Interferometry used for landslide and land subsidence detection in the undermined area and in the area with abandoned open brown coal mines

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Chapter 1

Objectives of the project

The project evaluates the possibility to detect land movements in the region sparsely covered by vegetation and partly with no vegetation at all. We decided to use scenes acquired during winter time, when the vegetation cover is nearly stable. The interferometric results should be compared to in situ measured data by several geodetical and geotechnical methods. However, only a small part of the brown-coal basin is also investigated by geodetical and geotechnical methods. Contribution of the project lies in proving the possibility to use interferometry data also in vegetated area and enable other specialists to study similar region in late autumn/winter/early spring time with unchanging vegetation. The measurements of places of this type could be studied by this method.

1.1 Chabařovice Area

The area of open cast mine Chabařovice and surrounding ground is investigated, which is not directly affected by mining activities. The area consists of two parts:

1. Upper part of the area is located outside of the mine boundary on so-called virgin ground; this area is known for the shallow slides in relation to water infiltration in the Chabařovice area.

2. Lower part of the area is located directly in former open cast mine and being partially filled with clayey internal waste dump. The waste dump is located on inclined bed and the lowest part of it is assumed to be flooded by water forming a future lake.

   Figure 1.1 shows the map of the Chabařovice area, where other geotechnical and geodetical methods are provided in the same time.

1.2 Other areas

Potentially, the whole area of the coal basin is suspicious of landslides and subsidences. Except for the open mines, some of which are still active, there are a lot of old deep mines in the area. However, these areas are not registered in a map or a report.

After processing of the Chabařovice crop, lost of coherence appears in a large part of the area monitored by ground-based methods. Due to this problem and due to only the first experience with radar ineterferometry the objectives were changed to the testing of the method in the whole coal basin. Also the purpose was moved from pure application to studying the method itself by using different algorithms and configuration in every processing step. The interpretation of the results is also quite difficult and needs some experience.

However, there are many places suspicious of deformations near the Chabařovice area.

Fig. 1.2 shows the sketched map of the whole basin with the cover of imaging swaths.

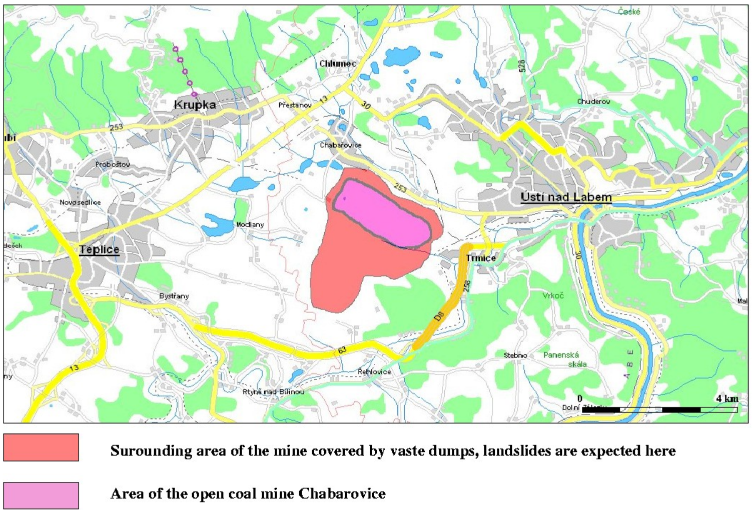

Figure 1.1: Location of the Chabařovice area.

1.2.1 Most

The Most city is surrounded by many open mines. Even a church had to be moved from a part of the city in the last century in order to allow mining. The road connecting Most with Chomutov, together with the railway and pipeline, carrying the Bílina river, lies between two large open mines on a made-up ground, which is about 150 m high. The deformations are assumed to be very large here, although the construction was performed in 1983. However, the area (the road, the railway and the pipeline) is very narrow.

