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Infrastructure Non-Linear Deformation Monitoring Via Satellite Radar Interferometry

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Abstract

The advantages of satellite radar interferometry for displacement monitoring are demonstrated in the cases of monitoring man-made structures, i.e., buildings, bridges and dams. Presented are the results from application of PSInSAR technology using ENVISAT radar images over urban area of Bratislava (Slovakia). As a whole, the investigated urban area of Bratislava is stable with the linear displacement trends of ±3 mm/year. However, a non-linear approach reveals small movements on the structures without prior interest of any regarding conventional monitoring technique. Thanks to the development of high resolution SAR sensors (e.g. TerraSAR-X) many permanent scatterers can be found in one individual man-made construction. Moreover, with the shorter revisit times, it is possible to process a long series of SAR data and expand standard PS model to account for a seasonal expansion due to changes in water level and/or temperature. The topic of separation between deformations and seasonal movements is discussed within the exploitation of TerraSAR-X data for deformation monitoring of Plover Cove Dam and building of Hyatt Hotel, both located in Hong Kong. Data have been processed using advanced processing techniques implemented in SARPROZ. These techniques show high potential for continuous monitoring of ground motion and structure stability in civil surveillance.

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Keywords: PSInSAR; non-linear deformation; infrastructure monitoring; seasonal component; SARPROZ;

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1. Introduction

The traditional way of measuring the deformation of man-made structures is using geodetic surveying techniques such as levelling or satellite navigation (GNSS). These techniques, tough undeniably very accurate and reliable, are based on detecting the changes at specific points with the prior interest and investments in human resources and special equipment [1]. Due to recent developments in high resolution SAR sensors and exploitation of shorter revisit times (e.g. TerraSAR-X, COSMO-SkyMed), InSAR has a potential to outperform spatial and temporal resolution of ground-based measurements, while providing similar accuracy. As a remote sensing technique, InSAR could provide information about the urban targets without the previous interest of any conventional monitoring technique and on continuous basis. It turns out that InSAR is suitable for systematic deformation monitoring of structure stability in civil surveillance.

Presented results are based on the processing of focused SAR data using Persistent Scatterers InSAR [2,3], an advanced multi-temporal interferometry method implemented in SARPROZ [4,5,6]. To highlight the benefits of high resolution SAR sensors for the deformation monitoring purposes, two datasets have been used: ENVISAT radar images for deformation monitoring in urban area of Bratislava (Slovakia) and TerraSAR-X data for deformation monitoring and seasonal component estimation over Plover Cove Dam and Hyatt Hotel (Hong Kong).

Nomenclature

ASAR	Advanced Synthetic Aperture Radar
CSK	COSMO-SkyMed
GNSS	Global Navigation Satellite System
InSAR	Interferometric Synthetic Aperture Radar
LOS	line of sight of the satellite
PIL1, GKU4	identifier of GNSS stations
PSInSAR	Permanent Scatterers InSAR
SAR	Synthetic Aperture Radar
TSX	TerraSAR-X

2. Infrastructure Non-Linear Deformation Monitoring via Satellite Radar Interferometry

2.1 Deformation monitoring of Bratislava urban area

Bratislava, the capital city of Slovakia, is situated in its south-west on the borders with Austria and Hungary and near the border with Czech Republic. With an exclusive location and good infrastructure, the city attracts foreign investors and developers, what has resulted in unprecedented boom in construction in recent years. In the last five hundred years, the Danube River, which crosses the city caused a hundred of devastating floods. Therefore flood occurs every five years, on average. From geological point of view, the Little Carpathians horst and the area of Vienna Basin contains a number of tectonic faults, where the ground motions as a result of geodynamic processes were mostly expected [7]. It was assumed that all the phenomena stated above had an impact on the spatial composition of the Earth's surface in the urban area of Bratislava. For this research, the 57 ENVISAT ASAR images from ascending (32) and descending (25) track acquired in period of 2002 – 2010 were utilized. For the evaluation of PSInSAR potential to detect and monitor ground displacements, PS derived time series of a deformation signal were compared to the field GNSS data from two stations coded PIL1 and GKU4 (Fig. 1). The results show good agreement with each other considering opportunistic position of PS points.

