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Deformations of highway over undermined Ostrava-Svinov area monitored by InSAR using limited set of SAR images

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Abstract

Part of Czech highway D1 connecting Ostrava city with Prague and Poland, is built over an undermined area of Ostrava-Svinov, with mines closed since 1991 in the area. Soon after its opening ceremony in 2008, the highway began to exhibit various significant deformations. An attempt of InSAR monitoring using ERS, Envisat and several TerraSAR-X Spotlight acquisitions was done in order to monitor progress of deformations, to consider suitability of satellite InSAR for such purposes and to search for footprints whether the deformations were caused by fading subsidence due to undermining or by another, local, reason. Only shallow subsidence was found in the area from Envisat data ranging 2005-2010. Highway deformations in late 2011 are observable from processing of limited set of 5 TerraSAR-X images using different methods. Detected deformations are very probably due to longitudinal thermal expansion of the observed highway bridge. This publication contains issues to be taken into consideration for appropriate interpretation and processing if the available input dataset is limited and not optimal.

Keywords: SAR Interferometry; thermal dilation; Envisat; ERS; TerraSAR-X; urban areas; highway deformations.

1. Introduction

Czech highway D1 maintains a proper transport connection between Prague and Brno, continuing to Olomouc. Since 1990s the possibility of prolongation of D1 to Ostrava and further over borders with Poland has been discussed. Centuries long black coal mining activities have finished in Ostrava region on or before 1994, thus in 2002 it was safe to begin with the construction. In May 2008, the highway over Ostrava was opened, continuing to Bohumin. However, soon after putting the highway into operation, it started to exhibit various faults – within this new 9 km section of D1, over 900 faults or deformations were found since 2008 [1]. Construction company has been accused for using improper material as a foundation for the highway.

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The highway leads directly through areas that were affected by black coal mining during centuries. All the mines in the Ostrava-Svinov area have been closed since 1991 [2], however a slow subsidence due to undermining or its secondary effects might be expected some 10 years after the mine closures or even today, according to experience of local experts, since the area of interest is geologically very diverse.

This paper summarizes results of application of satellite SAR interferometry (InSAR) for monitoring of movements and deformations of part of D1 highway leading over undermined area in Ostrava-Svinov using archived ERS and Envisat ASAR images to investigate potential deformation of surrounding undermined area – also 5 high resolution TerraSAR-X Spotlight-mode images (May-December 2011) were processed to observe deformations of the highway body itself, at bridges and a roundabout. This paper presents evaluation of observed deformations and demonstrates issues for consideration in the experimental processing of limited TerraSAR-X images.

Nomenclature

ASAR	Advanced SAR (instrument onboard Envisat satellite)
D1	identifier of observed highway in Czech Republice: Prague-Brno-Olomouc-Ostrava-Poland
InSAR	Synthetic Aperture Radar Interferometry
LOS	Line of sight of satellite
MT-InSAR	Multitemporal InSAR
PSI	Persistent Scatterers Interferometry
SAR	Synthetic Aperture Radar
StaMPS	Stanford Method for Persistent Scatterers

2. Investigation of ESA archive data

A huge dataset of C-band SAR ERS-1, ERS-2 and Envisat of more than 160 acquisitions ranging period of 1995-2010 of Ostrava area was already evaluated in [3] using StaMPS method of both Persistent Scatterers and Small Baselines multitemporal InSAR (MT-InSAR) techniques [4]. Processing results from ERS 1995-1999 and Envisat 2005-2010 are shown here to provide overview of deformations in the area of interest before the highway construction has been finished.

Activities of Svinov Mine (Sv) and Jan Sverma Mine (JS) in the area have finished in 1991 [2]. Majority of subsidence can be expected to vanish in 3-5 years after mine closure [5]. Yet, residual subsidence of slow rate in the area affected by mining activities has been detected also in 2005-2010 dataset of Envisat, as seen in Fig. 1.

