MONITORING OF SUBSIDENCE IN KARVINÁ MINING REGION USING INSAR METHODS

SLEDOVÁNÍ POKLESŮ V PODDOLOVANÉ OBLASTI KARVINSKA METODAMI INSAR

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Abstract

Whole Karviná region (CZ) is strongly affected by intensive mining of black coal. Subsidence caused by undermining has to be monitored by modern methods, such as satellite radar interferometry (InSAR). Character of the area, velocity and spatial scale of subsidence are challenging limits of InSAR. These limits were investigated, optimizing scenarios were found to increase the performance of InSAR techniques using C-band and L-band data to detect and estimate deformations due to subsidence in the region. While extents of subsidence troughs are often possible to delimitate, the deformation rates are usually underestimated. This was compared also to existing data from levelling. Thanks to InSAR ability to detect millimetre changes, a strong potential is seen in monitoring of slow deformations such as decay subsidence after closure of mines. InSAR techniques were evaluated as appropriate for a systematic monitoring of subsidence in the region, as complementary to levelling measurements.

Abstrakt

Celé území Karvinska je zásadně ovlivněno intenzivním dobýváním černého uhlí. Poklesy vzniklé poddolováním je zapotřebí sledovat moderními metodami, jako je družicová radarová interferometrie (InSAR). Charakter zasažených oblastí, rozsáhlost a rychlost poklesů způsobují problematické nasazení této metody. Byla prozkoumána omezení metody InSAR a bylo navrženo a testováno několik způsobů, jak umožnit použití technik InSAR nad daty radiového pásma C a L pro správnou detekci a odhad míry poklesů v regionu. Zatímco rozlohu poklesových kotlin je často možné pomocí InSAR ohraničit, rychlost deformací je velmi často podhodnocena. To bylo zjištěno srovnáním s naměřenými hodnotami z nivelací. Metoda InSAR má pro svou schopnost detekce milimetrových změn vysoký potenciál v monitorování pomalých deformací, jako jsou doznívající poklesy po ukončení těžby. Techniky InSAR byly vyhodnoceny jako vhodné techniky pro soustavné sledování poklesů v kraji, jako doplňkové metody k nivelačním měřením.

Keywords

radar interferometry, InSAR, subsidence, undermining, ERS, Envisat, Alos

Klíčová slova

radarová interferometrie, InSAR, poklesy, poddolování, ERS, Envisat, Alos

1 Introduction

The region of Ostrava-Karviná district in Moravian-Silesian Region, Czech Republic is largely affected by terrain changes due to over 200 years history of black coal mining. It is not practically possible to perform levelling missions or other demanding measurements on every subsiding site to properly achieve knowledge about a real subsidence in these areas. Subsidence is often estimated using some computational model, but also several attempts to use common remote sensing data were performed here.

It can be said that a mining industry (together with a heavy industry) shaped the history of the Moravian-Silesian Region of Czech Republic, mainly in its geographical and sociological aspects. Salt springs were exploited in history since 13th century in Orlová and Fryštát (part of Karviná today); the black coal was found in the middle of 18th century in Ostrava, then in other parts of the region as well.

Nowadays the Ostrava-Karviná coalfield (further as OKR, "Ostravsko-karvinský revír") represents the main area of coal mining in the Czech Republic since 90% of Czech coal stock is deposited here. Since the beginning of 21st century, OKR is the only area in Czech Republic where this high quality and economically very important raw material is exploited. On the other hand, the mining necessarily forms the whole undermined relief. Many civil structures were damaged or demolished during the 200 years mining history including historical objects, tramlines or other transportation networks. Subsidence in mine-affected areas reached a groundwater level and large areas including inhabited houses were flooded. The whole area is unstable even today. The post mining subsidence can be present on the mining site several years after an end of exploitation.

Since 1990s all mine activity stopped in Ostrava, the main black coal exploitation is now focused only in Karviná region with a view of not terminating mines before 2040. This work tries to observe changes caused by mining in the regional landscape by modern remote sensing using satellite radar interferometry techniques and to put fundamentals for a continuous monitoring using these techniques in Karviná region of interest (Bláha, et al., 2011).

2 On the Application of Satellite Radar Interferometry

Satellite Synthetic Aperture Radar (SAR) Interferometry, a technique that allows us nowadays to measure even sub-centimetre terrain changes on nearly any part of the world, is not an overnight miracle. It is a result of a long-time human scientific progress managed by observing physical reactions of the Nature used to observe physical reactions of the solid Earth. In this scope the technique allowed us to describe in details effects of earthquakes on the surface, behaviour and activity of volcanoes, to precise monitor a motion of glaciers or a creep on geological faults, to detect a danger of land or rock slides, to evaluate surface subsidence, as well as to perform topographical mapping, to detect places affected by floods or by a forest fire or even a growth of vegetation can be monitored using this advanced remote sensing technique (Hanssen, 2001).

The technique in general combines a knowledge of radio detection and ranging (radar) with a theory of interferometry, aerospace technologies and with a help of modern information technologies. The radar instrument can be installed onboard a satellite orbiting the Earth upon the ionosphere layer. The microwave spectrum of radiation used by the radar can fully penetrate throughout the atmosphere, unlike radiation of most of other wavelengths. The full microwave spectrum is defined as a spectrum of wavelengths in range between 1 mm and 1 m, while the practical range used in spaceborne SAR instruments is between 3 – 30 cm (disregarding missions that are not concerned in a solid terrain monitoring). Because only a difference within reflected fractions of wavelength is computed using interferometry, the technique can reach sensitivity for a terrain change in a milimetre scale in optimal conditions.

The main result is an image of interferogram that is the base for all the terrain evaluations. The interferogram phase image is created as a difference between two measurements of a radar wave phase, i.e. between fractions of a wavelength of a radio wave as was reflected from the surface. If these measurements are taken with some temporal delay, denoted as a temporal baseline between measurements, any terrain deformation during this delay will be detected in a form of these changes of wave phase that the deformation caused. If there was a subsidence during this time, the radio wave will travel longer through the atmosphere in the second pass causing a different phase. See Fig. 1 illustrating basic principle of satellite SAR Interferometry for deformation monitoring.

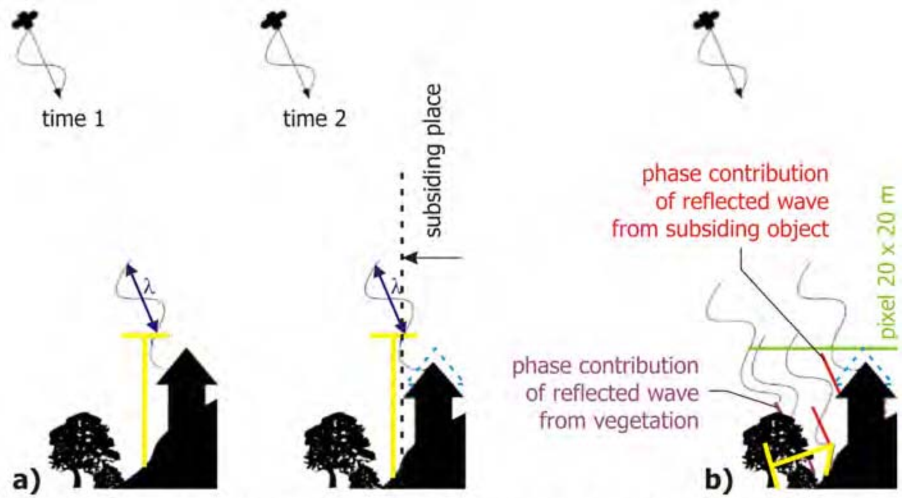


Fig. 1 Simplified SAR Interferometry for deformation monitoring:
a) phase changed induced by deformation (subsidence of building) in period between „time 1" and „time 2";
b) phase contributions within resolution cell.

2.1 Various SAR Missions Available for Monitoring in Karviná AOI

All the SAR satellites fly in a sun-synchronous dawn-dusk orbits that allow them to be permanently illuminated by sun and therefore to be powered almost entirely by its solar panels. The acquisitions are taken in descending and ascending flight direction. Most of the satellite mission sensors are only right side looking, therefore one acquisition can be taken in the morning time only (descending mode) and one in the evening (ascending mode). Because the radar response is sensitive to the geometry of reflecting objects, only acquisitions from the same direction and the same polarization angle can be used for InSAR processing. It is advisable and sometimes even necessary to plan the required acquisitions in advance to achieve appropriate interferometric pairs - also, even that satellites have almost a full global coverage, the areas that are to be acquired and archived need to be selected; data amounts are enormously boosting storage needs, data capacity onboard satellites is limited, as well as the length of simultaneous activity of the instrument.

Any application of SAR data depends on the frequency of used radar wave. For example, L-band (frequency of 1–2 GHz, i.e. wavelength of 15–30 cm) is much more sensitive for soil moisture than other bands. Its wavelength is much larger than a typical tree leaf so certain vegetation types are transparent to the L-Band sensor - the SAR receives more echoes from the ground compared to the vegetation. L-band is more susceptible to ionosphere effects than other bands. X-band (8–12 GHz, 2.5–3.75 cm) doesn't need so large antenna as other bands to achieve a high slant range resolution so it can be used for some fine scanning. Also the short wavelength will reflect from very small objects (tree leaves). X-band is more sensitive on atmospheric phenomena (heavy rain). Great penetration abilities are ascribed to P-band (0.3–1 GHz, 30–100 cm). No known satellite InSAR capable SAR system using the P-band exists, though. The common C-band (4–8 GHz, 3.75–7.5 cm) can be characterized as with average quality between X-band and L-band. An overview of SAR satellites of various bands available for InSAR processing is shown in Fig. 2. They differ in various properties such as terms of temporal or spatial resolution - and the band. Some basic parameters of most common SAR satellites are shown in Table 1.

