Monitoring surface deformation of high-speed railway using time-series InSAR method in northeast China

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Abstract. It is difficult to monitor the surface deformation along the high-speed railway for the complexity of the surface texture in extensive region. In this paper, based on sentinel-1A/B data, the surface deformation along the high-speed railway from Fuyu to Dehui was tried to evaluate using time-series PS-InSAR method. The results indicate that the surface deformation is not dangerous for the safe operation of the railway. Moreover, the surface depression near Dehuixi station is potentially dangerous for the safety of the railway. Finally, the cause of the surface deformation along the railway is mainly attributed to the human activity and the seasonal subgrade frost heave in the seasonal frozen soil.

1. Introduction
The High-Speed Railway plays an important role in the current Chinese economy, while it is difficult to monitor the surface deformation along the railway. Particularly in northeast China, the environment is extremely cold in the world. Moreover, in macro scale, influenced by the crucial climate, instable subsurface features, and the complex geological structures, the surface deformation is inevitable, which will be a potential dangerous issue for the safe operation of the railway [9]. Therefore, it is essential to monitor the surface deformation of the high-speed railway.

The traditional ways to monitor the surface deformation are mainly carried out by the precision leveling and GPS measurements, which are rather limited in the efficiency, timeliness, coverage, and even the cost [2]. As the Interferometric Synthetic Aperture Radar (InSAR) technology is little affected by the weather, and it can obtain large range and high-precision surface deformation, the technique has been widely used to monitor the surface deformation [10]. Currently, the methods are developed properly for monitoring railway deformation including Persistent Scattered InSAR (PS-InSAR) [5], Small Baseline InSAR [1], Distributed Scattered InSAR [6], and Stanford method for persistent scattered [7].

In this study, the SAR data from the Sentinel-1A/B satellites was employed, and the PS-InSAR method was tried to obtain the surface deformation of the high-speed railway between Fuyu Dehui.

2. Study area and data source
The Harbin-Dalian high-speed railway was built in 2012. The railway in Fuyu to Dehui section is about 60 km long, which is largely located in the permafrost zone of northeast China (Figure 1).
Moreover, the railway mainly passes through Songhua River. This makes it difficult to monitor the surface deformation along the railway.

In this study, the data we use is SAR image in C Band, which is provided by European space agency (ESA) sentinel-1A /B satellites. The SAR images are monocular complex images in VV polarization, with a central incident Angle of 38.89° and a spatial resolution of 15 m. From October 2016 to September 2019, 80 views of the SAR images are downloaded, covering the operation time of Fuyu-Dehui high-speed railway for three years. The data is proper to monitor the surface deformation for 39 times, largely once a month.

In order to ensure the orbital accuracy of the Sentinel data and to eliminate the flawless baselines and residual fringe errors caused by orbital errors, the Precise Orbit Ephemerides data published by ESA was used in this experiment. In addition, the SRTM 1 DEM data with a spatial resolution of 30 m downloaded from the NASA official website was used as the reference for SAR image processing.

Additionally, more than 90% of the regions approximated to the railway are agricultural land, where the average temperature varies greatly with the seasons. In this paper, the PS-InSAR method based on permanent scatterers (PSs) can well eliminate the incoherence phenomenon caused by such factors as the seasonal temperature change and the vegetation cover, which is adopted in this study.

3. Algorithm

3.1. PS-InSAR method
The PS-InSAR was firstly proposed by Ferretti et al. [4], which represents a specific class of D-InSAR techniques. Using the multi-temporal SAR images acquired over the same area, the appropriate data processing and analysis procedures are used to separate the displacement phase component from the other phase components. The key of PS-InSAR technique is to determine the PS points. The main outcomes of a PS-InSAR analysis include the deformation time series and the deformation velocity estimated over the analyzed PS points. Another outcome of a PS-InSAR method is the residual topographic error (RTE), which is the difference between the true height of the scattering phase center of a given PS and the height of the DEM in this point. The RTE is a key parameter to achieve an accurate PS geocoding [8].
PS-InSAR technique processing are shown in figure 2 below, the result can be divided into the following steps:

1. **The SAR data calibration and registration:** For any point in a SAR image, due to the influence of satellite perspective, orbital position, incidence Angle, atmospheric conditions and other factors during imaging, the amplitude information of the point will change constantly in time phase. Therefore, SAR image registration and radiometric calibration are required to unify the geometric position of time series data with the radiation intensity.