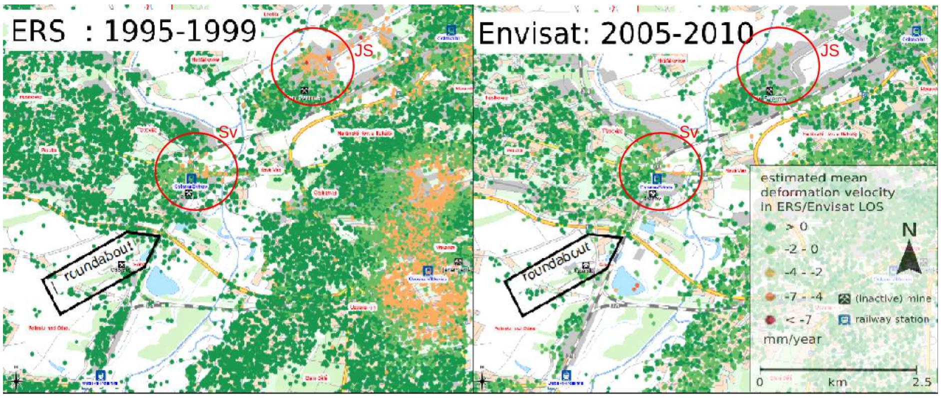

Fig. 1. Processing of archived ESA data using StaMPS PSI – residual subsidence are detected in circled areas around mines Jan Sverma (JS) and Svinov Mine (Sv) in both datasets: (a) ERS 1995-1999; and (b) Envisat 2005-2010.

To detect more PSI points over highway that was opened in 2008, a subset of 11 Envisat ASAR images from 2008-2010 was selected and reprocessed using StaMPS PSI - see Fig. 2. Linear deformation trends were detected over the surroundings of closed Svinov Mine (Sv) and over the newly built Svinov roundabout. A subsidence was correctly detected at Trebovice area (areal of thermal power plant). Very similar results were detected at the Svinov roundabout using SarProz PSI processing from the same limited dataset – an obvious linear deformation trend of selected roundabout point can be observed in graph in Fig. 2.

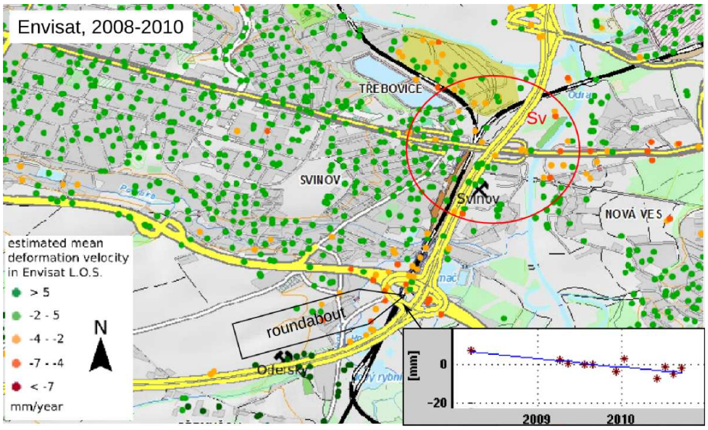

Fig. 2. Reprocessing of Envisat data subset from 2008-2010 using StaMPS PSI technique. The highway body leads over slowly subsiding surroundings of Svinov Mine (Sv). Deformation trend of selected roundabout point is depicted on graph based on SarProz PSI processing using same data.

3. High resolution SAR monitoring of Svinov roundabout

High resolution TerraSAR-X Spotlight data (around 2 m per pixel in the ground range) are more sensitive to shallow deformations [6] but also to various error sources - atmospheric effects [7], temporal decorrelation caused by motion of vegetation [8] etc. Since the number of 6 images acquired during the second half of year 2011 is too low to be processed using traditional PSI method [9], a careful investigation involving lower computation load has been performed to achieve reasonable results without bias that would be caused by estimated models. Final results are based on application of algorithms available at SarProz Toolbox software [10].

3.1. Analysis of input TerraSAR-X data

Combination of 6 available TerraSAR-X Spotlight images from 2011 was analyzed, finding appropriately low normal, temporal and Doppler centroid baselines. Atmospheric humidity and weather conditions have been achieved from a permanent meteorological station in a 4 km distance from Svinov roundabout, see Fig. 3.

From Fig. 3, it can be interpreted that normal baselines are not correlated in time, thus even within such small amount of data, the interferometric phase caused by elevation differences should be distinguishable from the deformation signal. The only exception has been image from 2011-09-26 that has high normal baseline and contains significant disturbance by rain showers that is dominant over other signals (as visually inspected from interferograms) – this image has been excluded from further processing, leaving the final set of 5 images of maximal $B_{n,max}$ = 126 m. The phase change due to elevation or due to DEM error in interferograms isn't significant in case of continuously varying relatively small elevation changes of highway structures - within such $B_{n,max}$, the whole phase cycle would correspond with maximal height ambiguity of $H_{amb,max}$ = ~33 m, according to Eq. 1 [8]:

$$H_{amb} = \frac{\lambda \cdot R \sin\left(\theta_{inc}\right)}{2B_n} \tag{1}$$

, where λ - base wavelength (0.0311 m for TerraSAR-X), R - distance between Earth surface and satellite (R_{TSX} = $5.736 \cdot 10^5$ m), Θ_{inc} - incidence angle (27.77° in this case).