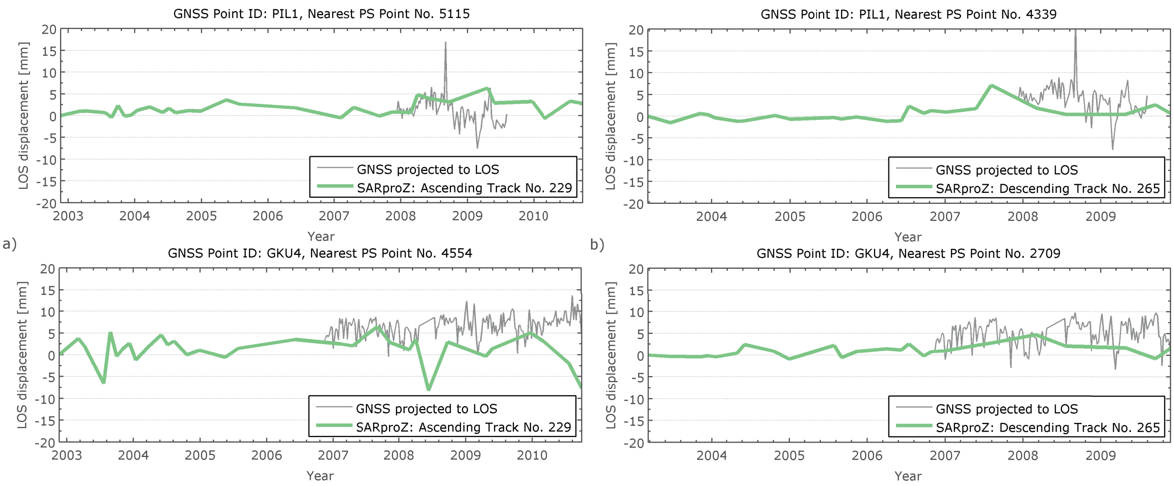

Fig. 1. Time series of GNSS deformation signal projected to the line-of sight vs. PSInSAR derived results from the nearest PS point for a) ascending track, b) descending track.

As researched by the standard PSInSAR methodology with the linear model assumption, the investigated urban area of Bratislava is stable with the linear deformation rates around noise level (±3 mm/year) (Fig. 2).

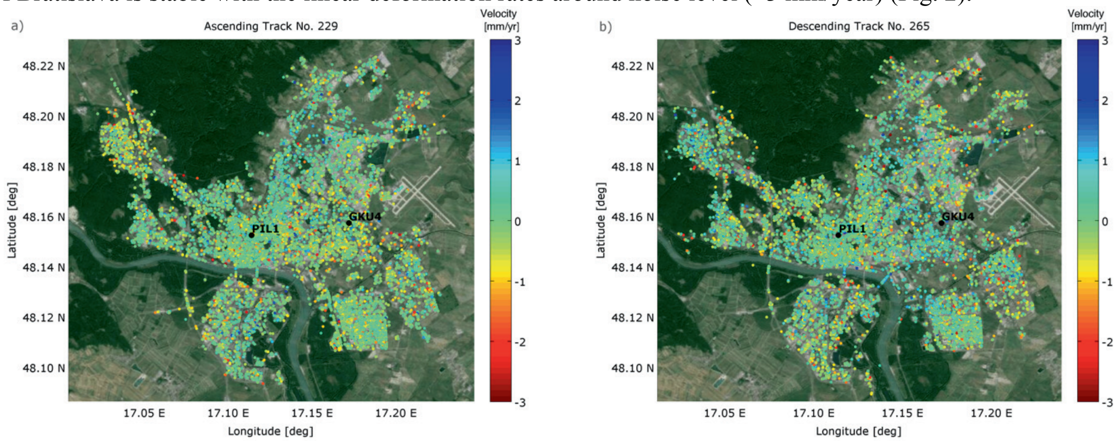

Fig. 2. Deformation maps of Bratislava urban area from PSInSAR processing of a) ascending track, b) descending track. Locations of GNSS stations are depicted by black dots labelled PIL1 and GKU4.