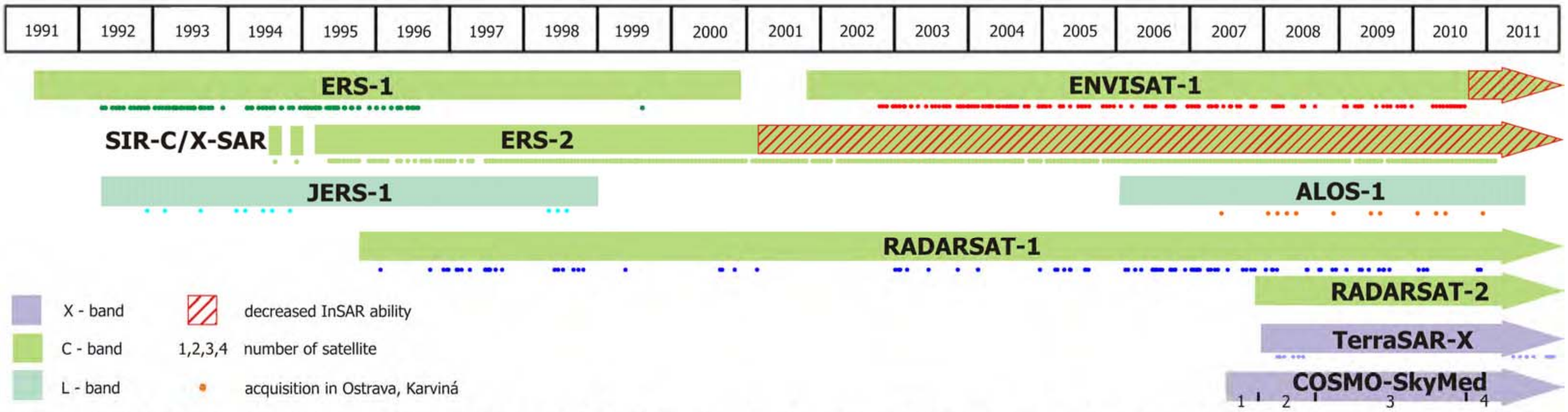


Fig. 2 Activity of SAR satellites offering data for InSAR processing in central Europe. Available acquisitions of Ostrava or Karviná area of interest are marked by black dots.

Tab. 1 - Overview of selected SAR satellites

Satellite SAR	Revisit time	Standard incidence angle	Standard ground resolution	Wavelength	Polarisation	Agency
ERS-1, ERS-2 SAR	35 days	23 degrees (21°–26°)	26 m	5.57 cm	Only VV	ESA
Envisat ASAR	35 days	23 degrees (15°–45°)	25 m	5.56 cm	HH/VV, Dual	ESA
Alos Palsar	46 days	34.3 degrees (8°–60°)	10 m	23.6 cm	HH/VV, Quad	JAXA
TerraSAR-X	11 days	32 degrees (15°–60°)	3 m (up to 1 m)	3.11 cm	Single, Dual	DLR

New planned missions such as Sentinel-1 constellation, SAOCOM, Alos-2, Radarsat constellation, TerraSAR-X-2, SJ-1C, Kompsat-5 and 7 and possibly other SAR missions ensure of reconnaissance of usefulness of such instruments and a need of following development in this area. Named satellites are to form a new generation of high quality SAR instruments to observe local or global land changes on the Earth.

2.2 Basic Overview of InSAR Processing Techniques for Deformation Monitoring

Differential InSAR processing (DInSAR) is a basic technique to derive only phase changes due to temporal surface movements (deformations). Every phase difference between two corresponding points is composed by various phase yielding sources. Amongst the deformation, this is a phase caused by the Earth curvature (DInSAR corrects using precise orbit data that simulates phase caused by a local ellipsoid), phase term caused by a delay of radar wave propagation through the atmosphere (various non-straightforward attempts for DInSAR exist), main noise (that is filtered using various techniques in DInSAR) and topography induced phase (DInSAR removes the topography phase term using some digital elevation model scaled to the line of sight according to the SAR baseline estimations).

Since the DInSAR leads to achieve an image of terrain changes between two acquisitions in some time delay, it still copes with such problems as an atmosphere-pass phase induction, errors of external data (orbital data, DEM) or generally a decorrelation (loss of correlation of received radar reflections between combined SAR images, i.e. situation where the phase of a pixel in interferogram is influenced by other sources than by reflection from observed object). It is possible to minimize the effect of some error sources by processing more radar images in a stack. For example, to understand the land movement in a large time delay, it is possible to create differential interferograms of a shorter temporal difference, that will not be affected by temporal decorrelation (caused by movements of reflecting objects within a resolution cell, e.g. growth of vegetation) significantly, and then to combine them in time order to achieve a full time scale model of deformations. Because a physical character of observed objects will cause a high variance of phase measurements in time and from various angles, only a subset of pixels representing stable radar wave scattering objects through the whole stack are used in praxis.

In fact, this process is more complicated because of various error sources during processing of each interferogram. Most of them can be filtered using the stack processing. If a sufficiently high number of interferograms is used to combine together, it is possible to denote too distinct values that may be filtered out or to form a trend model of atmosphere induction (that is temporally very variable, in comparison with a continuous deformation trend); so-called atmospheric phase screens (APS). Several methods have been developed to carry out this processing idea. They differ mostly in the way of selecting the proper pixels that will be used for the terrain change investigation. As basic techniques that are used in multitemporal processing, the Persistent Scatterers Interferometry method and methods known as Small Baselines techniques should be mentioned.

In the end, the multitemporal InSAR (MT-InSAR) processing will result in a set of points with estimated movement in a high precision. As was stated in (Komac et al., 2007), for a typical ERS interferogram with B_{perp} = 300 m a deformation can be estimated with a precision of 2.8 mm, but if used in a MT-InSAR stack, this accuracy of deformation estimation will be enhanced to around 0.1 mm/year (depending on quantity of acquisitions and a density of detected points).

3 Applied Methods and their Limits Monitoring the Area of Interest

Natural conditions limit proposed outstanding performance of SAR Interferometry (InSAR). Conditions of Karviná region where the InSAR was applied are far from being optimal for its application. The region is not any arid area with low vegetation and stable atmospheric conditions neither the present deformations are in the easily interpretable rate of cms/year but often reach many decimetres per year exceeding detection limits of standard C-band satellite sensors.

3.1 Decovering Source of Inspiration Thoughts

Bulk scientific publications show various studies during c. 20 years of intensive InSAR investigations in order to overcome radar sensor limitations for the practical monitoring usage. Several advanced methods were designed often based on processing multiple SAR images or other additional data.

As one example showing attempt of InSAR monitoring in very close conditions to Karviná area of interest (AOI), Perski (2003) proceeds in subsidence investigation of Upper Silesia area in Poland using C-band SAR data from ERS and Envisat in various configurations. Due to factors causing decorrelation in the C-band interferograms (underestimated phase unwrapping, decorrelation due to vegetation movement etc.) the amounts of subsidence were evaluated only in autumn or winter interferograms. Subsidence was always identified in the area of current or recently closed exploitation activity. He applied also PSI method using TU Delft Persistent Scatterers Interferometry, DePSI (Perski et al., 2007). In this processing only urban areas could be monitored, with no significant subsidence detected.

His team also applies DInSAR technique for SAR images with different wavelengths. While popular C-band data from ERS or Envisat satellites need to be obtained with a very short temporal and geometrical baselines to reduce irreversible decorrelation, L-band data (JERS, Alos) is more suitable to detect faster subsidence even within long temporal gaps (Guang et al., 2009). Precise X-band acquisitions of TerraSAR-X with a short temporal baseline of 11 days provide more detailed overview of subsidence area and possibility of more accurate georeferencing (Krawczyk et al., 2008), but a longer temporal difference becomes prone to a decorrelation.

After Fringe 2003 conference, ESA initiated the Persistent Scatterer Interferometry Codes Cross-Comparison and Certification (PSIC4) Project to produce reliable information about the accuracy and dependability of these methodologies (Raucoules et al., 2009). A coal mining site in Gardanne, France was chosen as an area of interest. The deforming area is mostly non-urbanized with an expected rate of subsidence of up to 25 mm/year. Eight top expert teams with own PSI methods participated anonymously in processing of 109 ERS SAR data of 1992–2004. Because of absence of strong reflecting objects in vegetated areas, significant atmospheric delay variations and not included a priori information about the deformations that could have been used to identify the main deformation trends, as well as other error factors, none of the teams provided absolutely precise estimations. However even that the spatial coverage of identified PS pixels was usually very sparse, the subsidence and stable area were located correctly in almost all the cases. In mainly affected (note that also densely vegetated) areas the techniques underestimated the deformation velocity even for 10 mm/year and the results in general deviated less than 5 mm/year within the whole scene for all the teams. After PSIC4 evaluation, the teams achieved more external data (levelling amongst them) in order to fine tune their results and enhance their algorithms.

3.2 Applied Data for InSAR Processing of Karviná AOI

For SAR Interferometry processing, data were ordered in the framework of ESA: Category-1 project C1P.4578. Data were achieved from satellites ERS-1, ERS-2, Envisat and Alos, in the total amount of 12 SAR images of ERS-1, 123 ERS-2 images, 45 Envisat images and 7 Alos images, all of this from at least two different orbit tracks. Amongst raw Alos data, data were achieved in the single look complex (SLC) format. Scenes of ERS and Envisat cover entirely the area influenced by black coal mining in Moravian-Silesian region; scenes of Alos Palsar cover the area only partially, but with a higher resolution.

In the period of 1995–1996, six pairs in total of only one-day temporal baseline were available (so-called tandem mission ERS-1/ERS-2). From the whole set of ERS images, only 49 images of period 1995–2000 could have been used for a proper multitemporal InSAR processing. The reason was highly variable fluctuations of ERS-2 satellite after the total gyroscope failure on 13th January 2001. Large temporal gaps in descending track dataset of Envisat caused problems in MT-InSAR processing due to temporal decorrelation and measurable phase jumps of reflected radar wave. Since October 2010 images of Envisat are not appropriate for interferometrical processing in the investigated Moravian-Silesian region. Due to change in satellite orbit (descending of around 17 km) it is possible to combine only images in regions at 38° ± 5° of latitude where the orbit inclination is within tolerable limits for InSAR (Miranda, 2010).

