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Improving time-series InSAR deformation estimation for city clusters by deep learning-based atmospheric delay correction

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Highlights

- Land subsidence of two city clusters was measured using Sentinel-1 images.
- The pGA_Fi_BiGRU model was proposed to correct the seasonal ADs.
- The performance enhancement in AD reduction varied across different cities.
- Generalizability was demonstrated using the third city cluster.

Abstract

Atmospheric delay (AD) is the main source of error in time-series interferometric synthetic aperture radar (InSAR) deformation estimation over large areas. In this study, we propose a bidirectional gated recurrent unit (BiGRU) model to correct random and seasonal ADs adaptively.

The BiGRU model decomposes InSAR time-series measurements into non-seasonal and seasonal components by adopting a branched network structure and extracting component-wise features separately. To remove seasonal ADs and meanwhile preserve true seasonal deformation, a dense and fully connected layer with weighted feature learning was designed. Five typical time-series deformation patterns were simulated for model training, and its robustness was evaluated using synthetic data. We applied the trained model to two city clusters in China (Guangdong and Jiangxi-Hunan) using 178 Sentinle-1 images. The results showed that BiGRU with moderate Generic Atmospheric Correction Online Service (GACOS) and spatiotemporal filtering (pGA_Fi_BiGRU) reduced the standard deviation of InSAR time-series measurements by 64.3% in the Guangdong region and by 53.5% in the Jiangxi-Hunan region compared with the raw data. Compared with the traditional combined GACOS and spatiotemporal filtering processing methods, the pGA_Fi_BiGRU improved the AD reduction performance by 4.7% and by 8.5% in Guangdong and Jiangxi-Hunan, respectively. The InSAR time-series deformation after pGA_Fi_BiGRU processing removed residual ADs and preserved true deformation, which agreed well with the geodetic leveling and Global Navigation Satellite System data. The first overall subsidence velocity of the Irrawaddy Delta city cluster in Myanmar was then mapped, followed by time-series deformation estimation using pGA_Fi_BiGRU. Representative time-series deformation due to groundwater extraction, coastal erosion, and accretion were properly derived, suggesting that the proposed model can be generalized to other city clusters with different atmospheric noise and geophysical dynamics.

Introduction

Time-series interferometric synthetic aperture radar (InSAR) has proven to be a powerful geodetic imaging technique for capturing tiny surface displacements over large-scale areas (Berardino et al., 2002; Bürgmann et al., 2000; Crosetto et al., 2016; Ferretti et al., 2001). However, the accuracy of the deformation estimation is challenged by atmospheric delays (ADs) including ionospheric and tropospheric delays during microwave transmission (Hanssen, 2001). Ionospheric delay is primarily reflected in the low-frequency band SAR signals such as P-band and L-band SAR, while tropospheric delay dominates ADs in the high-frequency C-band and X-band SAR signals. Previous studies have shown that a 20% variation in the relative humidity of the troposphere could result in 10–14 cm measurement errors, and a 10 cm seasonal ADs could lead to a deformation bias of up to 23.8 cm (Fattahi and Amelung, 2015). When monitoring large-scale city clusters, the magnitude and distribution of ADs may vary significantly in the spatial domain, degrading the accuracy of deformation estimation and possibly misinterpreting geophysical dynamic phenomena. It is therefore imperative to effectively mitigate the effects of ADs for accurate deformation estimation.

Tropospheric delays, including vertically stratified and turbulent components, are primarily attributed to spatiotemporal variations of temperature, pressure, and relative humidity (Bekaert et al., 2015a; Yu et al., 2018). Vertical stratification implies that areas with complex topography, such as mountainous regions, can experience different atmospheric conditions at different elevations. In the temporal dimension, stratified effects show seasonal changes throughout the year. Vertical components can be modeled based on available digital elevation model (DEM) data. The turbulence effect is caused by the mixing of different turbulent processes in the atmosphere, and can be attributed to local weather conditions, strong convective effects, and variations in local land cover (Zebker and Villasenor, 1992). Because the turbulence effect rapidly responds to the spatiotemporal variation of these factors, it is difficult to characterize it with a deterministic model, challenging accurate time-series InSAR estimation.

