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*Editorial*

# Geodetic Monitoring for Land Deformation

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## 1. Introduction

Land deformation is a pervasive hazard that could lead to serious problems, for example, increasing risk of flooding in coastal areas, damaging buildings and infrastructures, destructing groundwater systems, generating tension cracks on land, and reactivating faults, to name only a few. Hazards caused by land deformation have been reported in many places around the world. Consequently, it is critical to monitor land deformation so that the land surface change and/or movement can be better understood and managed for safeguarding lives.

In the past decades, modern geodetic measurement techniques such as radar interferometry (InSAR), global navigation satellite systems (GNSS), light detection and ranging (LiDAR), close-range photogrammetry (CRP), Robotic Total Station (RTS), digital levelling, etc., have played a very important role in measuring land deformation. With the continuous advancements in geodetic measurement techniques, precise land deformation can be detected in high spatial and temporal scales with the diversification of sensors and processing methods. This has led to extensive applications in the spatio-temporal analysis of areas prone to deformations. These applications have become momentous for surveyors, environmental engineers, disaster managers, urban planners, etc. As such, we organized this Special Issue to cover the latest developments and applications in geodetic measurement techniques.

The Special Issue "Geodetic Monitoring for Land Deformation" of *Remote Sensing* consists of 14 individual works by researchers from various countries and a variety of geodetic measurement techniques and applications, including landslide monitoring, glacier mapping, infrastructure deformation detection, mine subsidence monitoring, and land surface mapping. This editorial provides an overview of the studies presented in this Special Issue. For the ease of access to the readers, a summary of the input data and techniques used in each paper and their applications is provided in Table 1.



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**Table 1.** Overview of geodetic monitoring methods, data, and geohazard types that are discussed in the fourteen research papers composing the Special Issue "Geodetic Monitoring for Land Deformation" of *Remote Sensing*. Papers are sorted in ascending order according to their publication date.

| Source | Title | Geographic Focus | Applications | Techniques | Data |
|---|---|---|---|---|---|
| Wu et al. [1] | Comparative Analysis of the Effect of the Loading Series from GFZ and EOST on Long-Term GPS Height Time Series | Global | GPS Height Time Series | Comparative Analysis | GNSS |
| Wyszkowska et al [2]. | Determination of Terrain Profile from TLS Data by Applying $M_{split}$ Estimation | Not applicable | Determination of Terrain Profile | $M_{split}$ Estimation | TLS |
| He et al. [3] | Analysis and Discussion on the Optimal Noise Model of Global GNSS Long-Term Coordinate Series Considering Hydrological Loading | Global | GNSS Long-term Coordinate Series | Comparative Analysis | GNSS |
| Cai et al. [4] | An Accurate Geocoding Method for GB-SAR Images Based on Solution Space Search and Its Application in Landslide Monitoring | Sichuan | Landslide Monitoring | GB-SAR Interferometry | GB-SAR UAV |
| Jia et al. [5] | A Semi-Automatic Method for Extracting Small Ground Fissures from Loess Areas Using Unmanned Aerial Vehicle Images | Qinghai; Gansu | Ground Fissure detection | Image Classification, Image Segmentation, Feature Extraction | UAV |
| Gong et al. [6] | Retrieve Ice Velocities and Invert Spatial Rigidity of the Larsen C Ice Shelf Based on Sentinel-1 Interferometric Data | Antarctica | Glacier Flow Monitoring | InSAR, Pixel Offset Tracking | Sentinel-1 SAR |
| Luo et al. [7] | A Loading Correction Model for GPS Measurements Derived from Multiple-Data Combined Monthly Gravity | Global | GPS Time Series | Comparative Analysis | |
| Kuang et al. [8] | Displacement Characterization and Spatial–Temporal Evolution of the 2020 Aniangzhai Landslide in Danba County Using Time-Series InSAR and Multi-Temporal Optical Dataset | Sichuan | Landslide Monitoring | InSAR; Pixel Offset Tracking | Sentinel-1 SAR; PlanetScope |