Due to small amount of available Alos Palsar acquisitions that include too large temporal and also geometrical baselines it doesn't seem feasible to use single track MT-InSAR methods. Additional acquisitions were ordered, however due to Alos observation strategy the area of interest was temporally always distributed very sparsely, in up to 6 (including low-resolution) acquisitions per a track per year. In April 2011 the Alos satellite mission ended unexpectedly due to satellite failure.

3.3 Applied Processing Methods in Karviná AOI

Amongst basic differential InSAR (DInSAR) processing of two SAR images to evaluate subsidence between their acquisition dates, also multitemporal InSAR processing was used - Persistent Scatterers and Small Baselines techniques as implemented in StaMPS (Hooper, 2008). Several adaptations were performed to increase their reliability applying in the current AOI, see (Lazecký, 2011). Also several filtering options were investigated to optimize DInSAR results. An original technique of non-local mean filtering (Deledalle, 2010) was adapted by Lazecký (2011) to be used for DInSAR interferograms filtering. Overview of applied advanced filters are shown in a real example in Fig. 3 of ERS-2 interferogram showing subsidence of around 6 cm in ERS-2 LOS within 35 days in inhabited area of Havířov-Dolní Suchá 23 February 1998 – 30 March 1998 (area is 1.7 km^2).

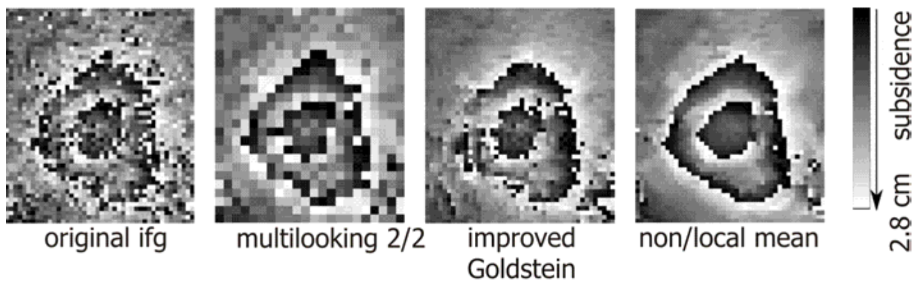


***Fig. 3** Various phase filters applied to partially decorrelated differential interferogram from ERS-2 SAR images 23. 2. 1998 to 10. 3. 1998 of undermined Havířov-Dolní Suchá. A subsidence of ~ 6 cm per these 35 days can be interpreted in the area of 1.7 km^2.*

4 SAR Interferometry Monitoring Results in Karviná Area of Interest

The main achievement in applying InSAR technique for monitoring subsidence is the opportunity to observe changes within large areas using data from archive of relatively long-time acquisitions - data of Karviná AOI are available since 1992 (see Fig. 2). Such advantage is demonstrated in Fig. 4 and Fig. 5 - differential interferograms from 1998 (ERS-2) and 2008 (Alos Palsar, with phase recomputed to correspond with the ERS-2 wavelength) showing changes in subsidence in the region. Note that the ERS-2 acquisitions were taken in dates without vegetation activity; therefore the 1998 interferogram is not decorrelated as most of other ERS/Envisat interferograms. Fringes depict real subsidence in rate of 2.8 cm per fringe (full colour cycle) in the satellite line of sight that is not far from vertical direction.

These interferograms are further investigated in the text, together with validation from levelling points at places also shown in the maps. Unfortunately only a small portion of interferograms within the work exhibits such a high degree of overall coherence. Data from C-band instruments (ERS, Envisat) are usually decorrelated in vegetated areas and had to be processed by multitemporal InSAR (MT-InSAR) techniques to provide overview of subsidence at least of selected stable points (most of these correspond to exposed houses or other urbanized areas with very low vegetation cover).

Results of MT-InSAR processing of 18 selected images (from original count of 49, including images of non-optimal configuration or with too high decorrelation/atmospheric disturbances) of ERS-1/ERS-2 ranging from the 08/1995 until 06/1999 are demonstrated as a map of mean deformation velocity as computed by StaMPS, in Fig. 6. The fading subsidence from closed mines in Ostrava is also clearly visible on the left side of the map.

This fading subsidence can be further investigated - as found out in (Lazecký, 2011), some subsidence in the order of millimeters per year was detected also on the former mining sites in the period of 2003–2010, that is, even more than 15 years after mines closure (post-mining area is commonly preceded to stabilize after up to about 5 years after mine closure). This detection however requires a deeper investigation in order to indicate real sources of the subsidence. Unfortunately, no levelling or other geodetic data are available for comparison with the MT-InSAR-evaluated results in Ostrava. The mentioned processing results of Ostrava are demonstrated again as a map of mean deformation velocities in Fig. 7. Note visible darker marks north from inactive mines Ludvík or J. Fučík that depict the subsidence of up to 2 cm during the whole period of 12. 2002 – 09. 2010.

The last figure (Fig. 8) of this chapter demonstrates an advantage of L-band data from Alos Palsar against commonly used C-band data from Envisat satellite for monitoring of subsidence in Karviná AOI. Acquisitions from both sensors were taken at similar dates. No significant atmospheric artefact was present in any of the dates that could influence phase measurements of the sensors. Yet the results are prominently different. A relatively fast subsidence of around 73 cm per 46 days detected by Alos Palsar in area undermined by Darkov Mine plants stayed undetected by Envisat. This is mainly due to vegetation activity. Radar waves are reflected from objects of size at least equivalent to the radar wavelength. While Alos Palsar wavelength of 23.6 cm penetrates through vegetation canopy, Envisat wavelength of 5.66 cm reflects from moving vegetation leaves, the received wave signal is temporally decorrelated. This is to demonstrate the most common problem with decorrelation of most of C-band interferograms of Karviná AOI.

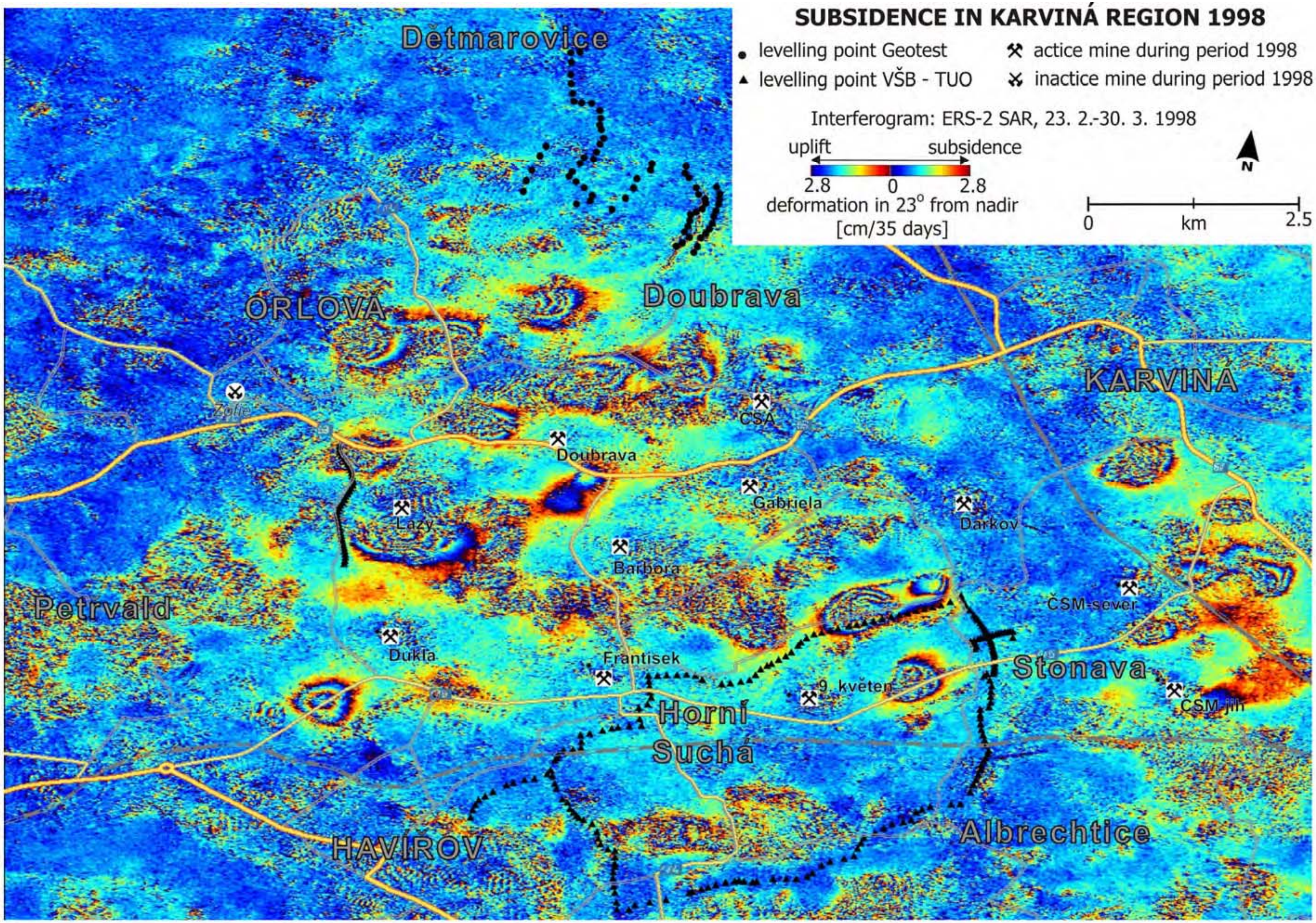


Fig. 4 Differential interferogram from ERS-2 SAR data, 23. 2. 1998 – 30. 3. 1998, displaying subsidence in Karviná AOI.

