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Multi-sensor InSAR deformation monitoring over urban area of Bratislava (Slovakia)

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Abstract

The integrated use of multiple Synthetic Aperture Radar (SAR) platforms for the deformation monitoring via satellite radar interferometry offers several perspectives for investigation of the behaviour of new and ageing structures, such as buildings and infrastructures, under varying or hazardous environment. Spanning almost 24 years of space-borne radar observations, this study aims to perform classical PSInSAR (Persistent Scatterer Interferometric Synthetic Aperture Radar) analysis incorporating measurements of ERS, Envisat, TerraSAR-X, Sentinel-1A and Radarsat-2 satellites. The results from the processing of different sensing geometries over Bratislava (Slovakia) urban area are presented, focusing on the description of characteristics associated with the specifics of every satellite platform in use. The discussion over technical feasibility of infrastructure monitoring is accompanied by the outline of possible future needs for the utilisation of the wealth source of information provided by the satellite radar imagery.

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1. Introduction

The formidable advantage of space-borne Interferometric Synthetic Aperture Radar (InSAR) is its ability to monitor small displacements over wide areas without the need for in-situ observations, while providing accuracy similar to the conventional terrestrial techniques (e.g. levelling or Global Navigation Satellite Systems, GNSS)[1]. InSAR has currently been applied in a number of applications encompassing the use of space-borne sensors operating at a range of wavelengths and resolutions. Results from multiple systems (operational since 1992) often reveal different features in the exact same scene. The repeat-pass nature and different system characteristics give rise to the low coherence due to temporal decorrelation over surfaces with vegetation changes or other surface change processes and geometrical decorrelation due to large perpendicular baseline between acquisitions[2]. The wide variety of currently available space-borne SAR sensors allows for the combined use of different frequencies and spatial resolutions for completeness and comparison reasons. Emphasizing the operational safety of anthropogenic structures as a common radar scattering objects and usual targets of conventional monitoring techniques[3], the InSAR technology appears to be a credible candidate for providing continuous deformation monitoring throughout the historical decades until now. Following the ongoing research, SAR data acquired by ERS, Envisat, TerraSAR-X, Sentinel-1A and Radarsat-2 satellites are utilized in order to improve the knowledge about the spatial and temporal evolution of the buildings and infrastructures within the urbanized area of Bratislava, capital city of Slovakia. Thanks to the relentless boom in construction, floods occurring every five years on average, geology containing number of tectonic faults and considerable amount of heritage structures in the center and industrial complexes on the outskirts, structures safety concerns gain in importance. Moreover, with the evidence of buildings affected by the static problems[4] and components of Gabcikovo-Nagymaros waterworks in surrounding, the efficient asset management to meet stringent demands on safety and reliable performance of such objects becomes a discipline of capital interest. With already operational Sentinel-1A mission and free accessible near-real time data, the experiments and comparisons on the performance of the system for urban deformation monitoring are carried out in order to develop effective monitoring strategies that would be able to continuously collect the physical and dynamic parameters of the areas of interest.