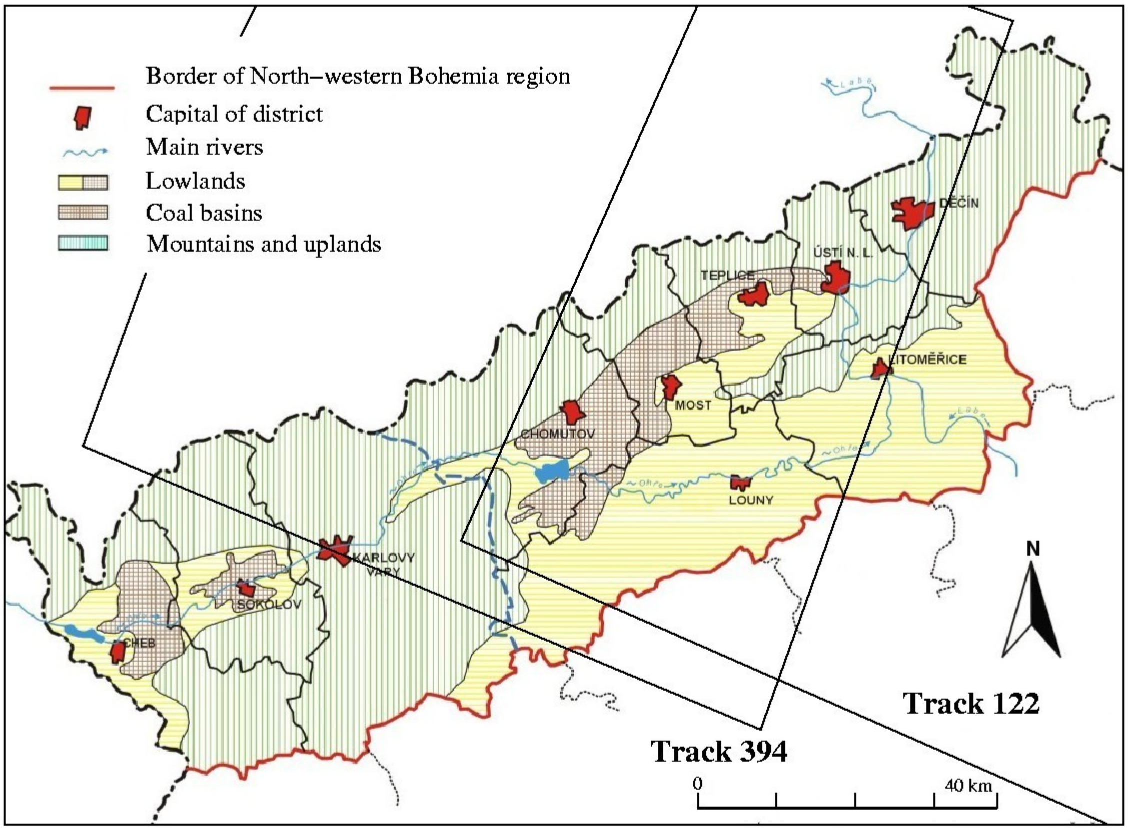

Figure 1.2: General geomorphological map of the northern Bohemia with ERS satellite swaths sketched. The expected suspicious places of subsidences and land movements are first of all in the coal basins region. Chabařovice mine is located between the Ústí nad Labem and Teplice cities in the northern part of the basin.

Chapter 2

Detailed description of the project

2.1 Data Used

2.1.1 Data selection

Data selection was performed with respect to the Chabařovice area.

Therefore the following criteria were used:

- the scenes contain the Teplice and Ústí nad Labem cities;
- the scenes are acquired in winter time, between November 1^{st} and April 10^{th}, between 1998 and 2004;
- the temporal baseline is not longer than one year, i.e. at least two scenes must be acquired during the winter;
- scenes from different track cannot be processed into an interferogram due to a large difference in the incidence angle;
- the perpendicular baseline $B_{\perp}$ is to be as short as possible (shorter than approx. 100 m);
- there are no precipitations at the date of acquisition and three days before (climatology data were used);
- there is no snow cover at the date of acquisition.

2.1.2 ESA data

Five ERS scenes were provided by ESA; however, at the time we are able to process only three of them (track 394).

The scene acquisition parameters are shown in table 2.1.

satellite	date	frame	track
ERS-1	Mar 7, 1999	2583	394
ERS-2	Mar 8, 1999	2583	394
ERS-2	Dec 28, 1998	2583	394
ERS-2	Nov 13, 2002	2583	122
ERS-2	Feb 26, 2003	2583	122

Table 2.1: Data ordered and used.

However, the open-source DORIS software is not able to coregister the pair acquired in winter 2002/2003, probably due to a large divergence of the orbits during acquisition ($0.0055\,^{\circ}$, while for other pairs it is only $0.0009\,^{\circ}$ to $0.00019\,^{\circ}$).

The other three scenes form three pairs, which are described in tables 2.2 and 2.3.

pair	master acquisition date	master sat.	slave acquisition date	slave sat.
topo	Mar 8, 1999	ERS-2	Mar 7, 1999	ERS-1
defo 1	Mar 8, 1999	ERS-2	Dec 28, 1998	ERS-2
defo 2	Mar 7, 1999	ERS-1	Dec 28, 1998	ERS-2

Table 2.2: Particular scenes used for each pair. More details about the pairs can be found in table 2.3.

	topo pair	defo pair 1	defo pair 2
baseline length B[m]	120.4	98.7	42.8
baseline length change (absolute) [m]	2.0	2.3	3.7
baseline orientation α[°]	-5.3	13.2	130.4
baseline orientation change (absolute) [°]	0.005	0.27	3.5
horizontal baseline B_h[m]	119.9	96.1	-29.3
vertical baseline B_v[m]	-11.3	22.5	31.8
horizontal baseline change (absolute) [m]	2.0	2.3	7.4
vertical baseline change (absolute) [m]	0.1	0.0	1.8
perpendicular baseline $B_\perp$[m]	110	98.3	-15.9
parallel baseline $B_\parallel$[m]	49	9.3	-39.6
look angle (scene center) Θ[°]	18.6	18.6	18.5
height ambiguity h_a[m]	69	77.2	-471.3

Table 2.3: Baseline parameters of the data.

The advantage of the defo 1 pair is that the orbit divergence between the two tracks is small and we have been able to process all the desired crops; however, the perpendicular baseline of the defo 2 pair is much shorter, allowing to better deal with the topography. However, we are not able to coregister some crops of the scenes, probably due to the same reason as before.