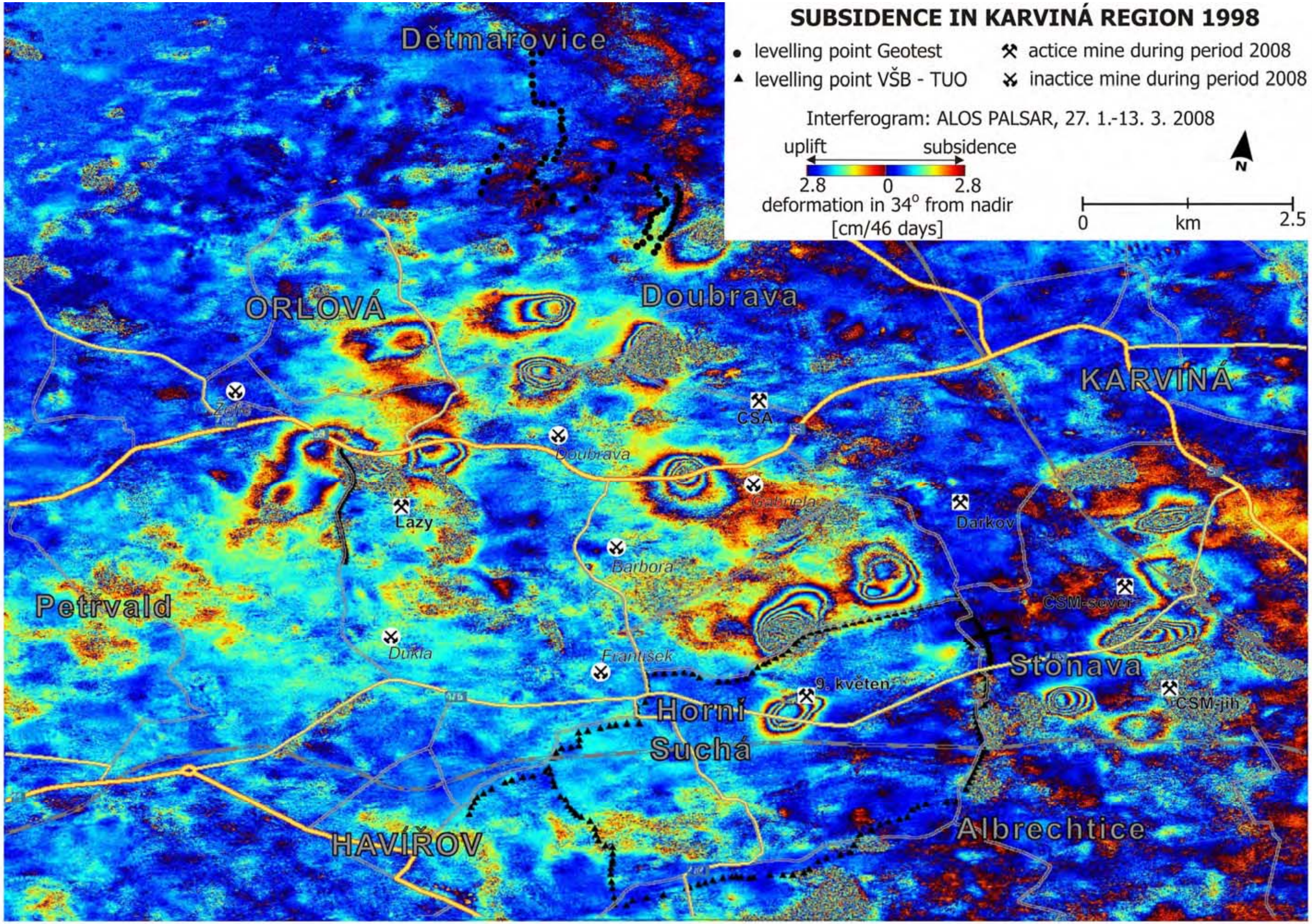


Fig. 5 Differential interferogram from Alos Palsar data, 27. 1. 2008 – 13. 3. 2008, displaying subsidence in Karviná AOI.

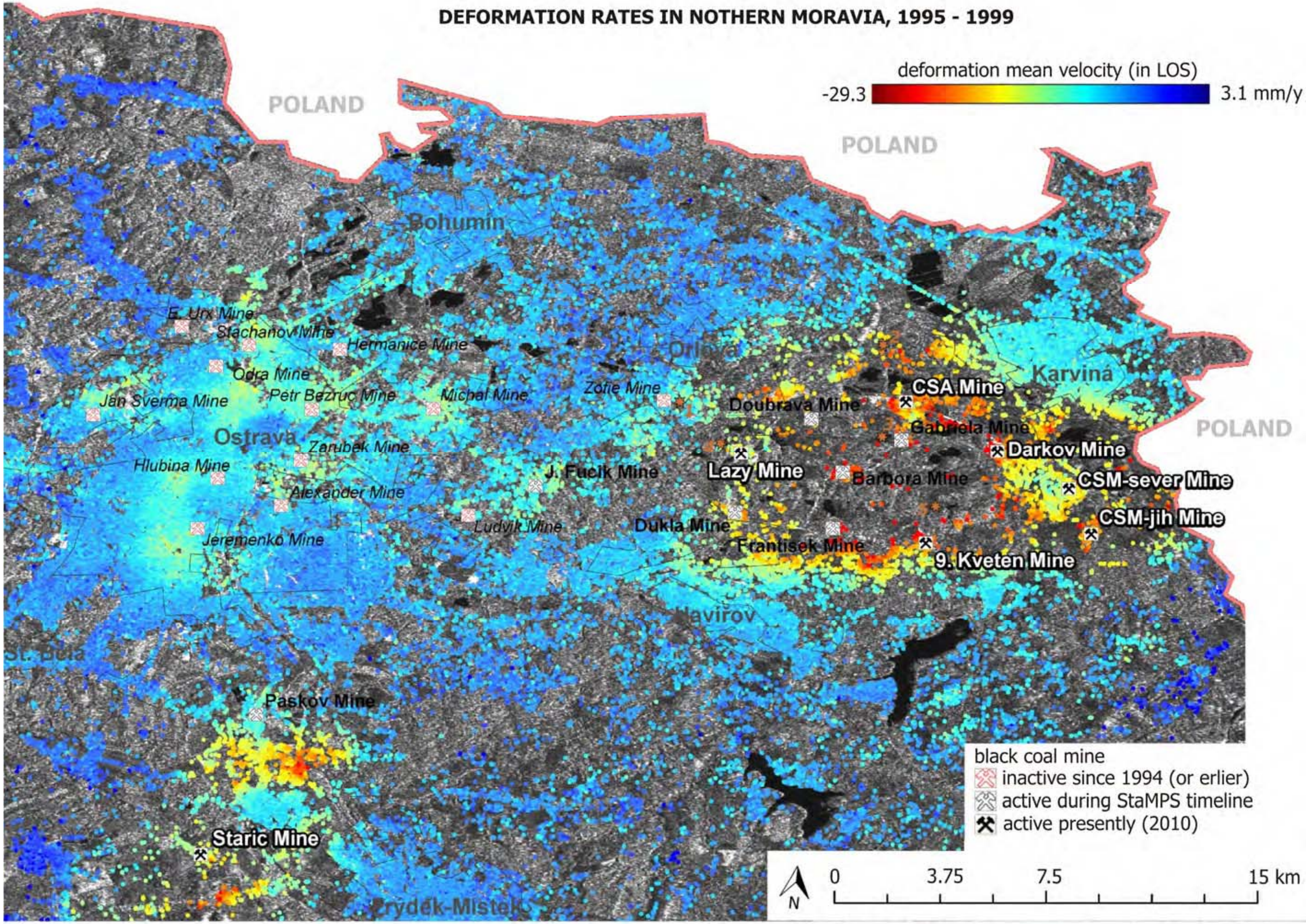


Fig. 6 Subsidence in Ostrava-Karviná mining region by MT-InSAR processing of ERS acquisitions, 8. 1995–6. 1999.

