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 such structures and to evaluate rate of their movements in sensitivity of first millimeters in direction of satellite sight (usually inclined by 20-55° from vertical axis). Therefore, it is possible 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 (InSAR) 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. Because InSAR is sensitive to both vertical and horizontal movements, it is necessary to distinguish between major causes of SAR phase changes – these are in case of bridges due to thermal dilation [2]. After removal of thermal component, it is possible to evaluate other bridge motions in millimeter sensitivity [3]. 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 [4]. 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).

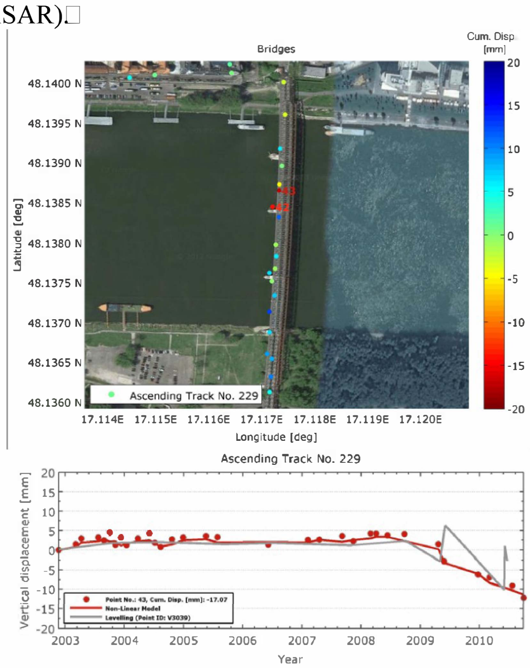

Fig. 1. Levelling vs. PSInSAR time series over bridge that was affected by the crash of a tug in 2010.

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 [5]. 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 13 images including the whole one year time span. Using high quality DEM based on national geodetical measurements and precise surface temperature values from sensors installed at near 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. The method of estimation of thermal expansion coefficient is extending principle of original PS InSAR [6] by adding information about temperature values as one of unknown parameters into the set of estimation equations, as implemented in SARPROZ [7]

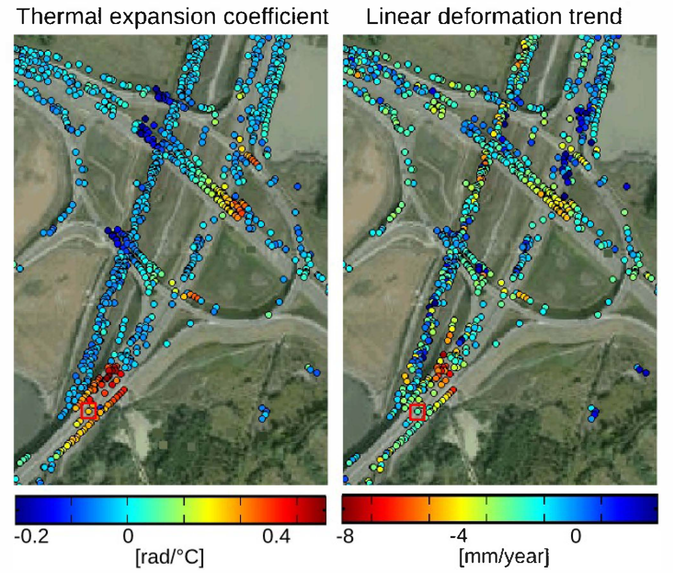

Fig. 2. Thermal expansion coefficient and linear deformation trend values of Ostrava-Svinov roundabout estimated using 13 TerraSAR-X Stripmap images (2013-2014). Red square depicts selected point 2274.

The reliability of decomposition of SAR phase difference w.r.t. reference point between phase change due to height difference Δh (correlation with perpendicular baselines $B_\perp$), thermal expansion $\Delta\ell$ (correlation with temperature changes ΔT) and linear deformation rate Δv in temporal period Δt is based on suitability of investigated dataset and assumption of linearity of these parameters. Accuracy or reliability of estimations can be described using function of variance of phase residuals δ_φ^2 expressed as temporal coherence $\xi_p \simeq e\text{-}(\delta_\varphi^2/2)$ [8]. Points figured in Fig. 2 have all rather high $\xi_p >$ 0.85, however lower number of 13 SAR images contains only one seasonal circle (one year). Information about dataset quality can improve evaluating reliability of estimations using variances $\delta_{\Delta\ell}^2$ and $\delta_{\Delta v}^2$ (Eq. 1 based on [9]):

$$\delta_{\Delta\ell}^2 \simeq \left(\frac{\lambda}{4\pi}\right)^2 \frac{\delta_\varphi^2}{M\delta_{\Delta T}^2} \quad , \quad \delta_{\Delta v}^2 \simeq \left(\frac{\lambda}{4\pi}\right)^2 \frac{\delta_\varphi^2}{M\delta_{\Delta t}^2} \qquad (1)$$

where M.. number of interferograms, λ.. radar wavelength.