2.1.3 Orbit data

For processing, the precise orbits computed by DEOS are used. These data are now considered to be most precise, having the radial error in the order of 5–6 cm and across-track error in the order of 15 cm [1].

2.1.4 DEM

As a reference DEM of the area, we use SRTM DEM, released by USGS, with the resolution of 3 arc seconds, i.e. about 90 meters in this area. The DEM is then radarcoded in the DORIS software and interpolated in the GRASS GIS, in order not to contain holes.

2.1.5 Other data

For comparison of the interferometric results with reality, geological map is used. We also have geodetical and geotechnical measurements available; however, these are measured within a different project in the Chabařovice area, where no deformations can be seen in the interferogram.

We also made a quick investigation of the places suspicious of deformation if the entrance was not prohibited.

2.2 SAR Processing

The original ESA data were obtained in RAW format, i.e. unfocused. SAR processing was performed in the open-source SAR processor SIOSAR, developed at the research centers in America, Europe and India. The basic algorithm is described in [4].

The frequency domain and time domain approach for Doppler centroid frequency estimation is combined in the software.

The allgorithms developed by Howard Zebker are also available in the software. Basic source code is written by Evely J. Price from Scripps Institude of Oceanography, and final release is provided by Dr. Y. S. Rao of Indian Institude of Technology, Bombay.

This software product is fully compatible with DORIS software and DEOS precise orbits are used for SAR processing. The output is the complex image with resolution 5616 by 28000 pixels in the range and azimuth directions.

2.3 Interferometric Processing

Conventional interferometric processing was performed in the open-source DORIS software. Phase unwrapping, if neccessary, was performed in the open-source SNAPHU software.

For topography subtraction, we used both three-pass and two-pass methods. For the three-pass method, the topo pair was used for subtracting the topography from both defo pairs. For the two-pass method, SRTM DEM was used for topography subtraction.

2.4 Comparison with Other Data

Finally, the interferograms are geocoded and the places suspicious of deformations are compared to the geological maps, or to the reality.

Chapter 3

Contribution of the development/ improvement of models

3.1 Orbit Error Investigation

As already stated, we use precise orbits computed by DEOS, which are said to be more precise in comparison to those computed by DLR. However, in 1999, the ERS-1 altimeter was already broken, causing the orbits to be less precise.

The influence of orbit errors on the interferogram was investigated, the results are described in [6] in detail. The results show that the orbit error influence is about 3 times larger than that corresponding to the RMS error stated in [5] (across-track and radial components); the RMS along-track orbit error is not stated at all.

The orbit error influence appears in three distinctive features:

1. the shift between the master and slave scenes is incorrectly computed from the orbits;

2. the geocoded interferogram (corresponding to the master scene) is shifted with respect to the reality;

3. the (deformation) interferogram may contain a slope or even fringes where not expected. However, the trend caused by orbit errors has much longer wavelength than the deformations (at least in our case). On the other hand, the orbit error influence cannot be recognized from the atmospheric delay in an interferogram here, both having the long-wavelength effect.

3.1.1 The shift between the scenes

The shift between the scenes, computed from the orbits and by magnitude correlation between the images (both methods are implemented in DORIS) is shown in table 3.1.

computation using	orbits		correlation		difference	
pair	azimuth	range	azimuth	range	azimuth	range
topo	-39	-7	-251	-7	-212	0
defo 1	27	-2	43	-1	16	1
defo 2	66	5	289	5	223	0

Table 3.1: The differences in scene shift computed using precise orbits and image correlation for the processed pairs (using image magnitude). All the values are in pixels. The values may change by a few pixels depending on the scene crop.

It can be seen that the radial and across-track errors, which cause the range shift, are small. The azimuth shift is only 16 pixels (approx. 70 m in the ground projection) in the case where both scenes are acquired by ERS-2, but it is much larger for the case where one of the scenes was acquired by ERS-1.

We attribute this error to a timing bias between the satellites.

3.1.2 Geocoding error

Geocoding was performed in the following way:

1. In order to prevent errors caused by phase unwrapping, we decided to use the height information from the SRTM DEM instead that from the tandem interferogram. The SRTM DEM was converted to the radar system in DORIS. Then, the phase of the radarcoded DEM should be the same (or very similar) as the unwrapped interferogram. However, the DEM is converted using the errorneous orbits. The radarcoded DEM was therefore shifted by the evaluated offset between the interferogram and the radarcoded DEM in order to correspond with the interferogram with an accuracy of few pixels.

2. The geocoding was performed using the radarcoded SRTM DEM, as it was an unwrapped interferogram, i.e. the slant-range to height conversion was performed, computing not only the height of the point above the ellipsoid, but also the latitude and longitude.

The geocoded magnitude image was then compared to a geocoded optical image. A shift may be seen in both directions (more details can be found in [6]): about 4050 m in the azimuth direction and about 1900 m in the range direction. We consider these errors to be quite large. We attribute the shift in the range direction to an inaccurate value of the look angle Θ or to an processing error.

The shift in the azimuth direction is probably caused by a large along-track error of the master satellite.

3.1.3 Residual fringes

The orbit error influence not only depends on the actual error baseline length, but also on its orientation. While the sensitivity on the length is linear, the sensitivity on the orientation is sinusoidal, i.e. highly nonlinear. The orientation influences not only the value of the slope, but also the speed of change of the slope.