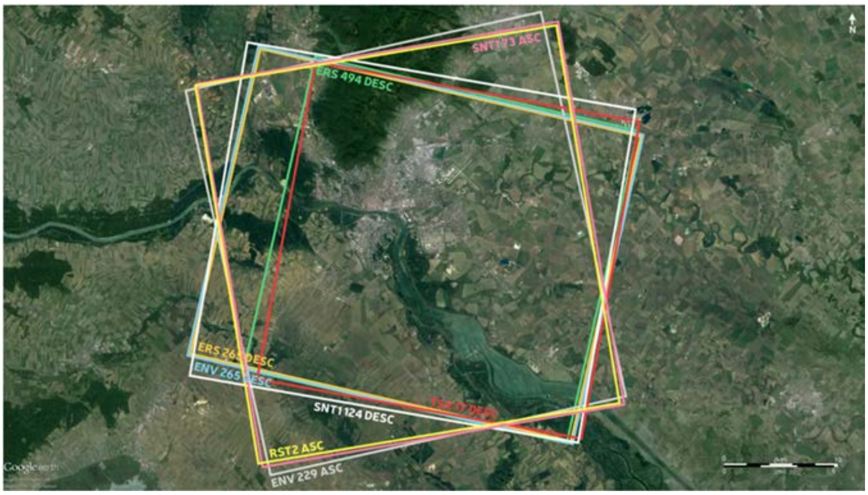

Fig. 1. An overview map of ground track of every SAR satellite platform in use.
(ENV – Envisat, TSX – TerraSAR-X, SNT1 – Sentinel-1A, RST2 – Radarsat-2, ASC – ascending, DESC - descending)

2. Study 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. The city has a total area of 370 km^2 and with a population of about 450 000, it is also the country's largest city. With an exclusive location and good infrastructure, the city attracts investors and developers, what has resulted in unprecedented boom in construction in recent years. Bratislava straddles both banks of the Danube River and the Carpathian mountain range begins in the city territory. In the last five hundred years, the

Danube River caused a hundred of devastating floods. From geological point of view, the Little Carpathians and the area of Vienna Basin are tectonically and seismically the most interesting regions of Slovakia[5]. The displacement time series over strategic objects are presented from monitoring of Cunovo dam. Cunovo dam is the first level of one of the biggest Europe's waterworks - Gabcikovo-Nagymaros (part Cunovo) producing 24 MW of electricity. In 1996, Europe's largest artificial whitewater slalom course, the Water Sports Centre Cunovo, was built on a river island at the head of the bypass canal. Interferometric Synthetic Aperture Radar (InSAR) techniques applied in this study shows high potential for continuous monitoring of ground motion and structural stability important for risk management applications.

3. Methodology

The work aims to perform Persistent Scatterer InSAR[6] analysis implemented in SARPROZ software[7,8], covering the target area with 332 radar images spanning 24 years (1992 - 2016) of SAR observations. The datasets analyzed in this work (Fig. 1) are summarized in Table 1.

Table 1. Dataset used and PS points availability

Satellite	Track	Pass	Images	Period	Master	Amount of PSs	Density (PS/km^2)
ERS	265	Descending	57	05/1992 - 12/1999	27-Jul-1996	11 295	43
	494	Descending	52	07/1992 - 12/1999	30-Mar-1998	13 337	51
Envisat	229	Ascending	32	11/2002 - 09/2010	07-Jun-2006	21 296	82
	265	Descending	25	03/2003 - 11/2009	30-Jul-2005	15 767	60
TerraSAR-X	17	Descending	75	10/2011 - 09/2014	02-May-2012	421 101	1625
Sentinel-1A	73	Ascending	36	10/2014 - 04/2016	01-Jul-2015	56 543	218
	124	Descending	38	10/2014 -04/2016	05-Jul-2015	56 782	219
Radarsat-2	Ord.	Ascending	17	05/2015 - 05/2016	30-Sep-2015	77 622	299