**Table 1.** *Cont.*

| Source | Title | Geographic Focus | Applications | Techniques | Data |
|---|---|---|---|---|---|
| Yan et al. [9] | Construction of "Space–Sky–Ground" Integrated Collaborative Monitoring Framework for Surface Deformation in Mining Area | Shendong | Mine Subsidence mapping | Collaborative Monitoring; InSAR; TLS; UAV; GNSS CORS; Ground Surveying | UAV infrared; TLS; Sentinel-1 SAR; GNSS; Steel ruler |
| Zhang et al. [10] | The Current Crustal Vertical Deformation Features of the Sichuan–Yunnan Region Constrained by Fusing the Leveling Data with the GNSS Data | Sichuan–Yunnan | Crustal Movement observation | Data Fusion; GNSS; Ground Surveying | GNSS; leveling |
| Xing et al. [11] | Measuring Land Surface Deformation over Soft Clay Area Based on an FIPR SAR Interferometry Algorithm—A Case Study of Beijing Capital International Airport (China) | Beijing | Urban Subsidence | InSAR; FIPR | TerraSAR-X SAR |
| Liu et al. [12] | Quantitative Evaluation of Environmental Loading Products and Thermal Expansion Effect for Correcting GNSS Vertical Coordinate Time Series in Taiwan | Taiwan | GPS Height Time Series | Comparative Analysis | GNSS |
| Jiao et al. [13] | Comprehensive Remote Sensing Technology for Monitoring Landslide Hazards and Disaster Chain in the Xishan Mining Area of Beijing | Beijing | Landslide Monitoring | InSAR; Change Detection | RadarSAT-2 SAR; Quickbird; GeoEye-1; Worldview-2; Pleiades; BJ-2; Aerial Photo |
| Han et al. [14] | A Deep Learning Application for Deformation Prediction from Ground-Based InSAR | Sichuan | Landslide Monitoring | GB-InSAR Time Series Analysis | GB-SAR |

## 2. Detection of Land Movement Using Remote Sensing Techniques

The use of modern geodetic monitoring technologies to accurately identify the deformation zones and examine their dynamics is one of the important applications in environmental monitoring. Time-series InSAR (TS-InSAR) has been widely used for mapping long-term deformation in recent years because of its capability for deriving accurate time-series measurements at millimeter accuracy with large spatial coverage. The conventional TS-InSAR technique often requires mathematical empirical models which may not be optimized for describing the nonlinear characteristics of the movement, such as temporal settlement evolution for soft clay. To overcome this limitation, Xing et al. [11] proposed a modified TS-InSAR algorithm, namely FIPR (FastICA Poisson curve reciprocal accumulation method) for mapping infrastructure built on soft clay. This proposed algorithm first separates the original InSAR unwrapped phase information based on FastICA, and then models each extracted deformation component based on its physical characters. The extracted soft soil-related physical deformation component is modelled with Poisson function, and the reciprocal accumulation method (RAM) is utilized to derive the model parameters to generate the total time-series deformation. Xing et al. [11] applied the proposed algorithm over the Beijing Capital International Airport in China, which showed an improvement in modelling accuracy by 36.6% and 16.1%, respectively, for the proposed model compared to the EWA-LM (linear model with equal weight accumulation) algorithm and the EWA-PC (Poisson curve with equal weight accumulation) algorithm.

Gong et al. [6] used a set of Sentinel-1 SAR imagery to retrieve the ice flow velocities of the Larsen C Ice Shelf (LCIS) in Antarctica and then inverted the rigidity of the LCIS based on the deformation data obtained. Since the Sentinel-1 SAR imagery from only one viewing geometry was available for the study, the direct retrieval of 2D velocity field was not possible. Gong et al. [6] proposed to use the artificial neural network (ANN) to recover the azimuth displacement obtained from pixel offset tracking (POT) techniques and integrated with the InSAR results to retrieve the 2D velocity field.

Feature extraction from remote sensing data is widely used to monitor geological hazards caused by land movement. However, conventional extraction techniques are not ideal when dealing with the image of the loess regions due to their rich texture information. Jia et al. [5] proposed an advanced MF-FDOG algorithm for rapid and precise acquisition of ground fissures in the loess areas. Jia et al. [5] applied the proposed data processing scheme with the UAV images acquired at the complex mountainous terrain regions in Qinghai and Gansu for ground fissures extraction. Jia et al. [5] demonstrated that small ground fissures in loess areas can be extracted from high-resolution UAV images with better accuracy and robustness compared to the conventional methods.

## 3. Mapping Ground Deformation with Fusion of Multiple Datasets

An interesting topic included in this Special Issue is the fusion of multiple geodetic techniques to enhance the mapping capability for various land deformation applications. With the rapid advancement in the diversity of geodetic monitoring techniques, modern geodetic monitoring techniques have the capability to obtain a full of multi-temporal subsidence patterns of the land with various spatial resolutions and coverage. Since different geodetic monitoring techniques have their unique strength, ways to fully utilize these techniques for land subsidence applications is an issue needed to be solved.