However, the adoption of non-linear deformation model reveals small movements on the structures without prior interest of any particular monitoring technique. When non-linear displacement movements are analysed, plotting the velocity map is useless. Cumulative displacement maps should be used instead. Here, the total amount of the millimetres that given point moved from the beginning to the end of the analysed period is mapped. The example of a non-linear movement detected by PSInSAR is shown in (Fig. 3). The depicted building is situated in the city centre near the Falkensteiner Hotel. The construction works on a hotel starts in September, 2007. From the time series of both ascending and descending track, it is clear that works on a hotel affected the stability of this building (Fig. 4) by the subsidence of up to –20 mm.

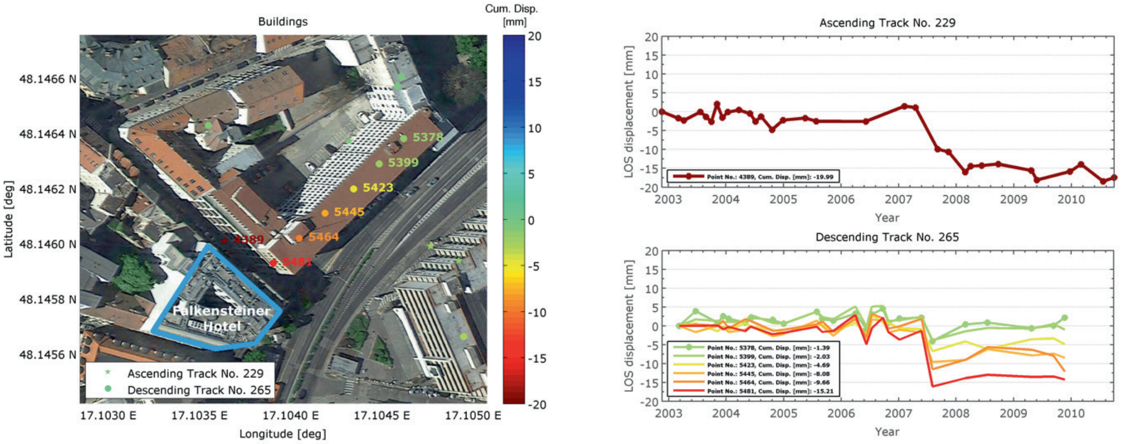

Fig. 3. Building affected by the mining of construction pit for a nearby hotel in September, 2007.

Fig. 4. Photo-documentation of structural deformations over building affected by the construction works on a nearby hotel.

The PS results over Gabcikovo Dam (Fig. 5) are showing slow subsiding motion. The time series are depicted for two nearby points obtained from different tracks. Incorporated non-linear deformation estimates indicate the similar behaviour observed by the ascending vs. descending acquisition geometry.

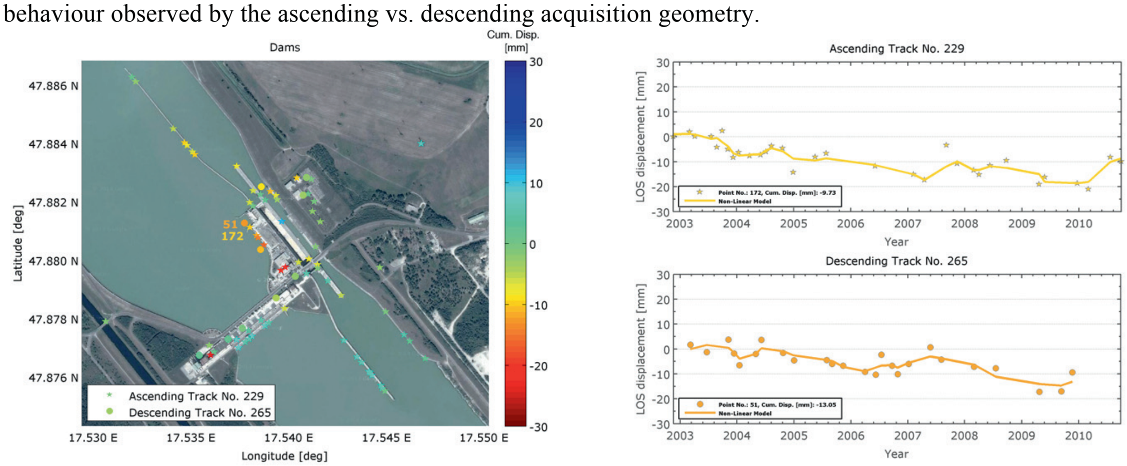

Fig. 5. Gabcikovo Dam as observed by the PSInSAR with assumption of non-linear deformation regime.