Assuming no other significant atmospheric contribution in the small area of interest and appropriate DEM model achieved from interpolation of local levelling missions results, any phase changes visible in highway structure body in interferograms should be caused by deformations. However, available images of the second half of 2011 are correlated temporally with continuous decrease of temperature. Thus, more images would be necessary to distinguish cause of detected deformation either as a trend correlated with time or as temporary deformation caused by thermal dillation of the bridge.

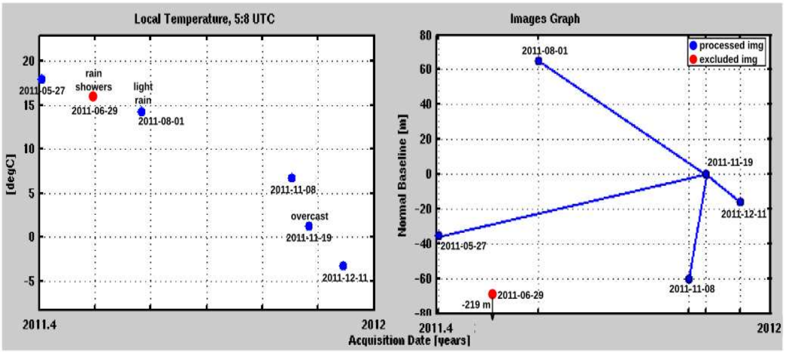

Fig. 3. Basic analysis of parameters of TerraSAR-X Spotlight images used for multitemporal InSAR processing.

3.2. Processing results using different InSAR techniques

Assuming no atmospheric effects within relatively small area of interest and neglectable effects of noise, the phase changes observed in 4D network of SAR image points (selected based on amplitude stability), related to common reference point, are assumed to be caused only by elevation and deformation changes w.r.t. reference point.

Common PSI method as implemented both in StaMPS PSI and SarProz PSI has failed in appropriately estimating both elevation and deformations related to stable reference point from small amount of 5 images. Because the elevation of highway is changing continuously in space, it was possible to achieve reasonable estimations of elevation (and subsequently also deformations) using methods that work with spatial network of short connections (up to 100 m) between processed points, with final least-squares integration into relation to reference point: both StaMPS Small Baselines Interferometry (SBI) and integrated PSI computation in the Atmospheric Phase Screen Toolbox of SarProz has been used, achieving similar reasonable results – see in Fig. 4.

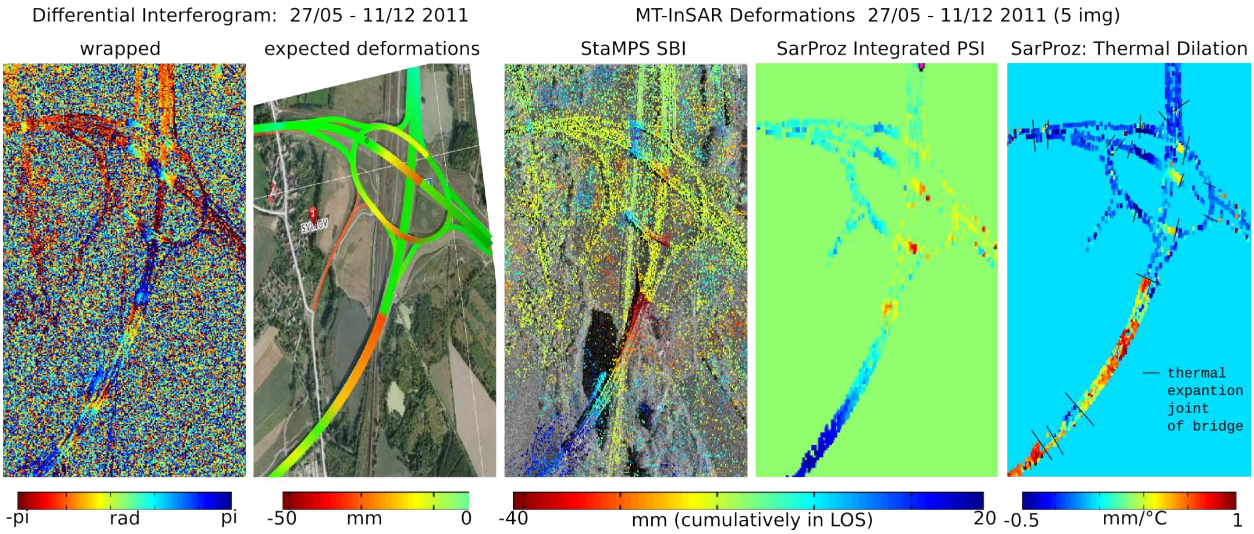

Fig. 4. Results of InSAR processing of dataset spreading 27/05-11/12 2011: expected using simple differential interferogram of 27/05-11/12 2011 (left) and estimated using multitemporal techniques: StaMPS SBI, SarProz Integrated PSI and SarProz Thermal Dilation (right).