The area of interest to investigate the displacement phenomena is covering approximately 15.8 by 16.4 kilometres (≈259 km^2). The Master acquisitions have been selected by optimizing the distribution of perpendicular and temporal baselines, together with assessing the information about the water vapour content and precipitation during Master acquisition time[9]. For all interferometric pairs, the absolute values of perpendicular baselines are less than 1500 m. In the best case, the temporal baseline varies with the integer multiple of 35 days for ERS and Envisat, 11 days for TerraSAR-X, 12 days for Sentinel-1A and 24 days for Radarsat-2. The variation of perpendicular baselines is higher for former SAR missions ERS and Envisat, where usually a few (from 1 to 3) acquisitions reaches the so-called critical baseline (≈1.1 km), after which the data are fully decorrelated. However, this is not the case of new-born missions like TerraSAR-X, Sentinel-1A and Radarsat-2 where the absolute values of perpendicular baselines are lower than 300 m, 250 m and 150 m respectively, considering the fact that critical baseline value changes for each sensor, specifically for X-band (≈5 km) observations. The same tendency of improved orbital characteristics in modern satellites is evident in regard to the time sampling of the acquisitions as well. Whilst ERS and Envisat data are unequally sampled to the extent of 10 months' gaps between observations (beside the time gap of ERS SAR data at the end of 1993 until beginning of 1995), the time intervals between two successive acquisitions of TerraSAR-X, Sentinel-1A and Radarsat-2 are shorter and/or sampled much more regularly. During the course of processing the precise orbit data have been applied if available, and external LIDAR digital surface model (DSM) data have been used in order to get precise geolocation of PS (Persistent Scatterer) points[10,11]. For the same purpose, single ground control point (GCP) showing clear and unique reflection in reflectivity maps from all tracks have been selected. The LIDAR data have been acquired by National Forest Centre[12] using Leica ALS70 airborne laser scanner and processed with Terrasolid software[13]. According to data provider[12], the accuracy of a digital surface model is in range of 80-100 cm over urbanized areas, what is to be evaluated by in-situ measurements in future analysis. The a-priori selection of PS candidates was based on a combination of quality parameters related to the amplitude of the radar signal. First, a threshold of 0.7 on amplitude stability index[14] for creating a network to estimate preliminary parameters and atmospheric phase screen (APS) was used. Thus, the APS is estimated using targets with high amplitude stability in order to carry out the robust inversion using spatial and temporal filtering. The space smoothness assumption is implicit in the space connections of the APS graph and later in assuming a common reference point. By calculating the temporal coherence after removing the preliminary estimated parameters and the estimated APS, the coherence value is examined whether it preserves high and homogeneous values over the vast majority of analysed area. This implies that the preliminary parameters and the APS are matching the phase series of the data and selection of a larger set of points based on reflectivity map is possible during APS removal. After APS compensation, phase time series are analysed. Two key parameters are estimated here: height and velocity. The time smoothness assumption for estimating the linear trend (velocity) of the displacement is implicit for this step. For all multi-temporal InSAR approaches the model assumptions are assumed in order to solve the system of equations. The time and space smoothness assumption adopted in this work similarly to the classical PSInSAR[6] methodology, may cause the atmospheric signal to be contaminated by the signal of interest. In other words, a fast movement or a non-linear deformation we might be interested in, might falsely leak into the atmospheric signal. A phase delay atmospheric corrections based on meteorological models with assessment of the tropospheric noise artefacts[15,16,17] is recommended in order to better evaluate such problems. Since the tropospheric noise is expected to be smaller due to the smaller extent of the study area and due to geological background there are no expectations of events such as fast or non-linear movements, it is not applied here. Finally, for each PS a displacement time series related to the reference point identified in the stable area are computed. A joint reference point with constant amplitude behaviour in all SAR datasets and visible throughout the whole monitoring period was selected. The area of a reference point is localised in the stable part of the Slovnaft industrial zone over concrete silo structure, frequently monitored by internal measurements, that are subject to the restriction on disclosure of information. The reference point is same for all tracks and all sensing geometries in order to propagate errors of the reference point to all datasets similarly and keep results comparable.