Another available ground truth data were levelling measurements over Old Bridge that was affected by the crash of an Austrian tug in 2010. The crash accelerated the deformation process observable since 2009 to such an extent that bridge has to be dismounted due to its emergency condition in 2014. Changes are observable in the time series from PSInSAR that are compared to the levelling data (Fig. 6). The misalignment between signals starting from 2009 may correspond to the different type of deformation phenomena observed at the points stabilized on the bridge deck (levelling) and scattered from the steel truss of the bridge (PSInSAR).

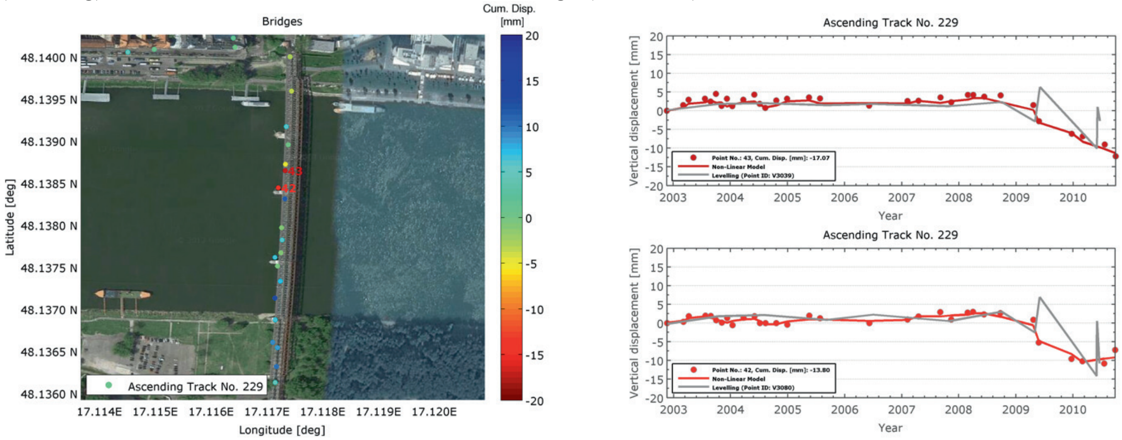

Fig. 6. Levelling vs. PSInSAR time series over bridge that was affected by the crash of a tug in 2010.

2.2 Deformation monitoring and seasonal component estimation over structures in Hong Kong

Thanks to the development of new X-Band high resolution SAR satellites, namely TerraSAR-X (TSX) launched by Germany and COSMO-SkyMed (CSK) by the Italian Space Agency, the possibilities of monitoring man-made structures of higher accuracy has become true. The new CSK and TSX sensors provide spatial resolutions in order of magnitude better than previously available satellite SAR sensors (e.g. ENVISAT). With shorter revisit times (11 days for TSX and up to 4 days for CSK), this appears to be more promising in monitoring dense linear-feature structures and rigid structures and providing more detailed ground features. For Plover Cove Dam monitoring we apply PS-InSAR technique to 73 scenes of data including 62 TerraSAR-X and 11 TanDEM-X images acquired between October 2008 and June 2012 in Hong Kong. Hundreds of permanent scatterers were successfully found and millimetric non-linear time series movements were detected on the road of the dam and embankments of the reservoir [8]. We correlated the PS-InSAR results with the water level data of the reservoir provided by Water Supplies Department (WSD) [9] of Hong Kong government. Using highly sampled dataset with external data about the water level of the reservoir it is possible to estimate its influence on the dam deformation.

