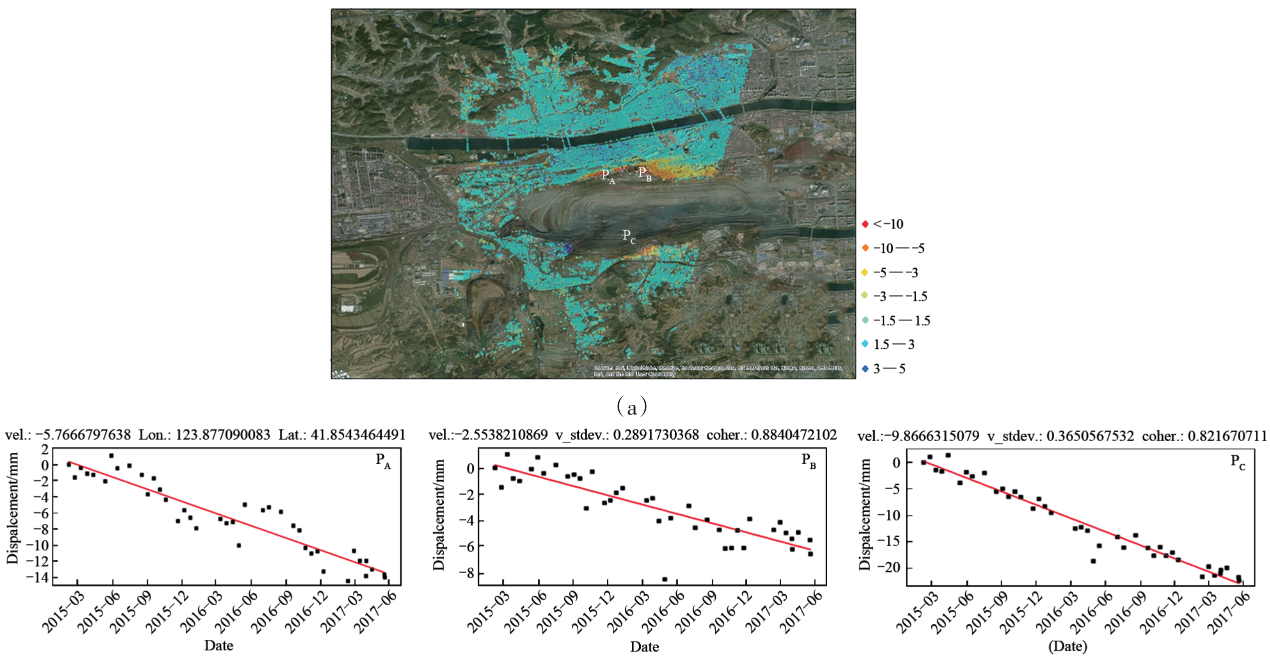


Fig.6 CSK Mean ground velocity map and displacement time series of 3 selected points

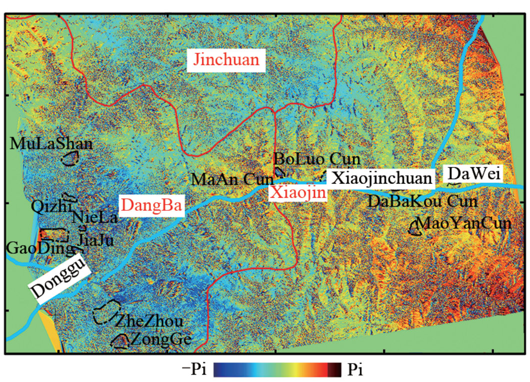
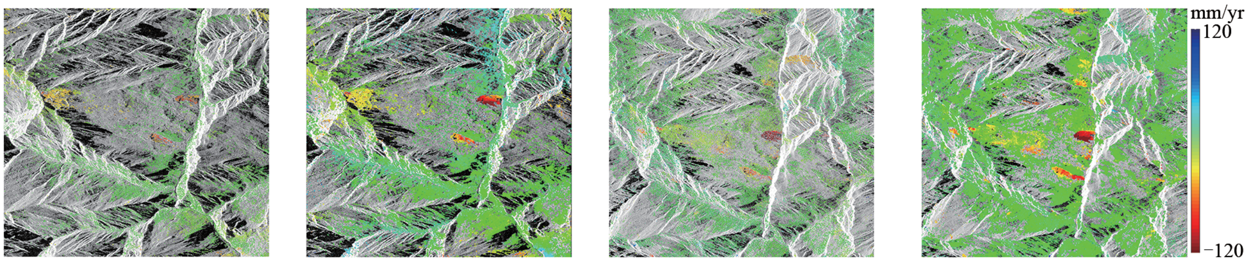