GNSS is currently of the most popular geodetic monitoring techniques for surveyors and engineers worldwide. One of the major limitations for GNSS in deformation mapping is that even though the of number stations has increased significantly in the past decades, the spatial resolution of the measurement is still one of its weaknesses compared to other modern geodetic technologies. In order to deal with this issue, Zhang et al. [10] fused the levelling measurements with the GNSS measurements to derive the regional vertical motion field of Sichuan–Yunnan region in China with enhancement in spatial resolution. Zhang et al. [10] used the least squares collocation method to obtain the crustal vertical movements in Sichuan–Yunnan region by combining the high-precision levelling data of 1970s–2010s and the GNSS observation of 320 GNSS stations in the China Crustal Movement Observation Network (CMONOC) and the China Continental Tectonic Environment Monitoring Network (CMTEMN) from 1999 to 2017. Zhang et al. [10] demonstrated that fusion can improve the precision of the vertical subsidence rates in large spatial scales with finer spatial resolution over the region.

Yan et al. [9] established a "space–sky–ground" integrated monitoring framework for mine subsidence monitoring applications. Yan et al. [9] successfully applied the framework for mapping the mine subsidence of a Shengdong coal mine and demonstrated that the framework established, together with the Analytic Hierarchy Process Technique for Order Preference by Similarity to Ideal Solution (AHP-TOPSIS) model, can obtain a more comprehensive information of the subsidence evolution of the site compared to the single monitoring technique.

**4. Monitoring Landslide and Slope Stability**

Landslides are natural phenomena distributed all around the world. In the past, mapping and monitoring landslides was difficult because many of the landslides occur in remote and rural areas that are often inaccessible. With the advancements in remote sensing technology, the use of remote sensing techniques for monitoring the landslide has become a very popular research topic in recent years, especially in China. Many studies have been conducted on the landslide monitoring methods with various remote sensing sensors and platforms.

Kuang et al. [8] jointly used the Sentinel-1A/B satellite SAR data and the PlanetScope satellites optical images to investigate the deformation time series for the Aniangzhai (ANZ) landslide in Sichuan Province, China. Kuang et al. [8] used optical pixel offset tracking (POT) and InSAR techniques to map the pre- and post-failure surface deformation over the ANZ slope. Kuang et al. [8] was able to identify and characterize several areas of pre-failure movements before the re-activation of the ANZ landslide, and suggested that the most significant triggering factor for the landslide was because of the heavy rainfall. In another article, Jiao et al. [13] collected multi-temporal remote sensing data to extract the deformation information of the landslides in Beijing, China from optical images and time-series InSAR. Jiao et al. [13] demonstrated the capability to use the high-resolution optical images and InSAR data to identify and track the surface deformation of the landslides in Anzigou ditch, Beijing. By analyzing the deformation time-series data together with the temperature and geological data, Jiao et al. [13] determined that the landslide evolution process is closely related to the geological conditions, where the medium and large landslides may occur and trigger a "Quarry–Landslide–Mudflow" disaster chain. The information obtained from multi-platform and multi-sensory remote sensing technologies can be very useful for geological disaster prevention and disaster warning forecasting.

Although the use of InSAR for monitoring ground deformation was first developed for spaceborne application, it has later extended to observations using ground-based SAR sensors because of its capability of high precision as well as high resolution in spatial and temporal domains. Ground-based synthetic aperture radar interferometry (GB-InSAR) has become a popular geodetic technique for monitoring slope instability, especially for landslide deformation monitoring applications. To accurately identify and locate the deformation target for early disaster warning, near real-time processing and high-accuracy geocoding are essential. To tackle the real-time processing problem, Han et al. [14] proposed an improved GB-InSAR time-series processing method based on the LSTM (long short-term memory) model. The method used the deformation and atmospheric parameters obtained from previous acquisitions as the dataset of the LSTM model to predict the deformation and atmospheric delay in the current acquisition. Since only the difference between the current acquisition and the previous one needs to be computed, the method greatly reduced the computer resources and processing time to deliver the time-series data in real time, which significantly improved the processing efficiency for deformation prediction and disaster warning forecasting. Han et al. [14] applied the proposed method to monitor the Guangyuan landslide in Sichuan Province, China. The results show that the proposed method processing time has improved by approximately 7.5 times compared to the traditional method with high deformation prediction accuracy and low memory requirement. To deal with the high-accuracy geocoding issue, Cai et al. [4] proposed an accurate GB-SAR image geocoding method based on solution space search. Cai et al. [4] proposed to use the external high-resolution DSM derived from the UAV photogrammetry to establish a GB-SAR coordinate transformation model to improve the geocoding accuracy. Cai et al. [4] applied the proposed method to monitor the Laoguanjingtai landslide in Sichuan Province, China. The results show that the method is useful in research aiming to overcome the problem of GB-SAR images for selecting the control points in a complex scattering environment. As a result, subpixel geocoding accuracy can be achieved.