4. Results

The line-of sight (LOS) velocities in millimetres per year obtained by PSInSAR processing are depicted for points with temporal coherence greater than 0.7 for every analysed track in Figure 2. The displacement rates are in common interval of ±5 mm/year, reaching the noise level of the technique. The positive values (blue colour) of LOS velocities are corresponding to displacement towards the satellite, i.e. uplift. On the other hand, red areas are showing subsiding parts of the displacement field or motion away from the satellite. Analysing the displacement maps, strong displacement momentum over wider areas of the image is not observable. The velocities are homogeneously constant, suggesting that the urban area is sufficiently stable, except the trends observable in Sentinel-1A (Fig. 2, f - g) that are most likely corresponding to the artefacts from processing of new TOPS (Terrain Observation with Progressive Scans) mode and need to be analysed further. The subsiding trends are also present in TerraSAR-X results within the vicinity of highways and railways communications (Fig. 2, e). Due to the different sensing geometries (ascending/descending) and satellites' characteristics the locations of PSs are corresponding to different points on the ground. Furthermore, due to varying incidence angle (ERS 23.2°, Envisat 22.8°, TerraSAR-X 31.1°, Sentinel-1A 39.2°, Radarsat-2 41.4°), the projection of the LOS displacement to the vertical direction differs for each satellite. Also, the scattering mechanism of C-band satellites (ERS, Envisat, Radarsat-2, Sentinel-1A) and wavelength of ≈5.6 cm differs from that of X-band (TerraSAR-X) in ≈3.1 cm wavelength. The Stripmap image mode of ERS and Envisat satellites also offers significantly lower spatial resolution of 30 m in comparison to 3 m resolution of TerraSAR-X data, 8 m for Fine Mode of Radarsat-2 data and 5x20 m spatial resolution of Interferometric Wide Swath mode of Sentinel-1A. For each sensor, the LOS velocities were projected to the vertical direction by dividing them by cosine of an incidence angle. The displacement maps can thus be connected together through the trivial regularization of the area into an equally sampled grid (Fig. 2, i). The strategy for connecting displacement maps holds for: 1) subdivision of the area into the regular grid of 100 x 100 m; 2) computing mean vertical velocities for the grid cells using all the scatterers allocated within the same cell, separately for each track; 3) merging grids from all tracks and computing mean of the vertical displacement for corresponding grid cells where PSs are present in all tracks (Fig. 2, i). A 100 x 100 m grid cell has been chosen as the availability of PSs in corresponding grid cells for all tracks is highest (2675) while going from 10x10 m (0), 20x20 m (73), 50x50 m (1662). This harsh process has informative character only and more complex approach should be considered. For the sake of bringing distortion into the spatial resolution of each sensor and biasing the estimated velocities, it serves for the identification of the areas that are observable from all sensors using classical PSInSAR analysis. The vertical displacements in common grid cells (Fig. 2, i) are not significant in size, however, spatially there are interesting differences in subsiding and uplifting tendencies over Petrzalka district and Slovnaft industrial zone.