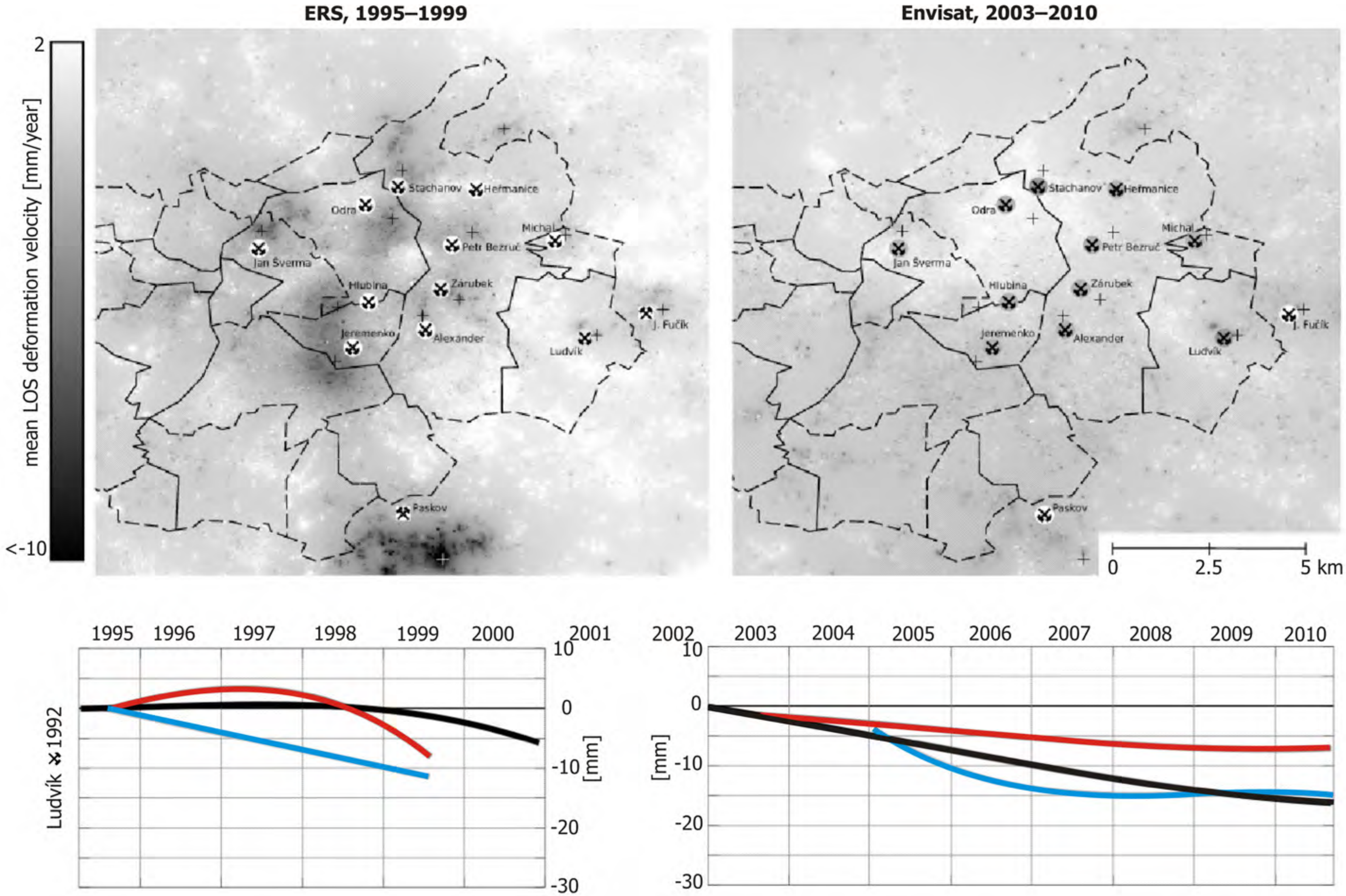


Fig. 7 Investigation of Ostrava area by MT-InSAR of ERS descending dataset of 8.1995-6.1999 (left) and Envisat ascending subset of 12.2002-9.2010 (right). Bottom graph shows estimated deformation trend of selected points in the Ludvík Mine surroundings.

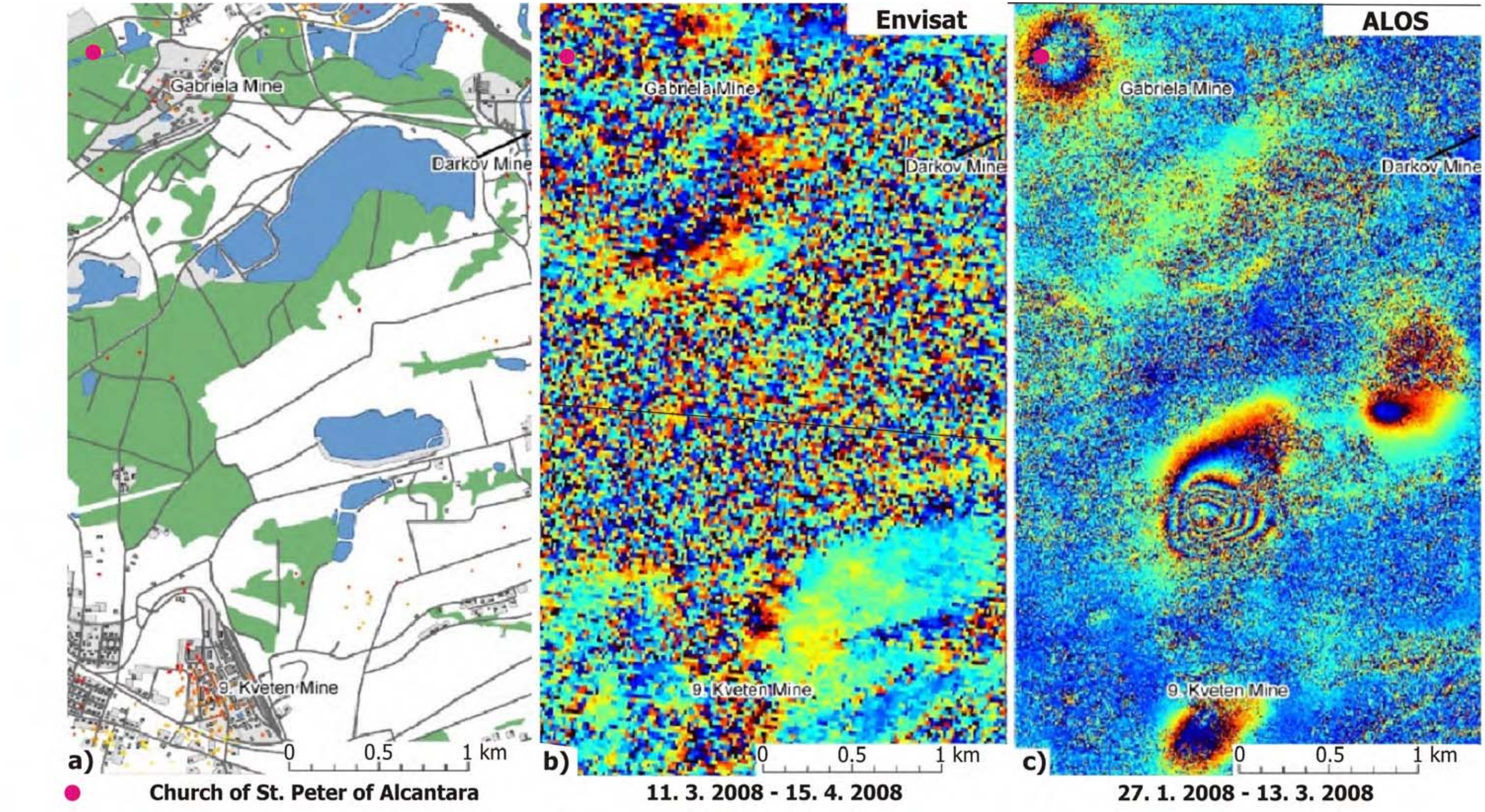


Fig. 8 Different results of interferograms from Envisat (b) and Alos (c)of area undermined by Darkov Mine plants from first quarter of year 2008.

Based on experience from proposed investigations, appropriate data for continuous monitoring of subsidence in Karviná mining region can be depicted - most of subsidence occurs out of urbanized areas, therefore areas causing significant decorrelation for radars of shorter wavelengths (C-band or even X-band). Such areas however can be monitored either by L-band data or by other band images acquired during periods of vegetation inactivity, i.e. during winter (note that used radar wave doesn't penetrate through snow cover, L-band waves may partially penetrate). For monitoring subsidence in urban areas, MT-InSAR techniques can be used advantageously. However, MT-InSAR processing of ERS/Envisat data hereby had to be performed with a series of approximations and filtering. This was again mainly due to presence of vegetation, together with other factors connected to current atmosphere conditions and orbit configuration of satellite during sensing. More appropriate MT-InSAR results can be achieved using more data of higher temporal and/or spatial resolution.

5 Validation of InSAR Measurements using Geodetic Data

To compare results from InSAR processing with geodetical reference data, both Envisat and Alos data could be used. Levelling lines L and P of Holkovice area and a line at Lazecká Road (Lazy Mine) constitute of levelling points of 50 m spacing monitored monthly using precise electronic instrument Leica NA 3003. Levelling profiles showing relatively fast subsidence in the areas are presented in Fig. 9.

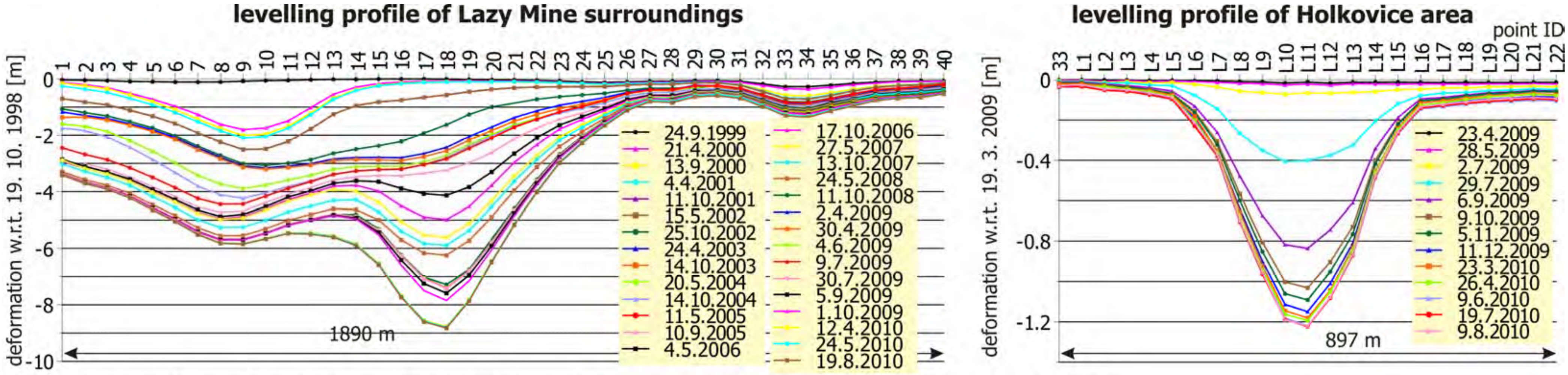


Fig.9 Profile plots of levelling results of (a) Lazy Mine area and (b) levelling line L of Holkovice

5.1 Holkovice Area

Area of Holkovice is situated nearby Stonava, one of most affected cities by subsidence due to undermining in Karviná region. As visible from situation map and interferograms of Fig. 10 the area is surrounded by several subsidence bowls of Mines Darkov and ČSM. The location monitored by levelling is affected by a subsidence of CSM Mine. Levelling is performed each month since 2009.