## 5. Improvement of Current Geodetic Measurement Techniques

Another major aspect included in this Special Issue is the research on the improvement of the conventional geodetic measurement techniques.

Wyszkowska et al. [2] proposed an approach to apply the $M_{split}$ estimation in determining the terrain profiles from terrestrial laser scanning (TLS) point clouds. In the study, both squared $M_{split}$ estimation and the absolute $M_{split}$ estimation were considered. Wyszkowska et al. [2] demonstrated that even if there are outliers in an observation set, the proposed approach is still efficient and can provide good terrain profiles compared to the conventional least squares estimation. The result also suggested that better results can be obtained with absolute $M_{split}$ estimation than with the squared $M_{split}$ estimation.

There has been growing interest in positioning techniques based on GNSS for mapping global land deformation with a rapid increase in GNSS continuously operating reference stations in recent years. The study of improving the displacement estimation accuracy has hence become a hot topic, especially in using various loading correction models to improve the accuracy of the GNSS time-series estimation. Wu et al. [1] conducted a comparative analysis to investigate the effect of different loading products from GFZ and EOS, on nonlinear signals in GNSS vertical coordinate time series of 633 global GNSS stations. The results show that the environmental loading corrections are able to reduce the nonlinear deformation signal in most stations around the world, with average reduction rates of 10.6% and 15.4% for all stations after GFZ correction and EOST correction, respectively. Positive root mean square (RME) reduction rates are observed in 82.6% and 87.4% of the stations after GFZ correction and EOST correction, respectively. Wu et al. [1] demonstrated that the effects of environmental loading corrections are inconsistent amongst all stations, the reason for which can be the influence of the annual phase difference between GNSS vertical coordinate time series and the environmental loading products. Liu et al. [12] later conducted a similar study but focused on the GNSS network in Taiwan. Liu et al. [12] quantitatively evaluated the driving factors of nonlinear signals in vertical coordinate time series of stations in the GNSS network, including atmospheric loading (ATML), hydrological loading (HYDL), and non-tidal ocean loading (NTOL) effects. Liu et al. [12] showed that there was no significant difference in correction performance of different environmental loading products. Liu et al. [12] suggested that the combination ATML (GFZ_ECMWF IB) + HYDL (IMLS_MERRA2) + NTOL (IMLS_MPIOM06) is the most suitable for GNSS network in Taiwan Province. Aside from using the common GCM-based loading models, Lu et al. [7] investigated the use of the multiple-data-based combined monthly gravity products LDCmgm90 to provide improved surficial loading models. Lu et al. [7] applied the LDCmgm90 loading model at 249 Global GNSS stations, and compared the results with the three GCM-based loading models, i.e., IMLS, EOST, GFZ models. The result shows that the correction obtained from LDCmgm90 is more effective in attenuating seasonal loading signals compared to the IMLS, EOST, GFZ models. In addition, the use of LDCmgm90 shows a significant improvement to most stations for both data-trend-removed and the data-trend-retained cases. He et al. [3] analyzed and discussed the optimal noise model characteristics of global GNSS time series data of 671 IGS reference stations from 2000 to 2021. He et al. [3] analyzed different noise model combinations and computed the optimal noise model for each station before and after hydrologic loading correction. The results show that optimal noise model characteristics of most stations can be classified into three main categories: white noise + flicker noise, generalized Gauss–Markov noise and white noise + power law noise. The maximum velocity influence value can reach 1.8 mm when hydrological loading is considered.

These selected 14 papers offer a significant contribution to geodetic monitoring for land deformation. With the advance of remote sensing techniques, increase in open earth observation data, and rapid development of machine learning and artificial intelligence, we look forward to upcoming novel research on land deformation mapping.

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