Fig.7 ALOS−2 PALSAR−2 D−InSAR result and delineated landslide map

Since the same approach was used in both datasets, for the selection of DS targets and PS points, they were jointly processed without the need for significant changes in traditional InSAR time series analysis processing chain. We employed the previously described DS and PS combination method and traditional InSAR time series technique (SBAS-InSAR) to PALSAR and ASAR imagery. The analysis of the final results allowed to verify the advantages of the presented methods.

The surface deformation map from Envisat/ASAR and ALOS/PALSAR show that the three landslides are clearly identified. GaoDing landslide is located on the top of the slope, while in the northern end the NieLa landslide is moving with a velocity beyond 10 cm/yr. These results are in line with ALOS2 PALSAR-2 results.



（a）Envisat ASAR SBAS （b）Envisat ASAR SBAS+DS （c）ALOS PALSAR SBAS （d）ALOS PALSAR SBAS+DS

Fig.8 The surface deformation in LOS direction with combination of SBAS and DS technique.

2.4 Maoxian Landslide monitoring with Sentinel-1 SAR data

The motion monitoring of landslide is very important in Maoxian County. Fig. 9 shows some results obtained using Sentinel-1 SAR images. Comprehensive analysis results show that the active landslides are mainly distributed on both sides of the Minjiang River in the middle of Maoxian County. Because the SAR images were taken in the East-West direction, most of the active landslides were obtained in the North-South direction. The landslides are mainly distributed around Feihong Township, Baibu Village, Huangcao Village and Fubuzhai Village. The terrain in the study area is undulate and the landslides occurred mainly in mountain slopes. The maximum subsidence rate of highly active landslides is about 6-8 cm/yr. Most of the bank slopes in Minjiang River valley are stable or basically stable, and the bank slopes are generally good. Most of the bank slopes in Heishui River valley are stable and the bank slopes are generally good. By comparing with the disaster points, it is found that most of the 45 landslide areas can form a good correlation with the known disaster points around them. Among the 45 landslide areas, 19 potential landslides are newly discovered, and there are some already known landslides around them as well. Some of the landslide types are different from the known ones from this study, which could be used to update the available landslide information.

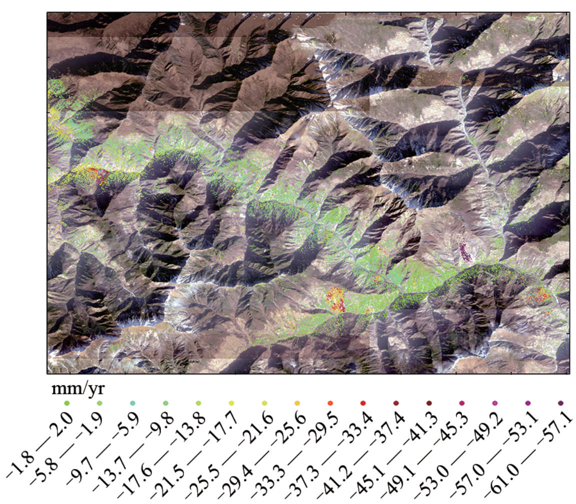


Fig.9 The monitoring results obtained by SBAS method

By means of analyzing the dominant factors of the slope, aspect, fault and stratigraphic lithology on the slope and the distribution of landslides, historical landslides were most widely distributed in slopes of 20-30 degrees, and they are yet rarely distributed in slopes of more than 40 degrees. The landslides are mainly distributed in the southwest, because of the characteristics of light intensity and humidity on the sparse vegetation. The faults are the main factor to control the landslides.