Several levelling jobs were planned during dates of flyovers of Envisat satellite during 2010. It was expected that it will be possible to compare results from both technologies. From Fig. 9b it was possible to see that during 2010 the subsidence of the levelling line L in the area (presented as a horizontal line in situation map in Fig. 10) was significantly smaller (up to 10 cm/year) than in previous year. With such relatively small amount of deformation, no problems due to phase unwrapping are expected using Envisat ASAR instrument - here, within one resolution cell (around 25 m) a deformation can be correctly captured if up to 1.4 cm in satellite line of sight without need of estimating of phase jumps (Hanssen, 2001).

However, in closer look at Envisat interferograms, other important problems were found that totally deprecated InSAR results in the area. In interferograms from 2010, the area has been always totally decorrelated. The most probable reason of decorrelations are frequent changes of atmospheric conditions connected with physical changes (movement of vegetation, mudded soil after heavy rain etc.). Even after a correct coregistration of input images the resulting interferograms are strongly charged by noise. Only phase difference between

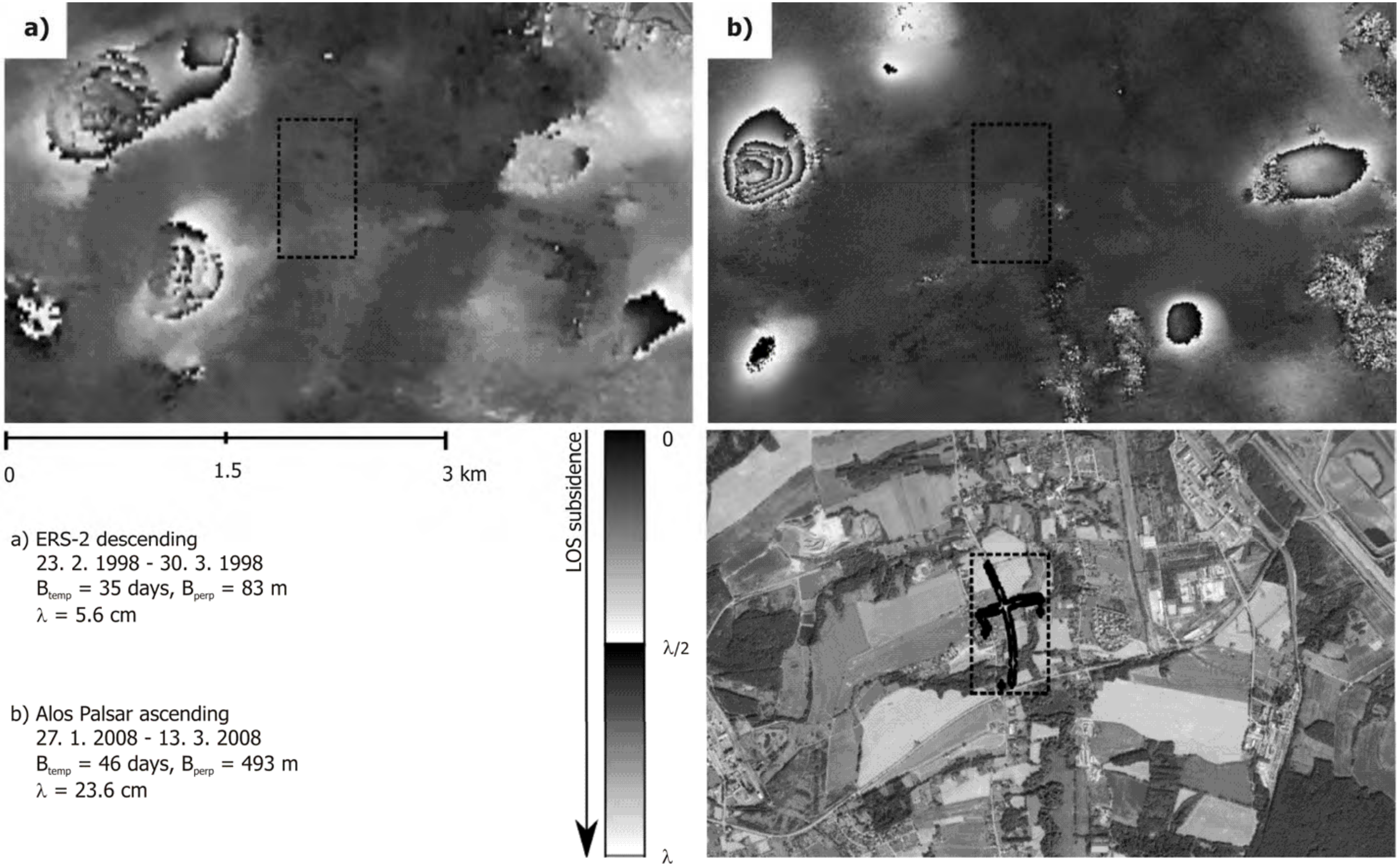
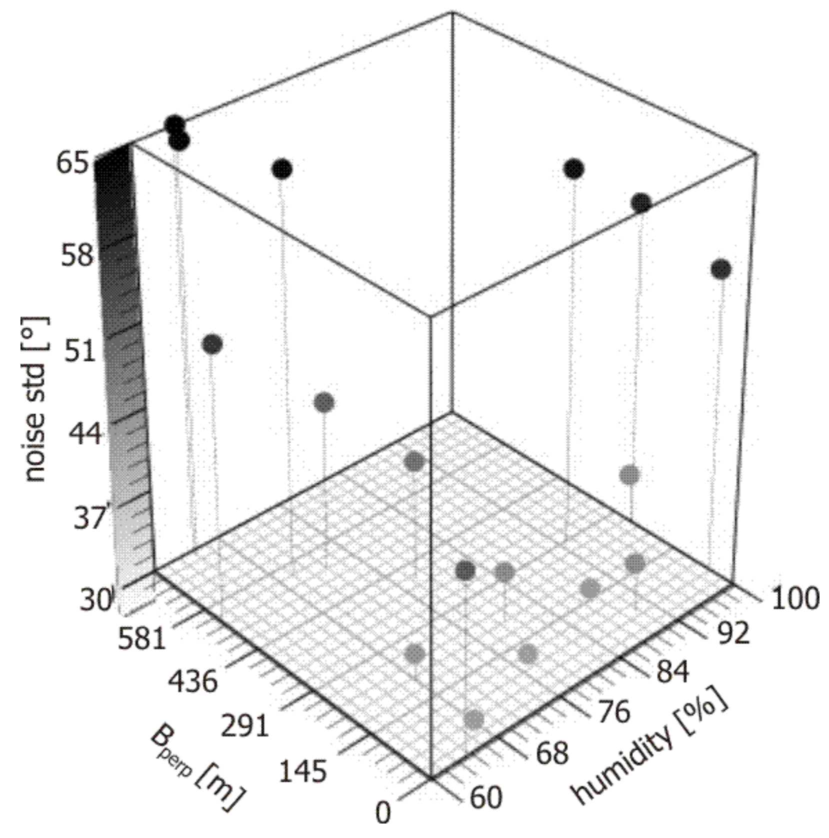


Fig. 10 DInSAR results around Holkovice area, differences within 10 years. Background image by Google Earth TM.

stably reflecting objects would be possible to evaluate from such decorrelated interferograms assuming a proper coregistration. This was the aim for processing using StaMPS: Persistent Scatterers technique. Tab. 2 describes weather conditions in particular time of Envisat acquisitions. The same figure demonstrates influence of parameters of orbital configuration (B_{perp}) w.r.t. reference image of 20.7.2009 and especially of atmospheric moisture on noise in interferogram (described by parameter of standard noise deviation σ_{noise} in StaMPS). Evidently it is not possible to properly evaluate an interferogram produced from acquisitions of improper conditions - practically an acquisition with a value of $\sigma_{noise} > 50$ contains too much noise to be left in the processing chain. They were only interferograms combining acquisitions from 11. 5. 2009, 20.7.2009 and 24. 8. 2009 were used for comparison with levelling measurements.

Tab. 2 Observed relation between B_{perp} and weather conditions (air humidity) factors on noise standard deviation σ_{noise}

Date	B_{perp} [m]	Humidity	Weather conditions	σ_{noise}
17. 01. 2005	35 days	60%	clear	53
21. 02. 2005	559 days	70%	mostly cloudy	63
02. 01. 2006	250 days	100%	light snow	57
09. 10. 2006	727 days	65%	clear	65
22. 01. 2007	717 days	65%	clear	54
26. 02. 2007	63 days	100%	overcast, light rain	55
17. 03. 2008	207 days	80%	mostly cloudy, rain?	34
06. 04. 2009	529 days	73%	scattered clouds	44
11. 05. 2009	199 days	68%	clear	32
20. 07. 2009	0 days	64%	partly cloudy	45
24. 08. 2009	54 days	68%	partly cloudy	30
07. 12. 2009	254 days	100%	overcast, rain?	34
11. 01. 2010	291 days	93%	overcast, snow?	61
31. 05. 2010	70 days	90%	rain showers	34
05. 07. 2010	111 days	78%	cloudy, rain?	30
09. 08. 2010	397 days	78%	scattered clouds	40



For these dates, values from levelling measurements from nearest measurement dates were interpolated. From these, differences corresponding to subsidence of levelling line L were computed. This subsidence was converted to satellite line of sight and wave-phase corresponding to these values was simulated. Only this simulated phase could be compared to the phase values of interferograms. It is necessary to point out that phase of reflected radar wave is influenced by all objects contained in current resolution cell (or even from surrounding cells) that is in Envisat ASAR case around 25 × 25 m (after performed multilooking). It is possible to assign the phase change contribution due to individual objects only in a restraint degree for dominantly reflecting objects, for example for corner reflectors, properly orientated buildings etc. This wasn't possible to ensure in this case - therefore this comparison is only preliminary.