As example, a point 2274 was selected containing thermal expansion component and non-zero estimation of linear deformation (see Fig. 4). Analyzing residuals, it can be said that the point is moving in rate of Δv=-2.5±2 mm/year and the phase correlates with temperature in rate of $\Delta\ell$ =0.69±0.096 mm/°C. Such reliability analysis proved goodness of fitting thermal expansion model but too uncertain model of linear deformation trend.

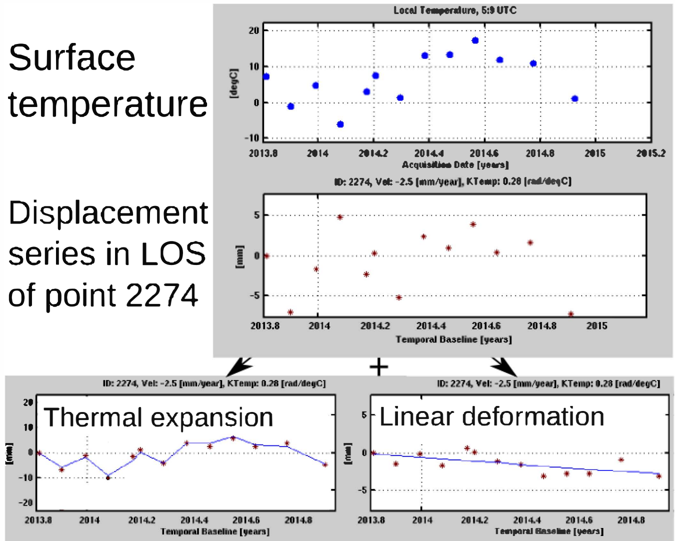

Fig. 3. Decomposition of displacement series of point 2274 into thermal expansion and temporal deformation components.

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 [7]. 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.

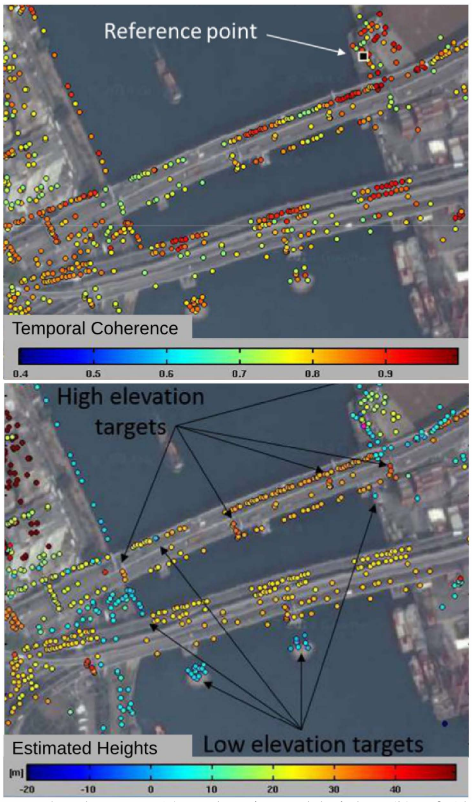

Fig. 4. Temporal coherence (a) and estimated heights (b) of Cheung Tsing bridge analysis.

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. One possibility to overcome this problem is to perform an analysis using phase difference of neighboring samples with assumption of spatially linear changes of estimated parameters (in this case, displacements).

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 is pushed 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.

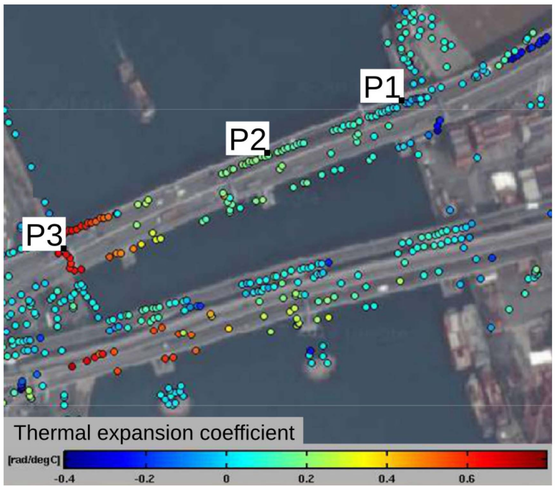

Fig. 5. Thermal expansion coefficient estimated from displacement time series .