Many approaches have been presented to correct ADs, which can be divided into three categories: (1) experience-based, (2) statistics-based, and (3) auxiliary data-based methods (Bekaert et al., 2015b). Experience-based methods rely on the empirical relationship between the InSAR phase and elevation to estimate and reduce atmospheric effect. They can correct stratified tropospheric delays and the accuracy depends on the DEM data used. Statistics-based spatiotemporal filtering methods for AD correction apply statistical, geo-statistical, or adjustment algorithms to mitigate tropospheric errors (Ferretti et al., 2001). Statistics-based methods assume that ADs are correlated spatially and randomly distributed temporally. It is difficult to address the temporally long-wavelength seasonal ADs. Auxiliary data-based methods rely primarily on meteorological data, Global Navigation Satellite System (GNSS) zenith delay measurements, and weather models (Delacourt et al., 1998; Dong et al., 2019; Parker et al., 2015). Although auxiliary data-based methods have powerful seasonal AD correction capabilities, their performance may be limited by the low spatiotemporal resolution or inaccuracy of the available data.

Considering the limitations of each algorithm, a combination of the abovementioned methods has been proven to achieve better performance for AD correction (Dong et al., 2019; Yu et al., 2018). In practice, residual seasonal ADs still exist because of the inaccurate and coarse-resolution auxiliary data used. Recently, the growing maturity and broad application of deep learning as a data-driven method have captured the attention of the InSAR community (Ma et al., 2024; Rouet-Leduc et al., 2021). Convolutional neural networks (CNNs) have been applied to phase unwrapping and subsidence detection (Anantrasirichai et al., 2020; Hakim et al., 2023; Yu et al., 2019). Compared to CNNs, recurrent neural networks (RNNs) present great advantages in sequence analysis, such as time-series prediction, random AD removal, and change detection. RNNs have been used to improve the accuracy of deformation prediction by incorporating the temporal information of deformation patterns (Wang et al., 2023). A gated recurrent unit (GRU) model has been introduced to mitigate random ADs in small areas (Zhao et al., 2021). The potential of deep learning methods in large-scale seasonal AD correction has hardly been tapped.

This paper presents a bidirectional gated recurrent unit (BiGRU) RNN model for adaptively correcting ADs in time-series InSAR deformation monitoring. To capture the vertical stratification and turbulence delays more effectively, we decomposed the time-series signals into non-seasonal and seasonal components using a branched network structure model-based simulation method. Five typical time-series InSAR signals (stable, constant, accelerated, decelerated, and seasonal) were simulated for training and testing. The performance of the proposed method was evaluated in simulated data, and in two city clusters with different AD distributions and geodynamic characteristics using Sentinel-1 images. We compared the results from BiGRU, Generic Atmospheric Correction Online Service (GACOS) and spatiotemporal filtering methods, and BiGRU with moderate GACOS and spatiotemporal filtering. The trained model was applied to another city cluster for generalization analysis, and representative ground subsidence after the AD correction was illustrated and interpreted. Finally, the main conclusions of this study are drawn.

Section snippets

Study area

Two city clusters, that is, the coastal Guangdong (GD) region and the inland Jiangxi-Hunan (JH) region of China in Fig. 1, were selected to evaluate the performance of the proposed algorithms for AD mitigation in detail. Besides, the Irrawaddy Delta (ID) city cluster in southern Myanmar was used to for generalization analysis of the trained model. The GD region is located in the coastal Pearl River Delta (PRD) of southern China, as shown in Fig. 1. It includes 12 cities (Guangzhou, Zhongshan, …

Time-series InSAR data processing

Generic Mapping Tools Synthetic Aperture Radar (GMTSAR) was used for SAR data preprocessing (Sandwell et al., 2011). The workflow is shown in Fig. 3. We used a pure geometric algorithm instead of the conventional geometric method followed by enhanced spectral diversity for coregistration of the Sentinel-1 TOPS-mode SAR images, which can efficiently achieve the required coregistration accuracy of higher than 1/200 pixel (Xu et al., 2017). Shuttle Radar Topography Mission (SRTM) DEM data were …

Performance evaluation of the BiGRU model in synthetic data

To evaluate the robustness and limitations of the trained BiGRU model, we quantified the impact of random noise, seasonal amplitude difference, data irregularity level, and number of images on model accuracy using simulated data. We added random noise levels ranging from 1 to 9mm (STD) to test the robustness of our BiGRU model against short-wavelength noise. Fig. 6a shows that the root mean square error (RMSE) for both non-seasonal and seasonal component increased by an increase in the noise …