Amongst comparison graphs in Fig. 11 also differential interferograms in the levelling line surroundings are shown (Jiránková, 2010). Interferograms are relatively strongly decorrelated even here - in these cases however also temporal decorrelation due to movements of physical objects are expected - for example changes in vegetation or movement of other objects larger than 5.6 cm. Due to low resolution of SAR instrument aboard Envisat and its other limitations for monitoring in non-homogeneous areas, it wasn't possible to compare its measured data with results of levelling entirely correctly. Even with this view, an attempt of their comparison was performed (Fig. 11) - the phase corresponds approximately at first two interferograms with a shorter temporal interval, 35 days, however also here the differences to levelling are significant, which is explained by reflection from many other objects in the surroundings of 25 × 25 meters resolution cells.

Better results are expected using more appropriate radar instruments - proper data of Alos Palsar are, unfortunately, available only for period of time when no levelling measurements are at disposal. Fig. 12 depicts phase values at the same levelling line, from Alos Palsar interferogram, from period of 27.1.2008 and 13.3.2008 (46 days). Even without comparative possibilities, these images with higher resolution of 10 × 10 m and longer wavelength 23.6 cm penetrating through vegetation and smaller objects are able to conserve much higher coherence than in the case of Envisat satellite. Observed subsidence trend should correspond with the reality in this area.

5.2 Lazy Mine Surroundings

The same issues in evaluating of subsidence and comparison with levelling results were identified also in the area of influence of Lazy Mine. Due to a high degree of subsidence the situation is even more complicated, errors increase due to wave phase jumps. Strongly decorrelated interferograms of Envisat were filtered using relatively aggressive method of NL-Mean (Deledalle, 2010) adapted by (Lazecký, 2011). Though it is not possible to evaluate the amount of identified subsidence after the filtration accurately, it is possible at least to identify subsiding locations and to observe their evolution in time. This is described in Fig. 13 where also the levelling line along subsiding Lazecká Road is figured.

For this levelling line also data from older period are available. Using them, it was also possible to compare levelling measurements with phase changes of Alos Palsar interferogram from year 2008. The closest dates of levelling measurement were at 13. 10. 2007 and 24. 5. 2008. Again the measured data were linearly interpolated to correspond approximately to expectable situation during days of Alos Palsar acquisitions, i.e. 27. 1. 2008 and 13. 3. 2008. Therefore it is necessary to have in mind possibility of large errors in reference data from such interpolated levelling data - results are probably biased! The resulting data comparison is shown in graph at Fig. 14. Again the subsidence amounts are valid for direction of satellite line of sight (i.e. around 34° from nadir), w.r.t. reference point (levelling point 26).

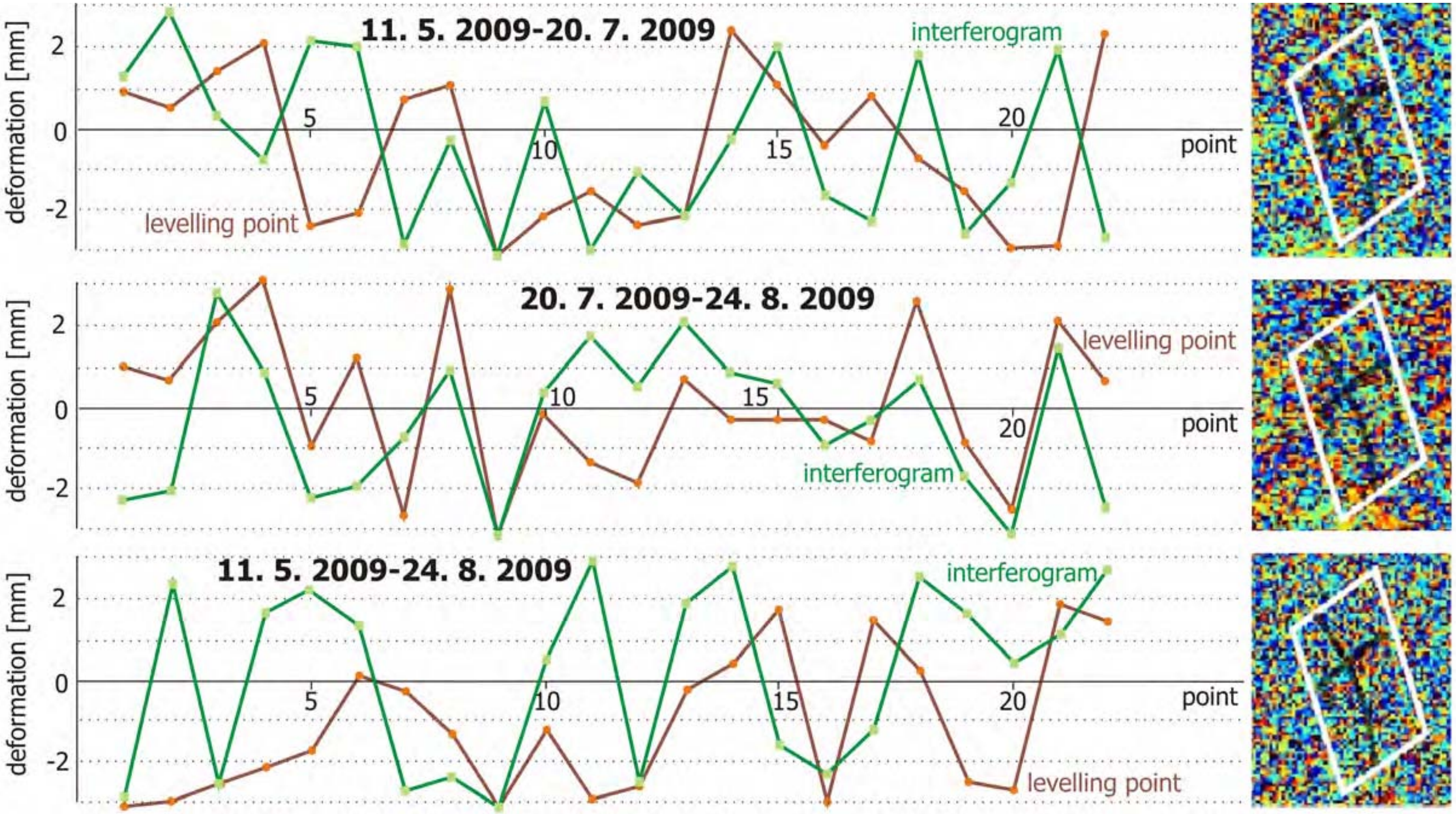


Fig. 11 Comparison of levelling measurements from line L and values from Envisat interferograms

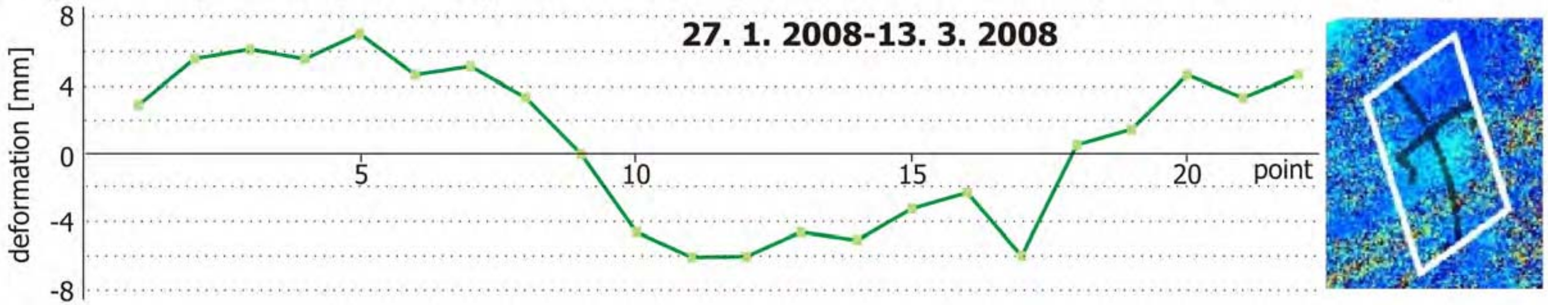


Fig. 12 Subcidence of levelling line L read from Alos Palsar interferogram (values related to L 9 levelling point)

5.3 Comparison with StaMPS Results

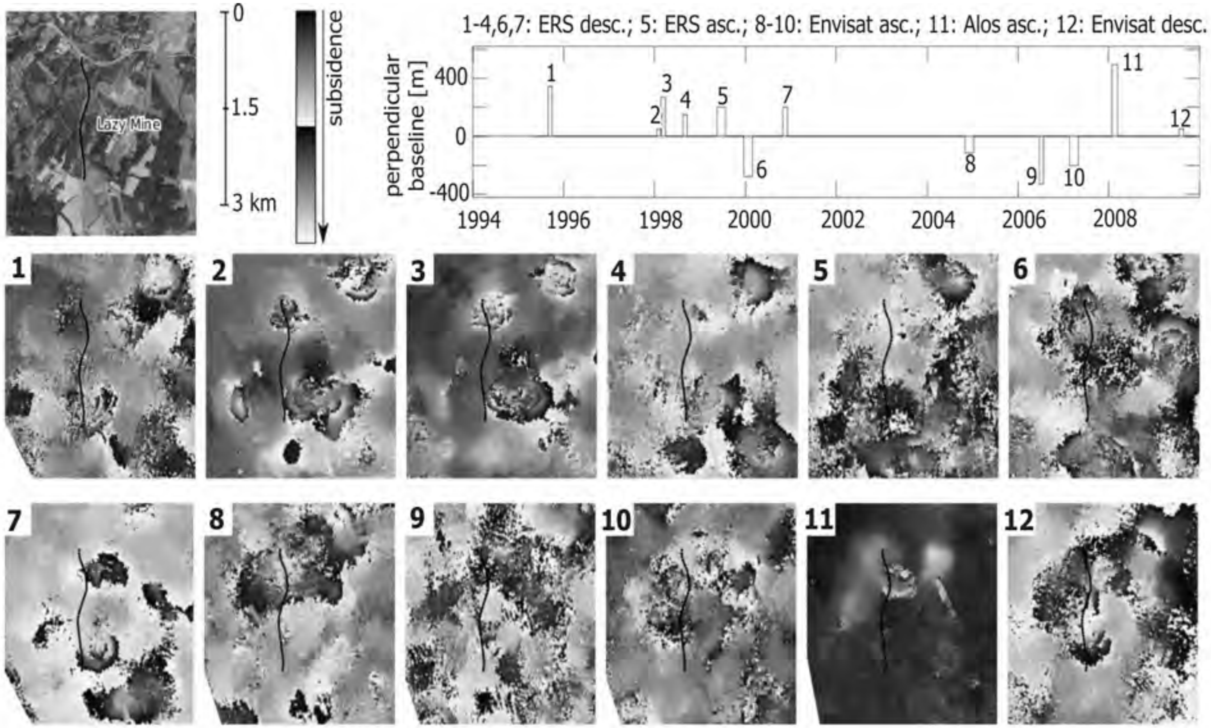


Fig. 13 DInSAR results of Lazy Mine surroundings, filtered by LN-MEAN algorithm Background image by Google Earth TM.