The fringes may be eliminated by several methods; of these, we have only tried the `cpxdetrend` script, developed at TU Delft. The other procedures, allowing to correct for the orbit of one of the satellites, were analyzed and will be implemented later.

However, we are only able to correct for the slave orbit error, i.e. for the baseline. In addition, the corrected orbit is not the correct one, i.e. the position of the satellite during acquisition, but the orbit allowing to generate interferogram without fringes. In other words, the correction not only contains the orbit error, but also the atmospheric influence.

3.2 Influence of topography on the coregistration error

[3]

During the internship of one of the members of the team the investigation of the topography influence on coregistration errors was performed. The SRTM data and geometrical configuration of our pairs was used in the model.

However, the results showed that the influence is in whole our area due to very small range in elevation neglectable. Thus the further improoving of fine coregistration algorithm in this way is senseless. Nevertheless this influence was investigated in other projects realised in other parts of the Earth surface (Las Vegas permanent scatterers deformation mapping) and the results were very interesting [2].

In interferometric data coregistration, both the windows and polynomial approaches influence the offsets calculation and coregistration results because of the topography in the area of SAR image. By using precise orbit data of ERS satellite and topographic information, we analyze qualitatively the relation between offsets difference and several influence factors as elevation, distance from near range to far range and perpendicular baseline and the selection of the order of polynomial in different topographies. The results show that the DEM influence in range direction has a direct ratio relation with the elevation and perpendicular baseline but an inverse ratio relation with the distance from near to far range, the DEM influence in azimuth direction has a direct ratio relation with the elevation but small correlation with the perpendicular baseline and the distance from near to far range. Moreover, in the polynomial approach different orders of the polynomial are needed in different topographies to achieve more accurate offset result. More details can be found in [2].

Chapter 4

Quality of ESA data

The ESA data are adequate for SAR interferometry. The only problem is geocoding, which is influenced by the large along-track orbit error. The along-track orbit error also causes the offset between the scenes computed from orbits to be very different from the one computed by comparing the images. Such a difference (800 to 1000 pixels) makes the automatic coregistration of the images impossible.

In addition, if the slant-range to ground-range conversion is performed in DORIS (i.e. with the use of the orbits), the shift with respect to reality is approx. 4100 m in azimuth direction and approx. 1900 m in the range direction. This test was only performed for a small crop of the image at near range.

Chapter 5

Results

5.1 Chabařovice area

As mentioned at the beginning, the particular aim of the research was to detect landslides and subsidence in the surrounding slopes of the huge open brown coal mine Chabařovice. The results of ground-based measurements were supposed to be compared to the interferometric results. Data selection was performed with respect to this fact and therefore older data were excluded. The area of interest was largely decorrelated in the deformation interferogram, although the coherence is quite good in the topo interferogram. It means that the surface changed in such a way that the ability of interference of the signal disappeared. This can be caused by two most significant factors:

- surface moisture and shape was changed (e.g. the snow fell down and melted between the two acquisition, changing the shape of the grass in the area),
- the surface moved approx. horizontally in the azimuth direction.

Topography of the region and ground-based measurements suggest that the landslides in this area appear mostly in the south-northern direction. Unfortunately, this is approximately parallel with the satellite ground track, causing the landslides to be undetectable by SAR interferometry.

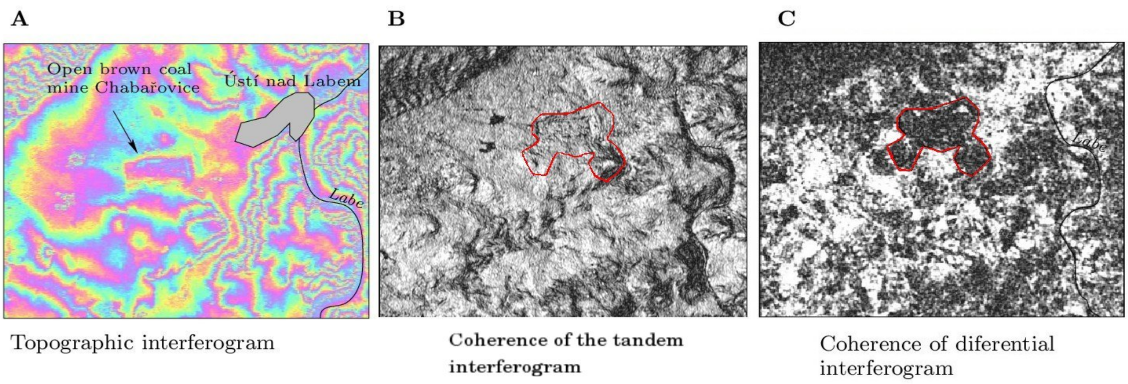

Figure 5.1: **A** shows the topographic interferogram. A good level of coherence even in the area of the open mine can be clearly seen. Although the coherence of the tandem pair is quite good (**B**), the coherence of the deformation pair (**C**) is lost in the area of the open mine (red-highlighted). It is probably caused by landslides in the azimuth direction.

Fig. 5.1 **A** and **B** show the area of interest (**A** - the topography interferogram, **B** - coherence of the topography pair). The decorrelation of the area of interest is apparent in the coherence image of the deformation pair (**C**, framed).

