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Editorial

Editorial for Special Issue "Ground and Structural Deformations Monitoring Systems Integrating Remote Sensing and Ground-Based Data"

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1. Introduction

Ground deformations due to landslides [1], land subsidence [2], sinkholes [3], volcanic eruptions [4], earthquakes [5] and coastal changes [6] affect many different communities around the world: the main effects can be environmental degradation, interruption of services, and damage to buildings and infrastructures.

Monitoring activities allow to obtain useful information to mitigate the risk, implement more sustainable urban planning and prevent damage to buildings and infrastructures. To this end, information related to the temporal and spatial distribution of surface deformation are essential to detect the most critical areas and understand the mechanisms of the causative processes [7]. These data can be acquired using satellite-based methods, mainly satellite images and Differential InSAR (Interferometric Synthetic Aperture Radar—DInSAR), and ground-based techniques such as classical topography, leveling, GPS-GNSS (Global Positioning System—Global Navigation Satellite System), TLS (Terrestrial Laser Scanning), including photogrammetric and ALS (Airborne Laser Scanning) acquisitions from drones-airplanes-helicopters: the obtained data provides useful information that must be managed taking into account advantages and disadvantages of each approach.

Multi-temporal DInSAR techniques (both Permanent Scatterer Interferometry—PSI and Small Baseline Subset—SBAS approaches) present many advantages [8], allowing to obtain deformation rates over wide areas in all-weather working conditions, with high spatial resolution, cost effectiveness, and millimetric accuracies. Furthermore, the calculation of the vertical and east–west components of the displacements is possible combining SAR images acquired in both ascending and descending geometries [7,9]. On the other hand, the information derived by these techniques are restricted to the urbanized and rocky outcrop areas, where the coherence of the ground-targets is maintained in time and the information is strictly influenced by the Ground Sample Distance (GSD) of the SAR images. In addition, the deformation values are provided along the Line of Sight (LOS) direction if only a single geometry acquisition is available and, in any case, the estimation of north-south component of the planimetric deformation is severely limited. Finally, the information must be calibrated using ground-based data and the temporal coverage is limited to the last thirty years [10].

Ground-based classical topography, in particular the geometric leveling, provides accurate data, in the order of 2 mm/km [11] that, in many cases, can cover many decades with multi-temporal measurements. The main disadvantages are: (i) only the vertical component of deformation can be measured, (ii) the technique is time- and cost-consuming, and (iii) the spatial resolution of the measured points is low.

The GPS-GNSS measurements allow continuous or repeated 3D acquisitions of points with accuracies to the centimeter [1,10]. Compared with the leveling, the costs are lower and

Citation: Fabris, M.; Floris, M. Editorial for Special Issue "Ground and Structural Deformations Monitoring Systems Integrating Remote Sensing and Ground-Based Data". *Remote Sens.* **2023**, *15*, 3013. https://doi.org/10.3390/rs15123013

Received: 23 May 2023
Revised: 6 June 2023
Accepted: 6 June 2023
Published: 9 June 2023

the spatial resolution can be similar (not permanent stations—NPS) or lower (permanent stations). The technique integrates well with the InSAR once the interferometric data are calibrated and the information on vegetated areas are densified [10].

The photogrammetric approach is very useful in acquiring 3D metric information over unstable areas. Thanks to the availability of data, multi-temporal aerial images are used to observe ground displacements for long periods, up to 80–90 years, with high spatial resolution and information distributed over large areas, but with accuracies ranging from tens of centimeters to meters [6]. At present, the use of drones equipped with a photogrammetric camera allows for repeated surveys of portions of the ground and/or buildings and infrastructures, to extract 3D models for monitoring deformations with accuracies in the order of centimeters and very high spatial resolution [12]. In addition, the development of the LiDAR (Light Detection and Ranging) technique, both with ALS and TLS approaches, including the use of the sensors on drones, has made it possible to improve the acquisition of 3D data with characteristics that, in many cases, are similar or better than the standard photogrammetric approach.

Ground- and satellite-based techniques are characterized by different approaches, procedures, spatial resolutions, accuracies, spatial and temporal coverage, but only the integration between them allows to overcome the limitations of each one, providing a complete and accurate 3D metric information for deformations monitoring. These reasons have driven this Special Issue to address the challenges related to the integration of different type of data, in very different geomorphological contexts and to define integrated deformation monitoring systems, necessary for the management of natural and/or artificial phenomena.

This Special Issue consists of twelve papers that have used different approaches and techniques, and ground-based and satellite-based data for monitoring deformations. In the next section, the general contribution of each work to the Special Issue is summarized.