However, after investigation of the linear model of deformation in time, relatively large phase residuals have been found, uncorrelated in time. This shows a non-linear type of deformations in time. Very good results were achieved by comparing detected displacements with temperature difference using periodogram, instead of by temporal comparison. This was achieved using SarProz function “Seasonal trend” - the result is visible in Fig. 4 (right). Phase residuals were much smaller after such analysis and without temporal linearity, assuming the observed deformation signal being caused only by thermal dilation. No linear deformation trend in time has been detected.

4. Computation of thermal dilation effect from LOS values

Assuming only thermal dilation as a source of deformation detected from the InSAR processing, it can be investigated whether this conforms with expected values. Using simplified equation Eq. 2 from [11]:

$$E = \alpha \cdot d \cdot \Delta T \tag{2}$$

, filled by values of thermal coefficient for reinforced concrete structure of $\alpha = 12 \cdot 10^{-6}\ K^{-1}$ and the thermal difference $\Delta T = 21.2°C$ between 27/05-11/12 2011, the longitudinal thermal dilation E can be expected for the bridge over Rojek lake of a length d = ~585 m as E = 14.9 cm.

While it would be possible to analyse sensitivity of LOS measurements of deformation on direction of the deformation by decomposition into sensitivity angles in N, E and nadir directions [8,12], we have used the assumption that all detected deformation is caused in only one known direction instead (i.e. longitudinal expansion of highway bridge due to thermal expansion) – thus we have used computation approach applied also in monitoring of motion of glaciers [13,14], in relative coordinates w.r.t. satellite orbit and LOS:

Having assumed horizontal angle of direction of deformation φ relative to satellite LOS (perpendicular to the satellite azimuth/heading angle), together with assumed vertical angle μ of deformation w.r.t. horizontal plane, the directed deformation $D_{\mu,\varphi}$ that would cause LOS measurement of D_{LOS} as the only source of deformation is:

$$D_{\mu,\varphi} = \frac{D_{LOS}}{\sin(\mu)\cos(\theta) + \sin(\varphi)\cos(\mu)\sin(\theta)} \tag{3}$$

, where θ is incidence angle of satellite LOS, in this case θ_{TSX} = ~27.77°. The longitudinal slope of the bridge over Rojek is varying from 0.9 to -3.65° and it will be simplified as in a horizontal plane, i.e. μ = 0°. The deformation over the whole bridge detected by InSAR from images 27/05-11/12 2011 is expected to be D_{LOS}=~3 cm (see Fig. 4) and it's direction is in average angle of φ = 31.39° from satellite range line (LOS direction). The final horizontal deformation can be computed as $D_{\mu,\varphi}$ = 12.4 cm.

Even though many inaccuracies were presented in this computation (e.g. unprecise measurements of temperature that were achieved from meteorological station 4 km from Svinov roundabout, simplified model for computation of thermal dilation and simplified assumptions of horizontal angle, ignorance of other deformation sources to D_{LOS} etc.), the values of E and $D_{\mu,\varphi}$ are relatively close.

5. Conclusions

From the archived data processing, it might be concluded that there is a minimal residual subsidence over areas previously undermined by mines closed since 1991 in the area. Few points were identified to be linearly subsiding during 2008-2010 – some of them were detected on the highway itself. Note that according to results from processing of ERS dataset spreading 1995-1999, there are no signs of continuous deformations in the Svinov roundabout construction site before the construction activities started. Linear deformations were not confirmed in the area from SAR images of late 2011. From this dataset, only highway deformations were observed – these deformations were interpreted as only due to thermal dilation of bridges.

Discontinuities of deformations observed at the highway from TerraSAR-X images directly fit with locations of thermal dilation joints of bridges. Expected thermal dilation of bridge over Rojek lake is slightly higher than value computed from LOS measurement. This fact however doesn't degrade application of InSAR as a tool for accurate monitoring of highway deformations but leads to further investigation using proper temperature data and larger dataset. A valuable combined analysis including estimation of both (major) thermal dilation and linear deformation trend in time is possible only using more appropriate dataset, spreading at least a whole year cycle.

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