5.2 Most area

Anyway, the whole scene covers an area of approximately 100 x 100 km, containing many open mines and other interesting places. The whole coal basin was successfully processed afterwards and many interesting events were explored.

Fig. 5.2 illustrates the subsidence of the road between Most and Chomutov, together with the railway and pipeline, as discussed in chapter 1.

Figure 5.2: The three-pass deformation interferogram of the highway between Most and Chomutov cities (**A**) and the photo of the area (**B**). The subsidence of the traffic corridor is clearly visible in the image **A**. Different subsidence depth can be also recognized in the interferogram. The railway is approximately 20 m higher than the road and the subsidence is more significant (only the power wires can be seen at the left side of the photo). In comparison to the average of the phase of the surrounding area, the highway subsided by approximately 0.35 cm in the 70 days, the railway subsided by approximately 1.13 cm during this period.

The color change of the interferogram in the area between the two open mines is clearly visible. The subsidence of the road is also confirmed by an informal discussion with specialists from Mostecká uhelná, a.s., the mining company responsible for ground-based measurements in the area.

5.3 Southern Part of the Scene

The area to the south from the coal basin looks very unstable (see fig. 5.3 or 5.4, containg the defo 2 interferogram of the southern part of the basin (5.4) or the area out of the basin (5.3)). However, the area imaged in figure 5.3 does not contain any open mines, and is not undermined. It is far away from the areas containing brown coal.

This area contains agricultural fields; the sharp edges between the places of different color in the interferogram suggest that these are the agricultural field borders. The "deformation" may also be caused by different farming at the fields, different soil moisture etc.

However, we are not able to distinguisdistinguishnd of deformation from the actual subsidences or landslides occuring in undermined areas or in areas near to open mines.

5.4 Other Areas in the Coal Basin

There are many smaller areas with different phase than their surroundings in the coal basin (see figure 5.5). We say that the areas are suspicious for deformations and a quick in situ investigation was performed. Often, there are old mines or waste dumps or mine dumps, or even a part of a power station there.

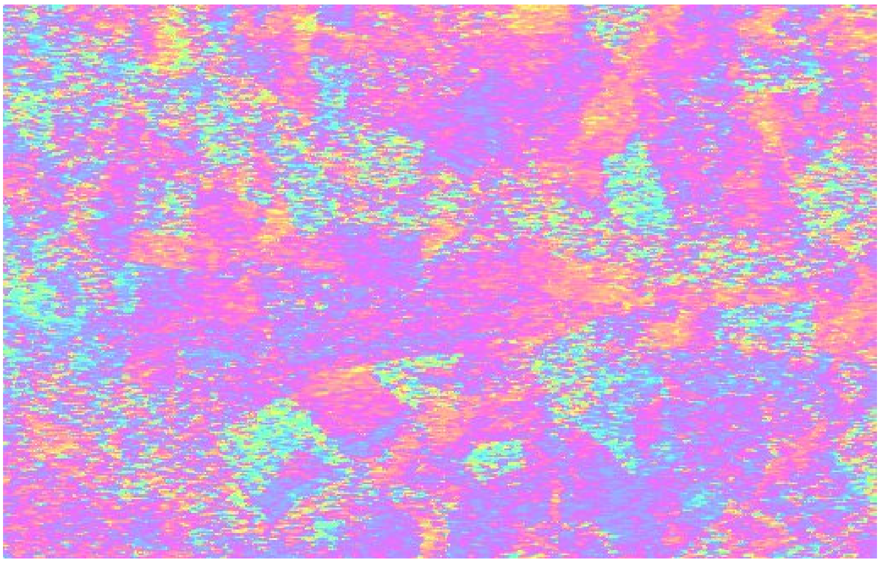

Figure 5.3: Three-pass deformation interferogram of the southern part of the scene. This area is out of the coal mines and therefore no deformations are expected here. Due to the fact that the "deformed" areas with different phase than their surroundings have sharp edges, we attribute the phase change to different farming activities at the fields.

For a proper interpretation, a topographic map needs to be discussed in order to avoid the cases where a wrongly subtracted topography causes the phase difference.

As the result of this work the map of suspicious places was made (see figure 5.6).

The description of the evaluated places from map displayed in fig. 5.6 is provided here.

- The northern shore of the Nechranice dam (area 1) is stroken by land movements coused by high level of the undreground water. This is probably the reason of the relative movements of the road placed there. In addition, the surounding of the power station Tušimice shows some interesting events connected with mining activity in the area.

- The suspicious place number 2 is considered to be interesting by its shape, smooth borders and first of all by its magnitude of subsidence. The difference is much larger than in the case of agricultural fields (see figure 5.3), and the centre of the area is decorrelated. In addition, the terrain is flat here, and with $B_{\perp} = 16m$ of the **defo2** pair, this cannot be considered a DEM error or atmospheric delay. In situ investigation showed that there is a sedimentation tank and the ash dump of the power station Počerady. It is a wide area between vilages Blažim, Vyškov, Břvany and Počerady. That suggests that subsidence can occur here.