By superimposing historical landslides and visibility partition maps, it was found that most of the historical landslides were located in the visible region, a few of them located in the low sensitive region, yet no historical landslide located in the invisible region, which indicated that images of Sentinel-1A ascending and descending tracks were suitable for the study on the identification and monitoring of landslides in the mountainous area in China. The 8 potential landslides and 1 potentially dangerous rock site were identified in the study area by making use of remote sensing interpretation signs in combined with the distribution of deformation points. Furthermore, historical landslides and field investigations have verified the validity of the results, and it is concluded that the images of descending track are more suitable for potential landslide identification in the study area.

4 CONCLUSION

Our results around Beijing confirm that the Sentinel-1 TOPS IW mode image is suitable for large scale land subsidence monitoring. The coverage of about 250 km×200 km, about 5 times bigger than the previous C-band ERS and ENVISAT ASAR data, will be one kind of important SAR data source for future land subsidence monitoring, and will be even improved after the lunch of Sentinel-1 C and D, bringing new opportunities for earth deformation monitoring.

The results presented in this study show clear and strong ground deformation effects, with high potential impact on the local infrastructures and population, caused by heavy industrial exploitation of mines and water pumping in the BASF region, Northeast China. The use of InSAR data allows to study these phenomena with an accuracy and a temporal sampling not possible otherwise.

Regarding landslides, it was found that the number of deformation points and the high velocity are mainly distributed in the front of the landslide, and the velocity is high in the middle of landslides and low in the two sides of landslides. Due to the de-coherence effect, the distribution and velocity of deformation points cannot be estimated in the east-west direction.

REFERENCES

Abidin HZ, Andreas H, Gumilar I, et al (2011) Land subsidence of Jakarta (Indonesia) and its relation with urban development. Nat Hazards 59:1753 - 1771. doi: 10.1007/s11069-011-9866-9

Adam N, Kampes BM, Eineder M (2004) The development of a scientific Persistent Scatterer System: Modifications for mixed {ERS/ENVISAT} time series. In: ENVISAT & ERS Symposium, Salzburg, Austria, 6 – 10 September, 2004. p 9

Amelung F, Jonsson S, Zebker H, Segall P (1999) Prospects of Volcano Geodesy with {ERS} Radar Interferometry. In: Second International Workshop on ERS SAR Interferometry, `FRINGE99', Liège, Belgium, 10 – 12 Nov 1999. ESA, pp 1 – 9

Berardino P, Fornaro G, Lanari R, Sansosti E (2002) A New Algorithm for Surface Deformation Monitoring Based on Small Baseline Differential {SAR} Interferograms. IEEE Trans Geosci Remote Sens 40:2375 – 2383

Calcaterra S, Cesi C, Di Maio C, et al (2010) Surface displacements of two landslides evaluated by GPS and inclinometer systems: a case study in Southern Apennines, Italy. Nat Hazards 61: 257 – 266. doi: 10.1007/s11069-010-9633-3

Chen BB, Gong HL, Li XJ, et al (2011) Spatial-temporal characteristics of land subsidence corresponding to dynamic groundwater funnel in Beijing Municipality, China. Chin Geogr Sci 21: 753 – 764. doi: 10.1007/s11769-011-0509-6

Chen M, Tomás R, Li Z, et al (2016) Imaging Land Subsidence Induced by Groundwater Extraction in Beijing (China) Using Satellite Radar Interferometry. Remote Sens 8: 468. doi: 10.3390/rs8060468

De Luca C, Bonano M, Casu F, et al (2016) Automatic and Systematic Sentinel-1 SBAS-DInSAR Processing Chain for Deformation Time-series Generation. Procedia Comput Sci 100: 1176 – 1180. doi: 10.1016/j.procs.2016.09.275

Dong J, Zhang L, Tang M, et al (2018) Mapping landslide surface displacements with time series SAR interferometry by combining persistent and distributed scatterers: A case study of Jiaju landslide in Danba, China. Remote Sens Environ 205: 180 – 198. doi: 10.1016/j.rse.2017.11.022

Fan HD, Deng KZ, Zhu CG, Xue JQ (2011a) Monitoring land subsidence by PS-DInSAR and SBAS methods in Tianjin city. Spie-int Soc Optical Engineering