2. **The differential interferometric phase SAR data processing:** A certain scene data in M-amplitude SAR data was selected as the main image and interfered with other SAR images to obtain the interference atlas. Then, external DEM or SAR data were used to remove the topographic phase of the generated DEM and generate the time-series differential interference dataset.

3. **PS candidates selection:** The phase stability is approximated by using the amplitude dispersion index representing the amplitude stability, and then the selection of PS candidate points is performed.

4. **Phase unwrapping of a sparse grid based on multiple images:** By using Delaunay triangulated irregular network to establish connection relation between candidate points, the phase gradient of adjacent points in sparse grid can be expressed as:

\[
\Delta \phi_{\text{diff}} = \left( \frac{4\pi}{\lambda} \Delta h + \frac{4\pi}{\lambda} T \Delta v \right) + \frac{4\pi}{\lambda} \Delta R_{\text{non-linear}} + \Delta \phi_{\text{APS}} + \Delta \phi_{\text{noise}}
\]  

where, \( e = \frac{4\pi}{\lambda} \Delta R_{\text{non-linear}} + \Delta \phi_{\text{APS}} + \Delta \phi_{\text{noise}} \) is denoted as residual phase. If the phase residuals of adjacent points satisfy \(| e | < \pi\), phase unwrapping in space can be carried out. Using the method of periodogram spectral estimation, \( \Delta v \) and \( \Delta h \) at the time when the overall coherence reaches the maximum value are taken as the estimated values of linear deformation rate and DEM error. As shown in formula (2):

\[
\xi_p = \frac{1}{M} \sum_{l,k} e^{j(\Delta \phi_{lk} - \Delta \phi_{HP} - \Delta \phi_{DP})}
\]

\[
\xi = \left| \frac{1}{M} \sum_{k=1}^{M} \exp(je) \right|
\]

Then using weighted least-square method for phase unwrapping, namely to \( \xi \) as weights, calculated from known reference points online sparse grid every bit of the absolute value of linear deformation rate and DEM error.

5. **Atmospheric Phase Screen (APS) estimation and subtraction:** After the linearity distortion and DEM errors of each PS point are estimated, the residual phase can be obtained by subtracting them from the initial differential interferogram, which mainly includes nonlinear distortion, atmospheric phase and noise.

   In the residual phase, the nonlinear distortion and atmospheric phase can be separated by temporal filtering and spatial filtering. When the atmospheric phase at any PS candidate point of each scene image on a time series SAR image is estimated, the Kriging interpolation method can be used to estimate the atmospheric phase corresponding to each pixel of each scene SAR image.

6. **Pixels to time series analysis:** After removing APS from the differential interferometric phase, the coherence of each point on the time series image is recalculated by using the coherence formula, and the final PS point is selected.

7. **PS points shape variables are estimated:** After the PS points are determined, the phase unwrapping of the multi-image sparse grid is performed again with the method described above, and the accurate shape variable estimation of each point is finally obtained.

3.2. **Data processing**

In this experiment, the Esri Sarscape software was used to operate the PS-InSAR processing, and the procedure was thoroughly postulated in Figure 2 [3]. At first, the SAR images were cut along the high-speed railway, about 30 km in orthogonal direction. According to the optimal value of spatial and
temporal baseline, the eighth data sets was selected as the main image to operate the registration and interference processing. The Delaunay triangular network method was used to determine the optimal solution among the adjacent PS points through performing the spatial phase unwinding. Thereafter, the spatiotemporal filtering was employed to remove the atmospheric phase error, and the overall coherence of each PS point was calculated again. Finally, the quadratic unwinding was operated, and the sparse grid solution of the final PS point was solved to obtain the average annual deformation in the LOS direction (a) and the vertical direction (b) (Figure 2).

3.3. Results and discussions

Figure 3 indicates that, from October 2016 to October 2019, the average annual deformation is -13.1 mm to 7.5 mm in the LOS direction, and -14.1 mm to 10.6 mm in the vertical direction along the high-speed railway. In the regions near Songhua River, the surface deformation is negative, and it is indicated as the slight depressions, and the maximum is up to 12.2 mm per year. The other section of the railway is shown as slight uplift.