- The subsidence of the traffic corridor (area 3; containing a highway, railway and pipeline) is the most clear result of our investigation. The interferogram is shown in figure 5.2. In addition, we can distinguish different subsidence of the highway and the railway (see figure 5.2).

- Areas numbered 4 and 5 are large waste dumps for the mines surrounding the Most city. However, the movements can also be caused by different cover and freezing in the winter. It is impossible to distinguish between these two cases having only one interferogram.

- Areas numbered 6 and 7 are very interesting; however, the defo pair has quite good coherence here. After comparison with a geological map, the areas almost exactly correspond to the mapped movements of vulcanic rocks. This often occurs in vulcanic mountains where the basalt layers are placed over tuffs and pyroclastic deposits. The relief in these areas also shows the rock movements. (The southern border of the basin is defined by the slopes of České stredohoří mountains, which is vulcanic.)

A B

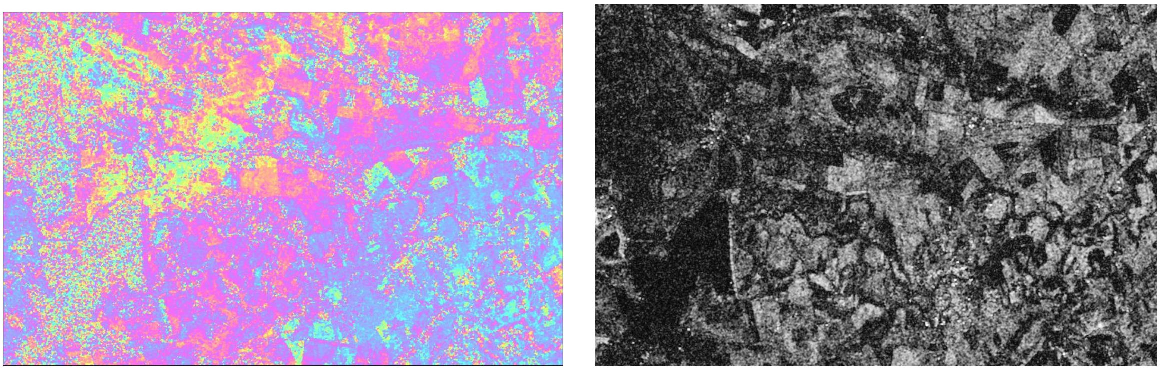

Figure 5.4: Differential interferogram of the southern part of the coal basin and its coherence. The coherence is high in a large part of the crop. We attribute the phase differences in some smaller areas to different farming at the agricultural fields (the "deformed" areas have sharp borders, suggesting they are agricultural fields). On the right side of the crop the huge open coal mines Nástup and Merkur can be seen (the decorrelated areas). The Nechranice dam can be distinguished too, together with the road to the north of it, having a different phase than its surroundings. We attribute the deformation first of all to the mining activity at the open mines to the north from it, potentialy also to the ascending level of the underground water near the dam.

- Area number 8 is very small, which appears suspiscious of deformation only in the interferograms of a small area (when processing a larger area, the coregistration is worse). However, in situ investigation showed that the area exactly corresponds to an old abandoned metal-ore driftmine with its sand waste dump (see fig. 5.7).