Fan HD, Deng KZ, Zhu CG, Xue JQ (2011b) Monitoring land subsidence by PS-DInSAR and SBAS methods in Tianjin city. Spie-int Soc Optical Engineering

Ferretti A, Fumagalli A, Novali F, et al (2011) A New Algorithm for Processing Interferometric Data-Stacks: SqueeSAR. Ieee Trans Geosci Remote Sens 49: 3460 – 3470. doi: 10.1109/TGRS.2011.2124465

Ferretti A, Prati C, Rocca F (2000) Analysis of Permanent Scatterers in {SAR} Interferometry. In: ? pp 1 – 3

Ferretti A, Prati C, Rocca F (1999) Monitoring Terrain Deformations Using Multi-Temporal {SAR} Images. In: CEOS SAR Workshop, ESA-CNES, Toulouse, France, 26-29 October 1999. p 4 pp.

Ferretti A, Prati C, Rocca F (2001) Permanent Scatterers in SAR Interferometry. IEEE Trans Geosci Remote Sens 39:8 – 20

Galloway DL, Hudnut KW, Ingebritsen SE, et al (1998) Detection of aquifer system compaction and land subsidence using interferometric synthetic aperture radar, ValleyAntelope, DesertMojave, California RID B-1945-2009. Water Resour Res 34:2573 – 2585. doi: 10.1029/98WR01285

Gili JA, Corominas J, Rius J (2000) Using Global Positioning System techniques in landslide monitoring. Eng Geol 55: 167 – 192. doi: 10.1016/S0013-7952(99)00127-1

Goldstein RM, Werner CL (1998) Radar interferogram filtering for geophysical applications. Geophys Res Lett 25:4035 – 4038

Guo H, Liu G, Liao J, et al (2014) Study of RADARSAT-2 synthetic aperture radar data for observing sensitive factors of global environmental change. J Appl Remote Sens 8:084593. doi: 10.1117/1.JRS.8.084593

Guo J, Hu J, Li B, et al (2017) Land subsidence in Tianjin for 2015 to 2016 revealed by the analysis of Sentinel-1A with SBAS-InSAR. J Appl Remote Sens 11:026024. doi: 10.1117/1.JRS.11.026024

Hanssen RF (2001) Radar Interferometry: Data Interpretation and Error Analysis. Kluwer Academic Publishers, Dordrecht

Hilley GE, Burgmann R, Ferretti A, et al (2004) Dynamics of slow-moving landslides from permanent scatterer analysis. Science 304: 1952 – 1955. doi: 10.1126/science.1098821

Hooper A (2008) A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approaches RID A-9614-2008. Geophys Res Lett 35:L16302. doi: 10.1029/2008GL034654

Hooper A, Segall P, Zebker H (2007) Persistent scatterer interferometric synthetic aperture radar for crustal deformation analysis, with application to Volcan Alcedo, Galapagos RID A-9614-2008. J Geophys Res-Solid Earth 112: B07407. doi: 10.1029/2006JB004763

Kampes B, Hanssen R, (Swart R2001) Deformation monitoring with radar interferometry, Analysis of permanent scatterers in {Tianjin}, {China}

Khan SA, Liu L, Wahr J, et al (2010) GPS measurements of crustal uplift near Jakobshavn Isbr\a e due to glacial ice mass loss. J Geophys Res 115:B09405. doi: 10.1029/2010JB007490

Liao M, Tang J, Wang T, et al (2011) Landslide monitoring with high-resolution SAR data in the Three Gorges region. Sci China Earth Sci 55:590 – 601. doi: 10.1007/s11430-011-4259-1

Liu G, Guo H, Perski Z, et al (2016) Monitoring the slope movement of the Shuping landslide in the Three Gorges Reservoir of China, using X-band time series SAR interferometry. Adv Space Res 57: 2487 – 2495. doi: 10.1016/j.asr.2016.03.043

Liu G, Guo H, Yue H, et al (2015) Modified four-pass differential SAR interferometry for estimating mountain glacier surface velocity fields. Remote Sens Lett 7:1 – 10. doi: 10.1080/2150704X.2015.1094588