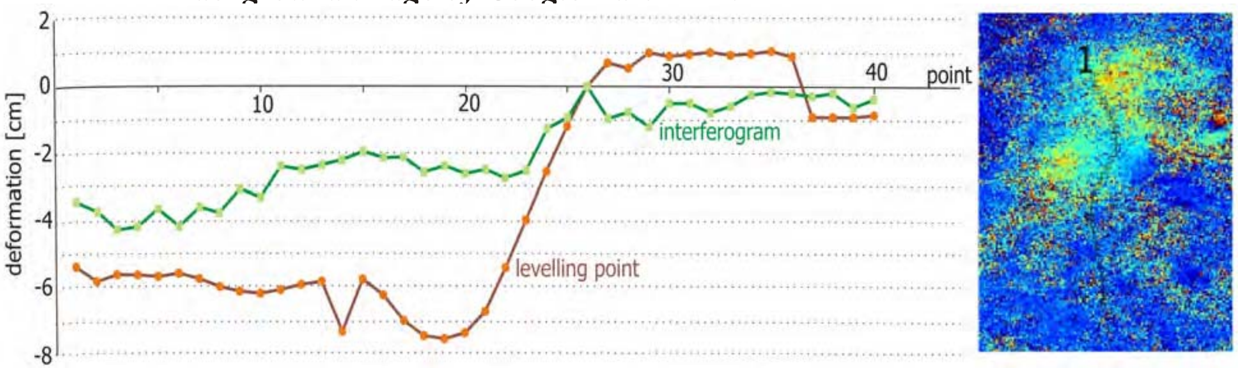


Fig. 14 Comparison of subcidence of Lazecká Road in Alos Palsar Line-of-Sight from Alos Palsar Interferogram of 27.1.2008 and 13.3.2008 (blue) and linear estimation from levelling from period 13.10.2007 and 24.5.2008.

Both investigated areas of Holkovice and Lazy Mine surroundings are covered mostly by natural areas as a forest, meadows, agricultural land or water reservoirs. Only in a small part of the area there are objects that behave stably in time and reflect non-depreciated strong radar signal. Such objects were not monitored by levelling but MT-InSAR processing could have been applied at them. For this processing, an implementation of Persistent Scatterers in combination with a Small Baselines technique in StaMPS (Hooper, 2008) was used. Due to a low number of stably reflecting objects and due to fact that there are subsidence often exceeding detection limits for Envisat radar, even this processing copes with errors. A result from Envisat data processing of period February 2007-September 2010 in the Lazy Mine area is illustrated in Fig. 15. This is a result of Small Baselines technique that allows using favourable combinations of images to identify a higher number of stably reflecting points - some of these points were detected also directly on the Lazecká Road. An attempt to evaluate a progress of subsidence according to interferometrical estimations of these points is also shown at Fig. 15. From the comparison with existing levelling measurement, however, a strong underestimation of subsidence is noticeable - the subsidence is too high to be properly evaluated using Envisat radar. Despite this, the method detected subsidence at correct locations that couldn't have been identified from differential interferograms directly due to strong noise of temporally unstably reflecting points in the surrounding.

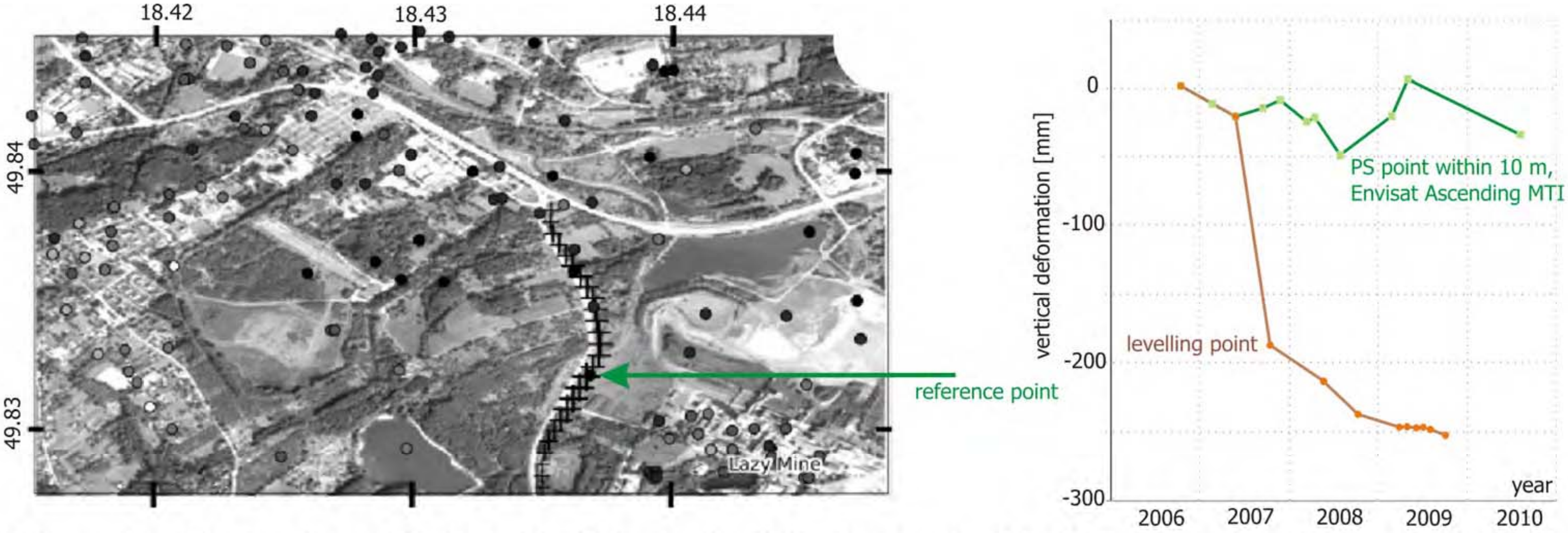


Fig. 15 Processing of Envisat data of 02. 2007 – 09. 2010 using Small Baselines method (StaMPS) with optimized parameters (Lazecký, 2011) Background image by Google Earth ™

6 Conclusions

By monitoring of progression of subsidence basin and solving problems of damage of natural and anthropogenic objects, very often problems occur just at the borders of the basin. In such cases, SAR Interferometry can contribute by showing exactly where the movement already happened and what area is still stable.

The multitemporal InSAR methods in general can unveil subsidence of a milimetre scale per a very long time period. With these methods it is possible to remove many sources of unneeded noise due to atmospheric artefacts, DEM and orbital errors in a quality that is not possible using only two images formed by DInSAR. Using modern algorithms it is possible to achieve almost real estimation of land deformation trend. Unfortunately it seems to be too sensitive to achieve a real trend in case of a fast subsidence that exceeds the pixel phase detection limits (half of carrier wavelength). This is related to phase unwrapping issues, mostly in cases of sparsely sampled deformation areas.

Comparison of levelling lines in Holkovice (Stonava area) and Lazecká Road in Orlová with results of InSAR technology was performed. Both locations subside in extreme rate due to mining activities, sometimes even exceeding subsidence of 1 meter per year.

In the area there are only a few objects that can be used are proper radar signal reflectors - conversely, the area often suffers by temporal decorrelation due mainly to the vegetation cover.

Advantages of using Alos Palsar data were demonstrated - its radiation of 23.6 cm wavelength is able to penetrate through vegetation. Unfortunately no appropriate data from levelling existed for the only available combination of Alos Palsar from the first quarter of 2008, thus it wasn't possible to compare results with reference data. Data from Envisat radar area available in the shortest temporal baseline of 35 days, spatial resolution of c. 25 m and wavelength 5.66 cm. With such configuration its images are able to evaluate in optimal (generally, climatic) conditions deformations up to 14.5 cm/year between the closest stably reflecting points. Due to difficult conditions in investigated area, interferograms from Envisat data were considered inappropriate - they can be used only to detect subsiding areas without proper quantitative evaluation of subsidence. Other situation can happen when investigating subsidence of a smaller rate in densely urbanized areas, as was demonstrated in monitoring of fading subsidence after mines closure in Ostrava - more at (Lazecký, 2011).

Observed areas can be monitored using other satellites. It is recommended to use data from planned satellite Alos-2 that should handle again wavelength of 23.6 cm and its resolution should be better than 3 m. Usage of C-band radar data (Envisat etc.) will be always problematical due to presence of vegetation. It is however possible to achieve high quality results using C-band data from instrument of higher spatial and temporal resolution (e.g. Radarsat-2 or planned Sentinel-1). Data from X-band radar (wavelength around 3 cm) are unusable for subsidence monitoring in the area, however thanks to its high resolution that can be better than 1 meter, at acquisition taken up to once per 4 days (constellation Cosmo-SkyMed), these X-band data can be applied for monitoring of areas without influence of vegetation, such as buildings, bridge constructions or (non-frequent) roads etc.

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