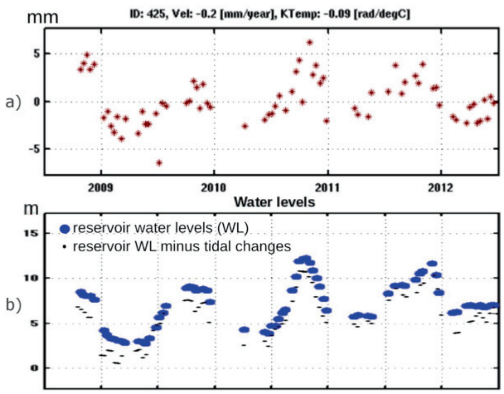

Fig. 7. Phase residuals recomputed as deformation in LOS (mm) of a) selected point on the dam surface, and b) water level of the reservoir (m) during acquisitions.

Water level data has been applied into the original dataset, in order to estimate this influence (Fig. 7). Majority of PS points over the dam shows strong correlation with water levels, with a correlation coefficient of up to k_{max} = ~0.65 rad/m. According to:

$$D_{\max} = k_{\max} \cdot E \cdot \lambda / 4\pi \tag{1}$$

where:

- D_{max} is the maximal deformation in LOS (mm),
- λ is the SAR carrier wavelength in (mm) (= 31.1 mm),
- k_{max} as the maximal estimated coefficient of linear correlation (rad/m) or (rad/°C),
- and E is the range of values of investigated parameter (m) or (°C),

it can be computed that if difference between the minimal and maximal water level is E = 9.8 m, maximal deformations caused by the water level can reach D_{max} = 16 mm in LOS. After correction of correlation with water level fluctuations, the residual signal shows a slowly approaching but linear trend, especially at the dam side closer to the reservoir. Very probably, this side is linearly subsiding - the subsidence velocity is estimated around 3 mm/year in satellite LOS [8]. Obviously this linear model of correlation with water level data seems simplified - a non-linear characteristics has to be searched for.

Following are the displacement analysis over the high-rise building of the Hyatt Hotel in Hong Kong (Fig. 8). The basement of the hotel structure looks stable, while the building facade is affected by the thermal expansion and by a slow constant displacement trend. Both displacement components are increasing with the building height. This is expected for what about the thermal expansion. An increasing linear displacement trend is on the contrary revealing an unexpected phenomenon. The only reasonable explanation is a horizontal movement, which corresponds to a slow tilting of the building. The top of the structure reveals 2 mm/year displacement in the satellite viewing direction, more than 3 mm/year if projected in the horizontal direction.

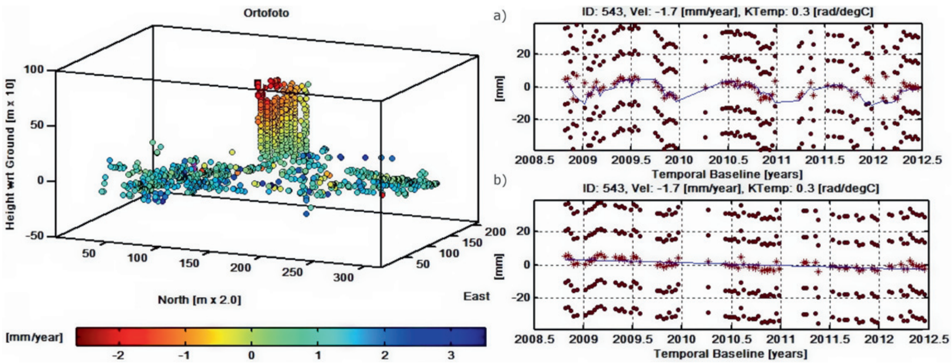

Fig. 8. Example of the displacement time series a) with the thermal expansion included b) after removal of estimated thermal expansion.

3. Conclusion

InSAR techniques can be recommended for the deformation monitoring of the man-made structures like buildings, bridges and dams. The main improvement achieved using PSInSAR technique was that uniform deformation at low rates could more accurately be assessed [10]. However, the standard PSInSAR algorithm is typically not successful in the case of higher deformation rates or non-uniform deformations [11]. In the case of information gaps for low-coherence areas or the difficulty to resolve high-phase gradients [12] a non-linear model for retrieving deformation signal has to be searched for. Thanks to the large dataset of frequently acquired high resolution SAR data (e.g. TSX, CSK), it is possible to properly discover various types of deformation movements. Due to their very high sensitivity, the influence of the various deformation sources, such as water level or temperature changes, can be precisely estimated.

Acknowledgements

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