Liu GX, Jia HG, Zhang R, et al (2011) Exploration of Subsidence Estimation by Persistent Scatterer InSAR on Time Series of High Resolution TerraSAR-X Images. Ieee J Sel Top Appl Earth Obs Remote Sens 4:159 – 170. doi: 10.1109/JSTARS.2010.2067446

Liu P, Li Z, Hoey T, et al (2013) Using advanced InSAR time series techniques to monitor landslide movements in Badong of the Three Gorges region, China. Int J Appl Earth Obs Geoinformation 21:253 – 264. doi: 10.1016/j.jag.2011.10.010

Luo QL, Perissin D, Li QH, et al (2011) Tianjin Insar Time Series Analysis With L- and X-band. Ieee

Marshall C, Large DJ, Athab A, et al (2018) Monitoring tropical peat related settlement using ISBAS InSAR, Kuala Lumpur International Airport (KLIA). Eng Geol 244:57 – 65. doi: 10.1016/j.enggeo.2018.07.015

Nakagawa H, Murakami M, Fujiwara S, Tobita M (2000) Land subsidence of the northern Kanto plains caused by ground water extraction detected by JERS-1 SAR interferometry. In IGARSS 2000. IEEE 2000 International Geoscience and Remote Sensing Symposium. Taking the Pulse of the Planet: The Role of Remote Sensing in Managing the Environment. Proceedings (Cat. No. 00CH37120). IEEE, pp 2233 – 2235

Ng AH-M, Ge L, Li X, Zhang K (2012) Monitoring ground deformation in Beijing, China with persistent scatterer SAR interferometry. J Geod 86:375 – 392. doi: 10.1007/s00190-011-0525-4

Novellino A, Cigna F, Sowter A, et al (2017) Exploitation of the Intermittent SBAS (ISBAS) algorithm with COSMO-SkyMed data for landslide inventory mapping in north-western Sicily, Italy. Geomorphology 280:153 – 166. doi: 10.1016/j.geomorph.2016.12.009

Perissin D, Wang T (2011) Time-Series InSAR Applications Over Urban Areas in China. Ieee J Sel Top Appl Earth Obs Remote Sens 4: 92 – 100. doi: 10.1109/JSTARS.2010.2046883

Perski Z, Liu G, Wojciechowski T, et al (2014) Monitoring the Activity of Landslides in the Coastal Zones of Reservoirs with SAR Interferometry. In: Sassa K, Canuti P, Yin Y (eds) Landslide Science for a Safer Geoenvironment. Springer International Publishing, Cham, pp 331 – 336

Rosen PA, Hensley S, Gurrola E, et al (2001) {SRTM} {C}-band Topographic Data: Quality Assessment and Calibration Activities. In: International Geoscience and Remote Sensing Symposium, Sydney, Australia, 9 – 13 July 2001. pp 3 pages, cdrom

Yan S, Guo H, Liu G, Ruan Z (2013) Mountain glacier displacement estimation using a DEM-assisted offset tracking method with ALOS/PALSAR data. Remote Sens Lett 4: 494 – 503. doi: 10.1080/2150704X.2012.754561

Yan S, Liu G, Deng K, et al (2015) Large deformation monitoring over a coal mining region using pixel-tracking method with high-resolution Radarsat-2 imagery. Remote Sens Lett. doi: 10.1080/2150704X.2015.1126683

Yue H, Liu G, Guo H, et al (2011) Coal mining induced land subsidence monitoring using multiband spaceborne differential interferometric synthetic aperture radar data. J Appl Remote Sens 5: 053518. doi: 10.1117/1.3571038

Zhang Y, Meng X, Jordan C, et al (2018) Investigating slow-moving landslides in the Zhouqu region of China using InSAR time series. Landslides 15:1299 – 1315. doi: 10.1007/s10346-018-0954-8

Zhao C, Lu Z, Zhang Q, de la Fuente J (2012) Large-area landslide detection and monitoring with ALOS/PALSAR imagery data over Northern California and Southern Oregon, USA. Remote Sens Environ 124:348 – 359. doi: 10.1016/j.rse.2012.05.025