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.

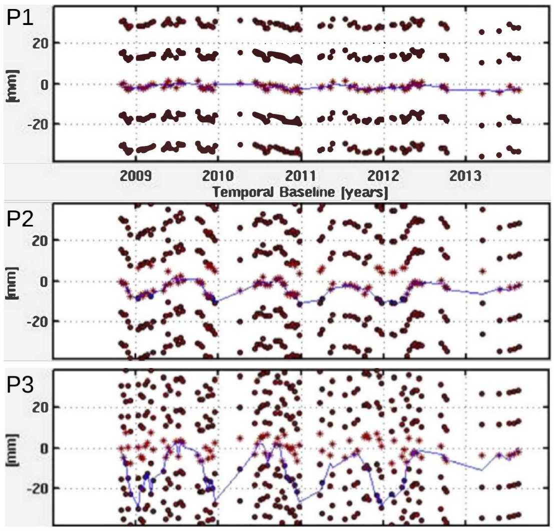

Fig. 6. Displacement time series of selected points P1, P2 and P3.

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, side-deck monitoring is also possible but with worse accuracy [10]. 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. Once the horizontal thermal dilation component of detected satellite line-of-sight movements of bridge is estimated, the (residual) linear deformation trend can be distinguished from the data accurately. For good results, at least two year periods of relatively high sampling is recommended.

Acknowledgment

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References

[1] Talich, Milan, "VERY PRECISE DETERMINING VERTICAL DEFLECTION OF BRIDGE STRUCTURES USING GROUND RADAR INTERFEROMETRY," presented at the IPG 2013, Bratislava, 2013.

[2] Montserrat, O., Crosetto, M., Cuevas, M., and Crippa, B., "The Thermal Expansion Component of Persistent Scatterer Interferometry Observations," IEEE Geosci. Remote Sens. Lett., vol. 2011, no. 5, pp. 864–868.

[3] G. Fornaro, D. Reale, and S. Verde, "Bridge Thermal Dilation Monitoring With Millimeter Sensitivity via Multidimensional SAR Imaging," IEEE Geosci. Remote Sens. Lett., vol. 10, no. 4, pp. 677–681, Jul. 2013.

[4] M. Bakoň, D. Perissin, M. Lazecký, and J. Papčo, "Infrastructure Non-Linear Deformation Monitoring Via Satellite Radar Interferometry," in Procedia Technology, Troia, Portugal, 2014.

[5] M. Lazecký, P. Rapant, D. Perissin, and M. Bakoň, "Deformations of highway over undermined Ostrava-Svinov area monitored by InSAR using limited set of SAR images," in Procedia Technology, Troia, Portugal, 2014.

[6] A. Ferretti, C. Prati, and F. Rocca, "Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry," IEEE Trans. Geosci. Remote Sens., vol. 38, no. 5, pp. 2202–2212, Sep. 2000.

[7] D. Perissin, Z. Wang, and T. Wang, "The SARPROZ InSAR tool for urban subsidence/manmade structure stability monitoring in China," in Proceedings of 34th International Symposium on Remote Sensing of Environment. Sydney, Australia, 2011.

[8] Colesanti, C., Ferreti, A., Novali, F., Prati, C., and Rocca, F., "SAR monitoring of progressive and seasonal ground deformation using the permanent scatterers technique," IEEE Trans. Geosci. Remote Sens., vol. 2003, no. 41, pp. 1685–1701, 2003.

[9] Wang, T., Liao, M., and Rocca, F., Time Series InSAR Analysis over Three Gorges Region: Techniques and Applications. VDM Verlag Dr. Müller, 2010.

[10] J. J. Sousa, I. Hlaváčová, M. Bakoň, M. Lazecký, G. Patricio, P. Guimaraes, A. M. Ruiz, L. Bastos, and A. M. R. Sousa, "Potential of Multi-Temporal InSAR Techniques for Bridges and Dams Monitoring," in Procedia Technology, Troia, Portugal, 2014.