Separation of seasonal ADs and true seasonal thermal expansion

Apart from seasonal ADs, some true deformations may also show seasonal trends in the time-series, such as bridge thermal expansion caused by concrete dilation and shrinkage with changes in temperature (Crosetto et al., 2016). It is therefore necessary to avoid removing true deformations when implementing the BiGRU model. When temperature increases, concrete materials of bridge structures will dilate as shown in Fig. 12c. One joint of the bridge girder is fixed and the other is relaxed. …

Conclusion

Due to diverse temperature, pressure, and humidity conditions, ADs may vary significantly over large-scale city clusters and degrade the accuracy of the InSAR deformation estimation. Spatiotemporal filtering is effective for removing short-wavelength noise, but insufficient for removing long-wavelength and topography-related seasonal ADs. The global weather model data are usually limited by the spatiotemporal resolution and inherent accuracy of the available data, resulting in residual seasonal …

CRediT authorship contribution statement

Peifeng Ma: Conceptualization, Formal analysis, Funding acquisition. **Chang Yu:** Software. **Zeyu Jiao:** Methodology, Software. **Yi Zheng:** Data curation, Resources, Visualization. **Zherong Wu:** Methodology, Visualization, Writing – original draft. **Wenfei Mao:** Software, Writing – review & editing. **Hui Lin:** Resources. …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

Acknowledgments

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References (35)

D. Bekaert *et al.*

Statistical comparison of InSAR tropospheric correction techniques

Remote Sens. Environ. (2015)

G. Brakenridge *et al.*

Design with nature: causation and avoidance of catastrophic flooding, Myanmar

Earth Sci. Rev. (2017)

D. Chen *et al.*

Recent evolution of the Irrawaddy (Ayeyarwady) Delta and the impacts of anthropogenic activities: a review and remote sensing survey

Geomorphology (2020)

L. Chen *et al.*

Landslide susceptibility assessment in multiple urban slope settings with a landslide inventory augmented by InSAR techniques

Eng. Geol. (2023)

M. Crosetto *et al.*

Persistent scatterer interferometry: a review

ISPRS J. Photogramm. Remote Sens. (2016)

J. Dong *et al.*

Improved correction of seasonal tropospheric delay in InSAR observations for landslide deformation monitoring

Remote Sens. Environ. (2019)

W.L. Hakim *et al.*

InSAR time-series analysis and susceptibility mapping for land subsidence in Semarang, Indonesia using convolutional neural network and support vector regression

Remote Sens. Environ. (2023)

S.Y. He *et al.*

Shrinking cities and resource-based economy: the economic restructuring in China's mining cities

Cities (2017)

T. van der Horst *et al.*

Monitoring land subsidence in Yangon, Myanmar using Sentinel-1 persistent scatterer interferometry and assessment of driving mechanisms

Remote Sens. Environ. (2018)

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Remotely sensing large-and small-scale ground subsidence: A case study of the Guangdong–Hong Kong–Macao Greater Bay Area of China

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> …MT-InSAR measurements' line of sight (LOS) deformation was directed towards the down-slope to identify slope dynamics. These measurement points will be used for the analysis of slope dynamics in Hong Kong (Ma et al., 2024a,b). It should be noted that we have only processed the InSAR data in proximity to the periods in the most recent ENTLI updates (2019) for the timeliness of the data.…

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> …As an ionized region coupling the thermosphere and exosphere, it serves as an important indicator of space weather conditions and influences atmospheric processes (Cander, 2019). Moreover, the ionosphere represents a primary source of error for radio signal-based systems such as telecommunications, navigation, and Earth observation (Cander, 2019; Ma et al., 2024). Numerous studies have also demonstrated the coupling between ionospheric activity and natural hazards such as earthquakes, tsunamis, typhoons, hurricanes, and volcanic eruptions (Astafyeva, 2019; Li et al., 2017).…

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> …Given these challenges, there is a pressing demand for a SAR-based reference-free surface melt detection method that offers higher accuracy and a more straightforward processing pipeline Recently, deep learning has shown superior performance in many computer vision fields (Ma et al., 2024b; Wu et al., 2023). Compared with conventional methods, deep learning methods generate features tailored for the applications automatically, rendering these methods a better choice.…

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