Potential of satellite InSAR techniques for monitoring of bridge deformations

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***Abstract*— Satellite SAR interferometry (InSAR) is proven as effective method for monitoring of deformations of both terrain and urban structures. By applying multi-temporal InSAR processing techniques (for example Persistent Scatterers InSAR – PS InSAR) to a series of radar images over the same region, it is possible to detect both vertical and horizontal movements of structure systems on the ground in the millimeter range, and therefore, to identify abnormal or excessive movement indicating potential problems requiring detailed ground investigation. Three case studies (in Bratislava, Ostrava and Hong Kong) presented within the paper demonstrate potential for monitoring deformations and movements due to thermal dilation of bridge structures.**

I. Introduction

While for precise study of bridge movements it would be necessary to use some in-situ method to capture such movements as bridge vibration or deflection that usually doesn't exceed few milimeters - for such purposes a ground-based radar interferometry can be recommended [1]. Satellite SAR radars have another advantages. With satellite SAR Interferometry specific bridges can be monitored to identify and investigate targets with suspicious displacement on a monthly (ERS, Envisat and Radarsat data) or weekly (TerraSAR-X and COSMO-SkyMed) time-scale. As a result, timely identification of potential problems can help mitigate their impact on structural health and lower infrastructure rehabilitation costs. Within this paper, three case studies are presented, showing potential of satellite InSAR techniques for monitoring of bridge deformations.

II. Monitoring of bridge in Bratislava

For this research, the 32 ENVISAT ASAR images from ascending track acquired in period of 2002 – 2010 were utilized. For the evaluation of PS InSAR potential to detect and monitor bridge displacements, PS derived time series of a deformation signal were compared to available levelling measurements over Old Bridge that was affected by the crash of an Austrian tug in 2010 [2]. 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 PS InSAR that are compared to the levelling data (see Fig. 1). 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 (PS InSAR).

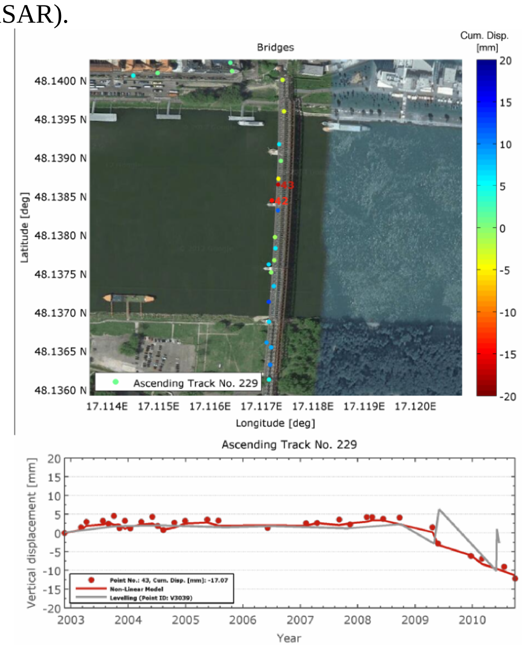


Fig. 1. Levelling vs. PSInSAR time series over bridge that was affected by the crash of a tug in 2010.

III. Deformation trend of bridge in Ostrava-Svinov

Highway bridges in Ostrava-Svinov are known to be deforming since its construction finished in 2008. Two main discussed reasons of these deformations are either residual subsidence due to mining activities of Ostrava until 1990s, or low quality build material used as background for construction. PS InSAR processing of ERS (1996-2001) and Envisat ASAR (2002-2010) data provided suspicion that the subsidence of undermined areas in close surroundings of newly built highway was active, though in very small rates [3]. For more appropriate analysis, 6 Spotlight images of TerraSAR-X (2011) were ordered. Because of small number of images, it wasn't possible to appropriately distinguish between deformations of the bridge and movements caused by thermal dilation.

More appropriate TerraSAR-X Stripmap dataset (2013-2014) contains 11 images. Using high quality DEM and precise surface temperature values of nearby highway, it was possible to distinguish between SAR phase contributions of elevation changes, linear deformation trend and thermal dilation. Basic estimation result is figured in Fig. 2. Reliability of this estimation is not high because of short timeline of dataset that is including less than one whole year cycle. The method of estimation of thermal expansion coefficient is searching for correlation between temperature values and SAR phase. In case of non-linearity of such correlation, the residuals after thermal expansion component filtering may lead to wrong estimations of temporal deformation trend – as visible in Fig. 3 showing processing result of point 931 depicted in Fig. 2 by red square.