2. Overview of Contributions

The papers included in this Special Issue cover a wide spectrum of applications related to the deformation monitoring systems integrating remote sensing and ground-based data in different areas of the world and characterized by multi-source information. The accepted works are briefly presented here in publishing order.

Beccaro et al. [13] have performed an interferometric analysis of satellite SAR data to detect and monitor ground deformations affecting the Ischia Island (Naples, Italy) between November 2002 and December 2019. The authors have processed different datasets, including Envisat, COSMO-SkyMed and Sentinel-1, using the SBAS multi-temporal differential interferometry technique. The derived ground velocity maps and displacement time series were validated through GPS measurements of 20 points distributed in the study area. They obtained a highest subsidence rate range from 10 to 20 mm/year and a clear correlation between the measured ground deformations and the seismic swarm that started on 21 August 2017 with a Mw 3.9 earthquake.

Vitagliano et al. [14] have estimated the periodic component of vertical land motion in Po River Delta (Italy) using a multi-component and multi-source procedure. The authors have considered GPS data acquired from April 2011 to June 2017 at the TGPO permanent station, together with hydro-meteorological and climate datasets of the study area. They implemented four models to verify the annual water pressure- and water mass-dependent processes. The results highlight that the ground oscillation is mainly related to the changes in soil moisture, even if the variation of the river water mass has a relevant contribution in the deformation. Furthermore, the authors have analyzed the joint contribution of different sources to evaluate intra-annual processes: these contributions were addressed as a non-linear problem and solved using the generalized reduced gradient method. The obtained combination, supported by a statistical analysis, provided the best correspondence with the geodetic data.

Zhang et al. [15] have proposed a two-stage deep learning network (InSARNet) to detect anomalous ground deformation in Maoxian County, Sichuan Province (China), using SAR data acquired by the Sentinel-1A mission from January 2015 to July 2017. The authors compared the proposed method with other commonly used detection models: the results highlighted better performances and higher quantitative evaluation indexes of the InSARNet method in mountainous areas. Combining the anomalous deformation areas with the location of roads and rivers, they have identified the potential landslides, providing a scientific theoretical support for local instability assessment.

Peng et al. [16] have proposed a calculation method to evaluate the ground tidal effect on DInSAR interferograms mosaic along the west coast of the US. The authors analyzed long strip differential interferograms, integrating the tide displacement measured by 1038 GPS stations of the Plate Boundary Observation (PBO) network (data from 2014 to 2019), the FES2014+osu.usawest model and the Solid Earth Tide (SET) model in the 2010 IERS Convention. They have generated a three-dimensional ground Ocean Tidal Loading (OTL) displacements grid: the results show displacement of SET and OTL effects up to 77.5 mm (19.3% of the displacement component). In addition, movements of up to 20.3 mm in the mosaicked interferograms can be estimated by the tidal residuals generated using the classical bilinear ramp fitting methods. Finally, they verified that the proposed method can eliminate the tendency of tidal displacement in complex coastal areas.

Peternel et al. [17] have analyzed continuous and periodic deformations of the Urbas landslide (Slovenia) integrating data from different sources: (i) 5 low-cost dual-frequency GNSS permanent stations that provided displacements estimation in the period October 2019-August 2021; (ii) 3 acquisitions of Unmanned Aerial Vehicle (UAV) photogrammetric images (September 2019, May 2020, and September 2020) that have been used to evaluate the rate of erosion and accumulation of material; (iii) a wire extensometer (data from September 2019 to August 2021), six piezometers and inclinometers; (iv) hydrometeorological measurements (groundwater table, rainfall). The authors observed different dynamics of the displacements in the landslide area associated with different triggering mechanisms, depending on the local geological and hydrogeological conditions.

Khan et al. [18] have studied land subsidence affecting the Greater Houston and surrounding areas (US) using InSAR data derived from Sentinel-1A images acquired in the period March 2016–December 2020: the results were validated using GNSS observations. To identify the areas undergoing significant land subsidence, the authors performed emerging hot spot analysis on InSAR displacements. Optimized hot spot analysis was applied to: (i) groundwater level data collected from 71,170 water wells in the period January 1990–March 2021, analyzing the correlation with the deformation patterns of fault surface; (ii) known locations of 5948 active oil and gas storage wells to assess the influence of oil/gas pumping. The results highlight that land subsidence is up to −9 cm of the total LOS displacement, and the main triggering factor is the high rate of water extraction, while the oil/gas withdrawal plays an important role only in a few areas.