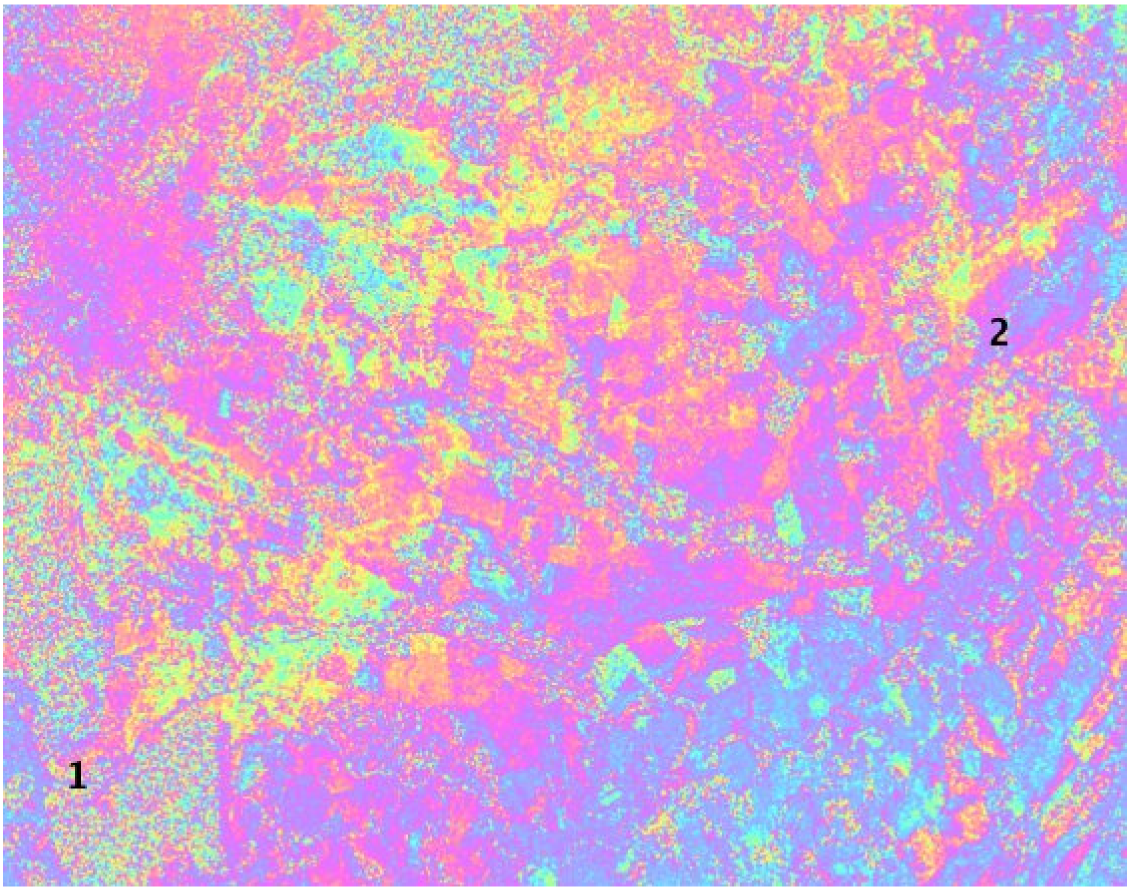

Figure 5.5: The interferogram of the lower part of the basin, identifying the areas suspicious of deformations. These areas are numbered in accord with the map (see fig. 5.6).

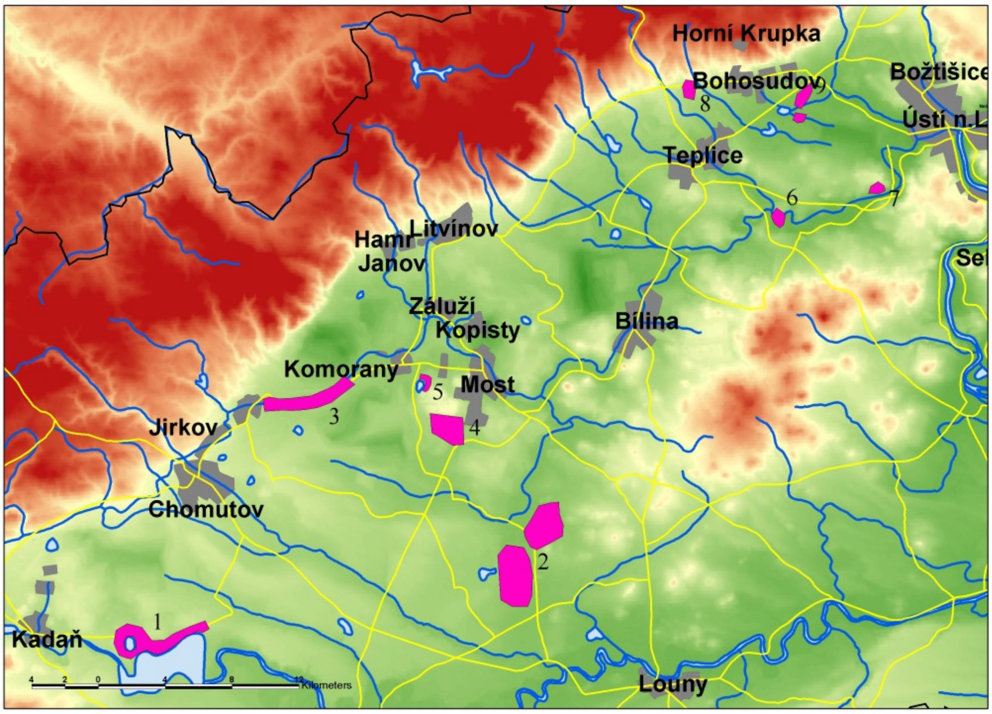

Figure 5.6: A map of the whole Northern Bohemia Brown Coal Basin. The areas suspicious of deformation are chosen by a qualitative investigation of the differential interferograms shown in figures above and are marked pink. The magnitude or even exact area of subsidence cannot be reliable derived from one interferogram. We can only say that the phase difference is caused by a subsidence or a landslide. For such an argument, other data sources were used as well (topographical and geological maps and in situ investigation).