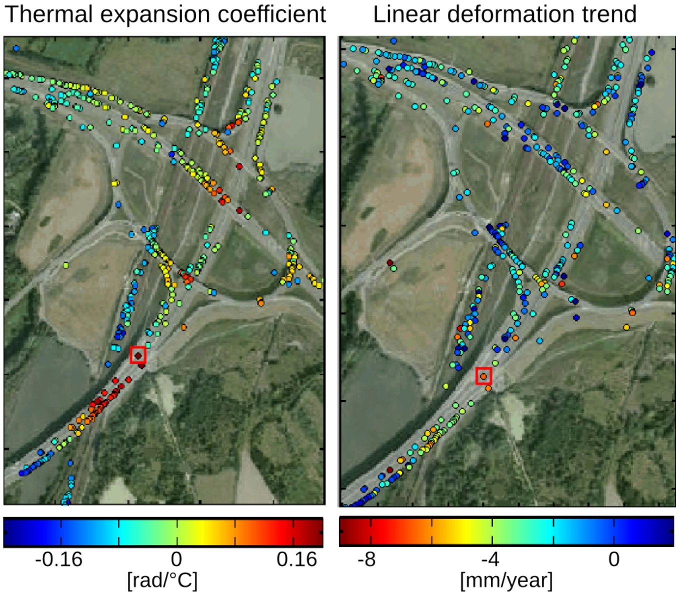


Fig. 2. Thermal expansion coefficient and linear deformation trend values of Ostrava-Svinov roundabout estimated using 11 TerraSAR-X Stripmap images (2013-2014). Red square depicts selected point 931.

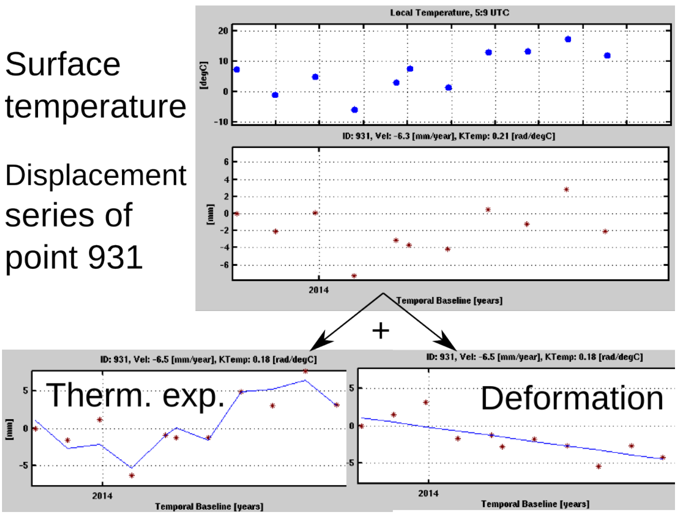


Fig. 3. Decomposition of displacement series of point 931 into thermal expansion and temporal deformation components. Potential errors are caused by inappropriate dataset (at least two year cycles are needed).

IV. TERRASAR-X ANALYSIS OF THE CHEUNG TSING BRIDGE

Totally, 80 TerraSAR-X/TanDEM-X stripmap images of Hong Kong area have been processed using SARPROZ software [4]. For each selected target, the height with respect to the reference point (outside the bridge) has been estimated, together with the displacement time series. In particular, the displacement time series have been analyzed considering a model correlated with the local temperature (which takes into account the thermal expansion of structures) and a model with a smooth temporal trend. Movements showing random variations at the satellite sampling time (11 days or more) are considered as noise. An example of noise-like movements are possible bridges oscillations (due to wind stresses or bridge load at the acquisition time of the radar). Targets with a high phase dispersion have been discarded.

It was found out that targets close to the piers of the bridges have a higher temporal coherence than those in the middle of the span (Fig. 4a). This is easily explained since the span is more subject to random-like movements (like oscillations), which are not considered in the model applied here. The targets shown in Figure 4a need to be carefully localized in order to correctly observe their displacement time series. Figure 4a shows in fact their geographic coordinates but it does not give an idea of their elevation. The analysis here applied returns also an estimation of the targets height, which can be used to understand their correct location. Figure 4b shows the estimated height in a color scale ranging -20m ÷ 50m. One can distinguish the radar reflections caused by the traffic signs hanged orthogonally to the highway. It is important to identify which objects are visible by the radar to correctly interpret their movement.

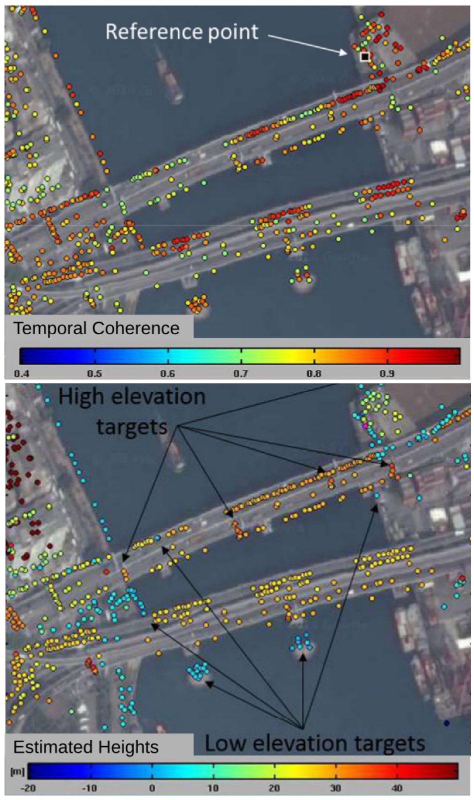


Fig. 4. Temporal coherence (a) and estimated heights (b) of Cheung Tsing bridge analysis.