Zhang et al. [19] have combined DInSAR and UAV photogrammetric techniques to perform high precision monitoring of surface subsidence caused by coal mining in the Yangquan mine (Shanxi Province, China). The authors processed four ascending Sentinel-1A SAR images acquired on 4 June, 26 June, 8 July, and 20 July 2020. They collected: (i) UAV data on the study area on 14 June and 20 July 2020 using a D2000 FEIMA drone, equipped with a visible light D-CAM2000 sensor; (ii) leveling data on 14 June and 21 July 2022. The authors processed the UAV images using the Structure from Motion (SfM) technique, extracting the Digital Surface Model (DSM) and the Digital Orthophoto Map (DOP) of the study area for each survey. Comparing the DSMs of successive periods, they obtained the surface subsidence of the basin. Combining DInSAR and UAV techniques, the results have gained from both the high precision of UAV measurements in the center of subsidence areas and from the preservation of DInSAR data in perimeter monitoring.

Fabris et al. [10] have proposed an approach to integrate GNSS and InSAR techniques for land subsidence monitoring in the Po River Delta area (northern Italy). The authors used GNSS data from 3 continuous stations (CGNSS) and 46 Non-Permanent Sites (NPS) with surveys every two years from 2016 to 2020, and Sentinel-1 and COSMO-SkyMed InSAR data of the 2016–2020 period. In the first phase of the proposed method, they calibrated and verified the interferometric processing by means of the CGNSS measurements; subsequently, the calibrated InSAR data were used to validate the GNSS observations of the NPS. Finally, the authors combined the datasets to overcome the disadvantages of each technique, providing an efficient monitoring system of the study area. The results show high land subsidence rates along the coastal area with velocities up to 16–18 mm/year.

Duchnowski and Wyszkowska [20] have addressed the application of M_{split} estimation method in the processing of TLS data acquired in two different time periods, to model vertical displacements. The method can be performed with two options (i.e., the squared or absolute) and with two approaches (i.e., two point clouds or one integrated point cloud). In their study, the authors considered TLS data disturbed by positive and/or negative outliers: they applied the M_{split} estimation verifying the two approaches. In the results of simulated data, the absolute M_{split} estimation shows better values and overperforms conventional methods. In addition, if the magnitude of the terrain displacement is unknown, it is much better to process observation sets from both epochs separately than using the combined observation.

Zhang et al. [21] have studied the formation mechanism and evolution law of ground cracks caused by coal seam mining in a gully area of the southwest of Linfen City (Shanxi Province, China). The static distribution and dynamic change of the cracks in the internal and external areas of the working face (for which the mining time was from 5 August 2020 to 8 December 2020) were monitored using GPS-RTK (Real-Time Kinematic) positioning, UAV surveys and field measurements (performed in September, November, and December 2020). The authors observed a maximum subsidence value of 6364 mm, and a maximum horizontal movement of 2228 mm. Combining field investigation and numerical simulation results, they divided the ground cracks into dynamic in-plane and boundary cracks. Finally, the authors established a "goaf–surface" structure model to analyze the formation mechanism of ground cracks.

Mazza et al. [22] have assessed the performance of different remote sensing techniques to monitoring the Pietrafitta earth flow (Benevento Province, southern Italy). The authors compared and combined ground-based data collected during the reactivation of the landslide (between March and April 2016) by means of Robotic Total Station (R-TS) (from 5 April to 31 May 2016), Terrestrial InSAR (T-InSAR) (from 30 March to 18 May 2016) and TLS (7 scans from 29 March to 16 June 2016) with data derived by satellite-based Digital Image Correlation (DIC) (high-resolution RapidEye satellite images of 19 March and 30 April 2016) analysis. They found coherent observed deformation trends from R-TS and T-InSAR while the DIC analysis detected the kinematic process of the landslide. Finally, the authors have suggested the integration between different monitoring techniques in a multi-sensor approach to fully observe and understand the process involved.

Caprino et al. [23] have compared, calibrated and integrated Multi-Temporal InSAR (MT-InSAR) data with on-site measurement of deformation affecting the Civic Tower of L'Aquila city (Abruzzo Region, Italy), after the seismic event of 6 April 2009. The authors processed 34 COSMO-SkyMed images, acquired from September 2010 to February 2013, using the Permanent Scatterer-InSAR (PSI) technique, to estimate the movement of the tower and the surrounding area. In addition, changes of the damage pattern in the period 2010–2013 were obtained from a ground-based monitoring system installed on the tower. They obtained a consistent measurement of displacement trends of the structure by using both methods, detecting a slight rotation/displacement in the period under investigation.

Author Contributions: The two authors contributed equally to all aspects of this Editorial. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The guest Editors would like to sincerely thank all the Authors who contributed to this Special Issue and the Reviewers who dedicated their time and provided the Authors with valuable and constructive recommendations. They would also like to thank the Editorial team of Remote Sensing for their support.

Conflicts of Interest: The authors declare no conflict of interest.

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