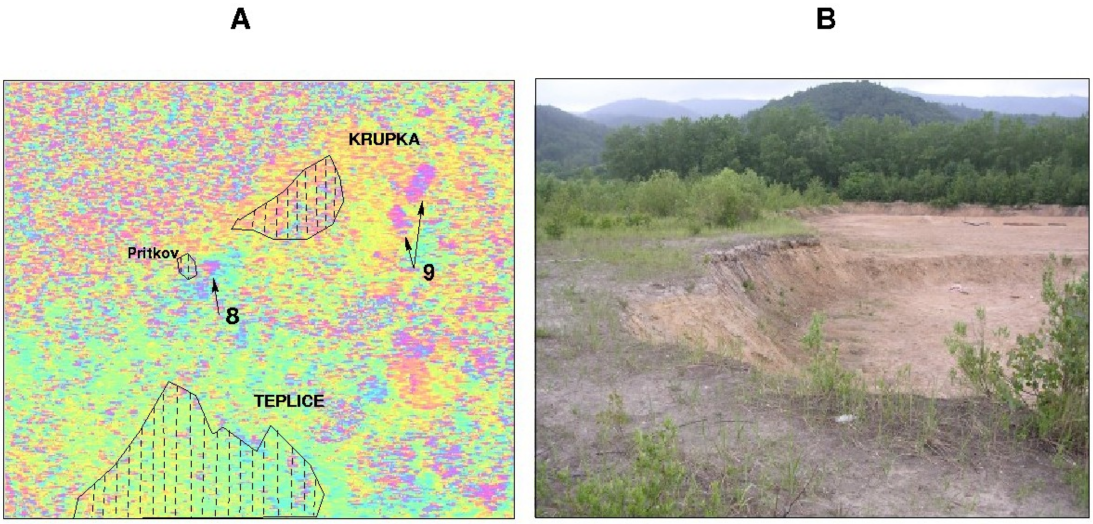

Figure 5.7: The deformation interferogram (**A**) identifying areas 8 and 9 on the map 5.6. The subsidence is clear to the south-east of the village Přitkov (8). **B** contains the photo of the area. It is a very old waste dump of the abandond metal-ore dritfmine. The dump is a small hill almost without vegetation, which is surrounded by a vegetated area. The material of the dump is a pure silic sand. The area 9 corresponds to waste dumps as well. But the extent, shape and age is quite different than the other one. This case is similar to the waste dumps around Most city. The movement can be caused by a real subsidence or by seasonal movements connected with other cover as well.

Chapter 6

Conclusions

The project showed that the interferometric applications are also possible in the conditions of the northern Bohemia, which is partly vegetated. It also showed that it is possible to monitor both subsidences and smaller landslides, but large landslides, as occur near Chabařovice, are impossible to monitor by SAR interferometry due to the decorrelation they cause. The decorrelation is here worsened by the fact that the landslides occured in the direction near to the flight direction of the satellite.

However, it is a problem to investigate deformations having only one interferometric pair. As discussed in the previous chapter, the artifacts may be caused by different farming on an agriculture field.

The project also showed that the amount of data is more important than its quality. We come to a conclusion that the criteria for data selection were very strict, providing only small amount of data. The weather conditions, which were the largest limitation during data selection, are probably not so important, because the atmospheric delay causes only long-wavelength effects in the interferogram.

All the data presented in the previous chapter come from three-pass interferometry. However, we also tried the two-pass method, but it has several disadvantages over the three-pass method:

- the resolution of the SRTM DEM, which we used, is worse than the resolution of the topographic interferogram; in addition, it contains holes which need to be interpolated, other holes arise after conversion of the DEM to the radar system;

- the radarcoded DEM is shifted with respect to the interferogram; this shift is caused by the orbit errors and must be evaluated manually, the DORIS software only allows to shift it by a (constant) integral number of lines and pixels; which may cause artifacts;

- in the area full of active open mines a DEM created in 2000 is out-of-date because the DEM changes very quickly.

- the advantage of the two-pass method in comparison to the three-pass method is that the radarcoded DEM does not contain decorrelated areas and does not need unwrapping, but the areas that are decorrelated in the tandem interferogram are always decorrelated in the deformation interferogram too; in addition, when investigating such small areas of deformation, the correctness of phase unwrapping is not so important.

In order to provide a better information about the deformation processes in the area of Nothern Bohemia coal basin, we decided to make a new data selection.

Chapter 7

Future Work

We would like to perform a new data selection now, with the following objectives:

- all the data will be from the same track, allowing to process them altogether in one stack;
- the data will be acquired in different seasons and different years, i.e. some pairs will have temporal baseline longer than one year, showing larger deformations;
- the data will contain one tandem pair with longer perpendicular baseline, allowing for the topography to be subtracted from the other interferograms;
- the perpendicular baseline of the other pairs will be as short as possible;
- data acquired during the years of broken gyroscope are checked for the value of Doppler centroid;
- no weather conditions are checked for the acquisition dates in advance; we would also like to evaluate the atmospheric influence for different weather conditions, which will be checked after processing of the interferograms.

We would also like to use ENVISAT data. However, we were only able to find one pair acquired in 2004. We consider the lack of ENVISAT data of this area to be a limiting factor.

In addition, we need to work on the coregistration of the scenes acquired by satellites on non-parallel orbits. We are now awating the commercial Gamma software, hoping that it will solve the problem. If it will not, we plan to adjust the DORIS coregistration algorithm in order to provide the coregistration of these scenes too.

We also plan to experiment with the fine coregistration technique in the areas with large landslides: to experiment with the coregistration as an instrument to detect large landslides in the azimuth direction, causing decorrelation. The landslides in the Chabařovice area were most significant in 1990s, amounting several meters in the horizontal direction.

Another experiment will be performed in orbit parameter adjustment. The artificial orbits will be assessed from the interferogram, allowing to compensate for the residual fringes, originating both from orbit errors and atmospheric delay. The tie points, used for orbit adjustment, will be given by a radarcoded DEM shifted to match the interferogram.

Chapter 8

Published Papers

Kianička, J.: Interferometria ako nástroj pre tvorbu digitálneho modelu terénu a jeho spresňovanie z inch zdrojov, Aktuální problémy fotogrametrie a DPZ, Praha 2002, CD.

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