The satellite looks down from West/South-West to East/North-East (about 10deg from the east-west axis). From this analysis, without a-priori information on the observed movement, we have no way to distinguish between vertical and horizontal displacement. For understanding the direction of the movement, a more detailed analysis is needed. Since the detected displacement is estimated from the phase of the Electro-Magnetic Radar signal, it is affected by an intrinsic ambiguity. In the displacement time series that will follow, the ambiguity is represented by plotting multiple replicas of the detected signal. When the phase dispersion is low (high temporal coherence), this phenomenon does not lead to any significant consequence. However, when the displacement is complex, when the phase dispersion is high, and in particular when data are missing, the ambiguity may lead to a wrong time series reading.

Figure 5 represents the thermal expansion coefficient. West side of the bridges presents a positive correlation with the temperature, while the east side shows a negative one. This means that one side is approaching the satellite when the temperature rises, while the other side ispushed further. This phenomenon can be explained by the horizontal stretch of the bridge spans caused by the temperature. With respect to the chosen reference, the pylon next to the East shore seems to be the barycenter of the bridge elongation.

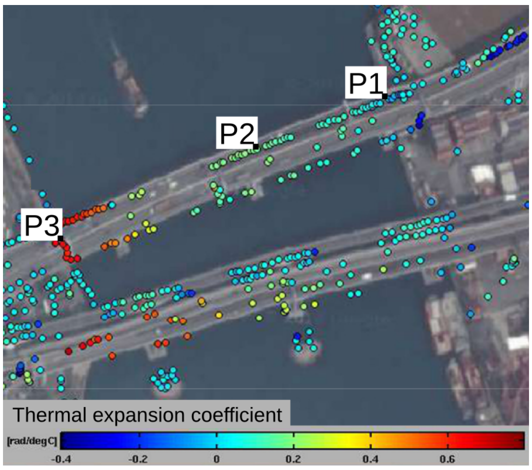


Fig. 5. Thermal expansion coefficient estimated from displacement time series.

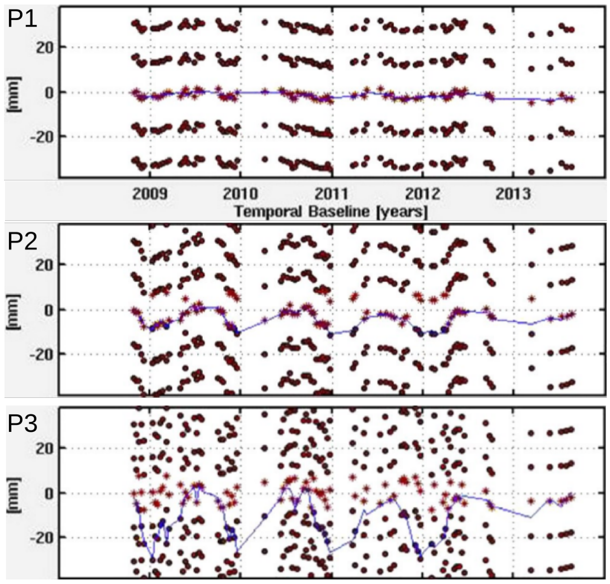
In Figure 6 a few examples of displacement time series are reported. Points are localized in Fig. 5. The displacement plot of P1 is basically stable, even if affected by slight random noise (coherence 0.8). Point P2 is right over the pier location. The point reveals stronger thermal expansion, and the displacement time series is much cleaner. We can in fact expect that the bridge is less affected by random-like oscillations over the pier. Point P3 is located on the traffic signs hanged over the bridge, at the west side of the bridge that is the one mostly affected by thermal expansion. As a final result, the thermal expansion of this target is very high, causing strong time series fluctuations. Still, the correlation with the model is high enough to hold the point as reliable.

Fig. 6. Displacement time series of selected points P1, P2 and P3.

V. Conclusions

There are many ways to monitor the structural health of constructions, such as bridges. Contact (sensor) methods make it possible to monitor strain, tilt, vibration and other features very sensibly, however only at selected points where they are located. For newly built bridges, these sensors may be connected in a monitoring system, with the possibility to remotely evaluate e.g. the reaction of the construction to a loading in real time. The most significant advantage of such methods is its sensibility and the possibility to monitor the most critical points of the construction. However, such methods are not optimal in case of already built constructions.

Spaceborne InSAR monitors usually the top-deck of the bridge in millimetric precision, side-deck monitoring is also possible but with worse accuracy [5]. In addition, its accuracy depends on the construction orientation and number of scenes used, which may be a limiting factor. However, at the same cost it is possible to monitor all bridges in an area covered by a scene (depends on resolution), and as the only method, it has the possibility to map deformation even in the past, if scenes were acquired. For good results (distinguishing between thermal dilation and linear deformation components), at least two year periods of relatively high sampling is recommended.



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