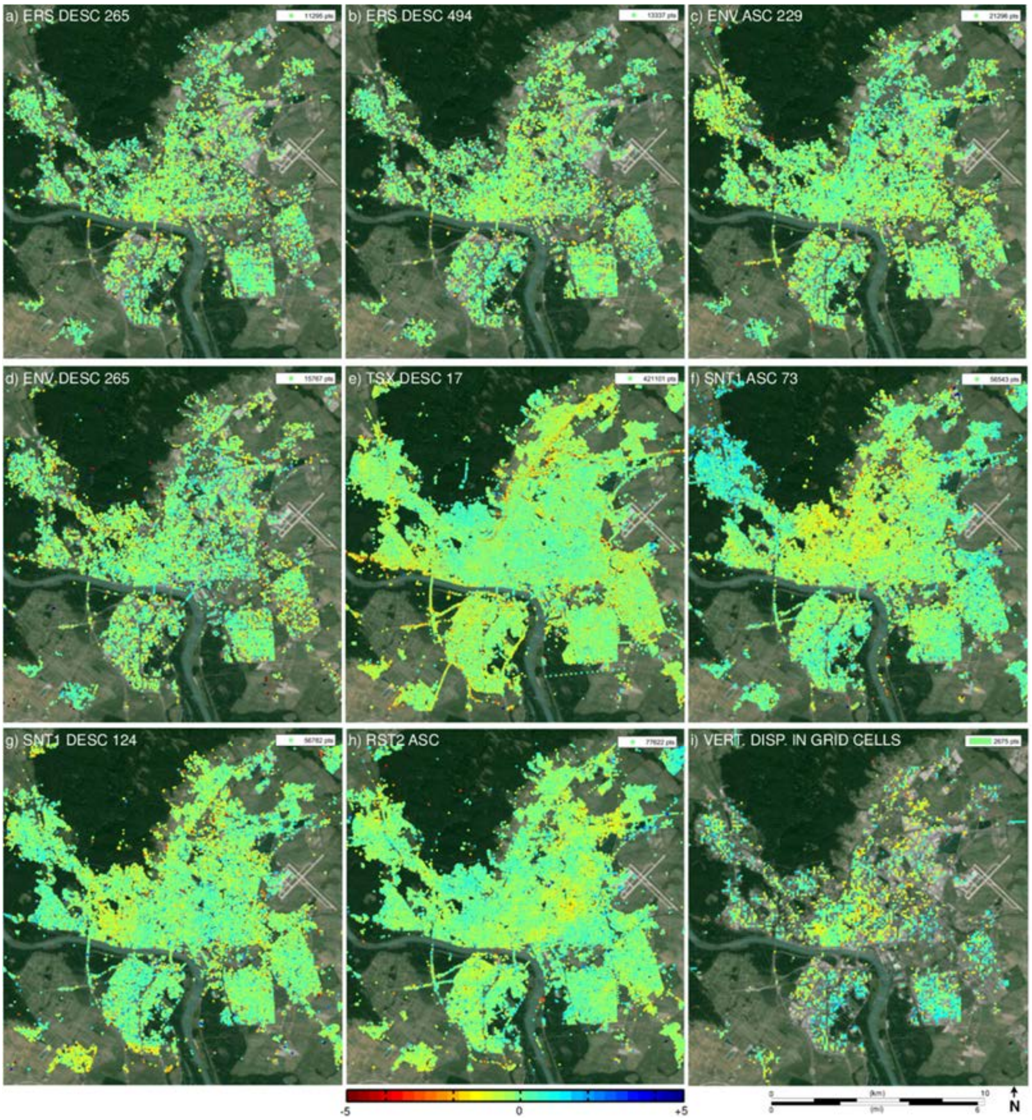

Fig. 2. Line-of-sight (LOS) velocities (mm/year) over Bratislava urban area from PSInSAR processing of (a) ERS descending track 265, (b) ERS descending track 494, (c) Envisat ascending track 229, (d) Envisat descending track 265, (e) TerraSAR-X ascending track 17, (f) Sentinel-1A ascending track 73, (g) Sentinel-1A descending track 124, (h) Radarsat-2 ascending track and, (i) mean vertical displacement (mm/year) in grid cells 100 x100 m with PSs available from all tracks.

5. Man-made structures monitoring

Thanks to the development of high resolution SAR sensors (TerraSAR-X) many permanent scatterers can be found in one individual construction (Fig. 3). Due to shorter wavelength (3.1 cm; TerraSAR-X) in comparison to those of C-band data (5.6 cm; ERS, Envisat, Sentinel-1A, Radarsat-2) the possibilities of monitoring man-made structures with higher accuracy has also become true.

Fig. 3. The PS availability over buildings of the Slovak University of Technology and the National Bank of Slovakia for different sensors. Visualized are the relative heights of PS points in (m) with respect to the reference DSM.

The displacement time series are demonstrated from the monitoring of Cunovo dam (Fig. 4) where terrestrial levelling data covering 21 years of monitoring period were available. From the TerraSAR-X measurements (Fig. 4) subsiding effects over dam peninsula are observable. For most of the components of the dam, the estimated velocities are within +-5 mm/year interval, however, significant displacement (of up to -10 mm/year) occurs over problematic parts of the dam peninsula and in Cunovo village on the west.