Moreover, we also checked the regions within the 1 km extended from the railway and found several regions with apparent surface deformation. The most dangerous region is about 200 m away from near Dehui station, where the average annual surface deformation is up to 14.1 mm. The depression area is extending toward the high-speed railway, which brings the potential risk for the safe operation of the railway.

To better understand the surface deformation along the railway, three typical PS points were selected, and the surface deformation in time series was obtained (Figure 3). Figure 3 indicates two interesting features about the surface deformation.

Firstly, the change of the surface deformation is seasonal. The largest deformation always occurs in winter, while the smallest deformation occurs in summer.

Secondly, in winter, the surface deformation is positive, while it keeps constant in summer.

Therefore, the cause for the surface deformation along the railways is mainly the temperature. In winter, the frozen soil brought by the extremely cold weather makes the uplift of the surface.

Moreover, the surface deformation is negative around Dehui station, which is different from the other two points. This verifies the influence of the temperature, for the depression is serious in winter.
because of the absence water in depth, while it is relieved in summer because of the enough water supply.

4. Conclusions
In this paper, based on Sentinel-1A/B data from 2016 to 2019, the surface deformation of the high-speed railway from Fuyu to Dehui were firstly evaluated using time-series PS-InSAR method. The results indicate that the surface deformation is weak, and it is not dangerous for the safe operation of the railway. However, in Dehuixi station, the surface depression area is not far away from the high-speed railway, which is potentially dangerous for the safe of the railway. By analyzing the deformation features of the typical points, the cause of the surface deformation along the railway is mainly attributed to the seasonal frozen of the soil.

For the limitation of the spatial resolution of the used Sentinel data, the surface deformation in the high-speed railway or the nearby regions is difficult to identify. More work should be done to keep the safe operation of the railway.

Figure 3. Time series deformation diagram of PS points

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References
[1] Berardino P, Fornaro G and Lanari R, et al. 2002 A New Algorithm for Surface Deformation Monitoring Based on Small Baseline Differential SAR Interferograms IEEE Transactions on Geoscience and Remote Sensing 40 2375-2383
[2] Corsetti M, Fossati F, and Manunta M, et al. 2018 Advanced SBAS-DInSAR Technique for Controlling Large Civil Infrastructures: An Application to the Genzano di Lucania Dam Sensors 18 2371
[3] Duan G, Gong H and Liu H, et al. 2016 Monitoring and Analysis of Land Subsidence Along Beijing-Tianjin Inter-City Railway Journal of the Indian Society of Remote Sensing 44 915-931
[4] Ferretti A, Prati C and Rocca F 2001 Permanent scatterers in SAR interferometry IEEE Transactions on Geoscience and Remote Sensing 39 8-20
[5] Ferretti A, Colesanti C and Prati C, et al. 2003 Monitoring landslides and tectonic motions with the Permanent Scatterers Technique Engineering Geology 68 3-14
[6] Ferretti A, Fumagalli A and Novali F, et al. 2011 A New Algorithm for Processing
Interferometric Data-Stacks: SqueeSAR *IEEE Transactions on Geoscience and Remote Sensing* **49** 3460-3470

[7] Hooper A, Segall P and Zebker H 2007 Persistent scatterer interferometric synthetic aperture radar for crustal deformation analysis, with application to Volcán Alcedo, Galápagos *Journal of Geophysical Research* **112** B07407

[8] Meisina C, Zucca F and Fossati D, et al. 2006 Ground deformation monitoring by using the Permanent Scatterers Technique: The example of the Oltrepo Pavese (Lombardia, Italy) *Engineering Geology* **88** 240-259.

[9] Shi G, Zhao S, and Li, X, et al. 2014 The frost heaving deformation of high-speed railway subgrades in cold regions: Monitoring and analyzing *Journal of Glaciology & Geocryology* **36** 360-368

[10] Zhu J, Li Z and Hu J 2017 Research Progress and Methods of InSAR for Deformation Monitoring *Acta Geodaeticaet Carto graphica Sinica* **46** 1717-1720