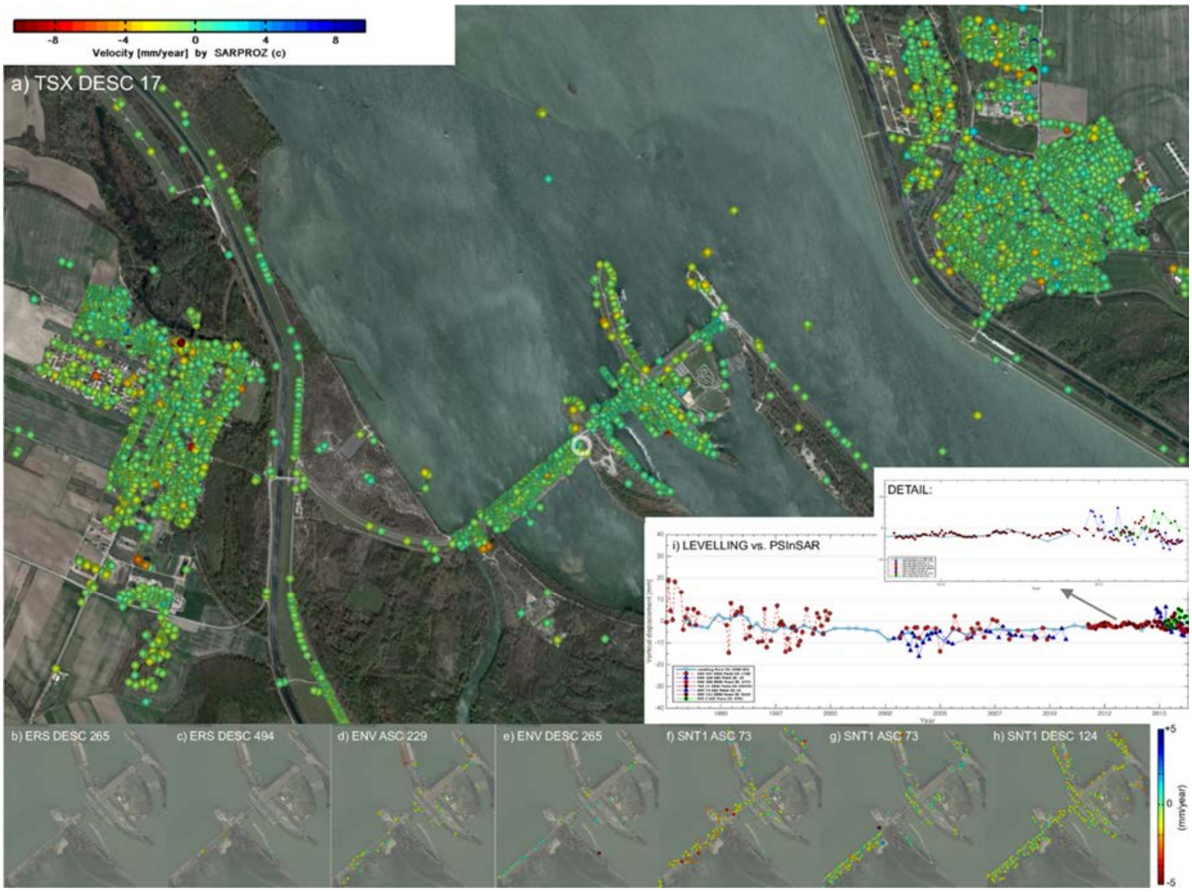

Fig. 4. (a) Line-of-sight (LOS) displacements (mm/year) over Cunovo dam and surrounding villages (Cunovo, Hamuliakovo) obtained from TerraSAR-X measurements. LOS displacement maps from other satellites in (b) – (h). In (i), PSInSAR vertical displacement time series in comparison to the levelling data (light blue). The vertical displacements (mm) plotted in (i) are corresponding to PS point located on the dam body marked in white circle in (a).

6. Discussion and future work

Since the results in Section 4 and 5 are obtained over wide urbanized area of Bratislava using global parameters, focus on a small areas and man-made structures is suggested in order to increase the PS densities and to better asses the displacement phenomena. As it is sometimes complicated to resolve imperfections in supposed models for estimated parameters globally, some of these imperfections can be minimized or even neglected while working on small areas (e.g. atmospheric effects[18]). Together with different strategies for changing the processing chain of the standard PSInSAR methodology (switching between different types of image connections, incorporating weights on ensemble coherence value, using different parameters for a-priori and a-posteriori selection of the points and others) implemented in SARPROZ, the PS density over objects with different dimensions/geometry/orientation/material and the amount of displacements (e.g. for long bridges) that could cause aliasing, can possibly be improved. In globally stable areas, where it is hard to distinguish what is and what's not a critical movement, the decomposition of line-of sight vectors into horizontal and vertical components is questionable, since it requires to affect the spatial composition of PS networks in order to bring points from ascending and descending geometries together (interpolation, regular grid, clustering, etc.). The same distortion to the final results would be involved by joining observation from different satellites into one continuous information. The question is, how to perform quality control in multi-sensor InSAR deformation monitoring? And how to assess scatterers with extreme velocities among low coherent areas? To fully investigate the research objective, the knowledge about the observation statistics of PSInSAR is essential for the description of the displacement parameters. To asses the precision and reliability of the estimated parameters and their relation to the signal of interest it is necessary to perform exploratory data analysis, data mining or even incorporating machine learning algorithms. The work on this site had motivated us to develop a simple platform for multivariate outlier detection and post-processing of multi-temporal InSAR results[19] applicable for the detection of deforming areas by merging displacement maps together, while keeping structure of the data and wealth source of information provided in each PS point.

7. Conclusion

According to standard PSInSAR analysis provided in this work, the investigated urban area of Bratislava is sufficiently stable in whole monitoring period from 1992 to 2016. PSInSAR applicability for the deformation monitoring depends on the spatial pattern (wavelength) and revisit time of SAR equipped satellites. The availability of persistent scattering targets using standard PSInSAR analysis and different SAR sensors varies significantly throughout the monitoring periods (Tab. 1, Fig 2, 3). Beside the temporal and geometrical decorrelation, that is preventing the density of PS points to reach higher levels, there are imperfections in supposed mathematical models for estimated parameters (non-linear movements, high-phase gradients, seasonal patterns, etc.) and other reasons of incoherence (e.g. sub-pixel position, side-lobe observations, orbital inaccuracies, atmospheric disturbances, etc.). Although, lot of advances have been achieved in exploiting low or partially coherent targets[20,21], and are certainly worth of applying in reprocessing of historical datasets, the assessment of model imperfections can be significantly improved by the utilization of larger datasets. Thanks to the development of new X-Band high-resolution SAR satellites, the possibilities of ground deformation monitoring in higher accuracies is real. The new X-band sensors provide spatial resolutions in order of magnitude better than previously available satellite SAR sensors (e.g. ERS, Envisat). This appears to be promising in monitoring dense linear-feature structures and rigid structures and providing more detailed ground features. Moreover, with the shorter revisit times (11 days for TerraSAR-X), it is possible to process a long series of SAR data and expand the standard PSInSAR model to account for a seasonal components or non-linear movements[22,23]. On the contrary, the improved coverage of Sentinel-1A's TOPS (Terrain Observation with Progressive Scans) mode with 6-days revisit period after launch of Sentinel-1B and higher spatial resolution of Radarsat's Fine mode with state-of-art orbit characteristics, is of great benefit for analysis provided on the national/regional scale and for complementing X-band data. Thanks to the free and open data policy of Sentinel-1A with enhanced swath coverage, foreseen data boost from constellation missions (Sentinel-1B, TerraSAR-X New Generation, Radarsat Constellation Mission, etc.) the new era of operational SAR could make its way to the broader user community. The credit for making SAR archives freely available is as important as improving satellite's characteristics. The breakthrough of the technology will help to define end-users demands on the the final products and analysis provided and also will strengthen the initiatives like nation-wide monitoring, near-real time analysis and others.

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