Detecting Land Deformation in the Area of Northern Bohemia using InSAR stacks (preliminary results)

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Abstract:

The area of Northern Bohemia contains a large amount of brown coal and also other minerals. A large area is covered by open mines, but there are a lot of smaller old mines, usually abandoned. The Earth crust is very unstable there, which was confirmed by the first InSAR project, processed during 2004-2005, where only three ERS-1 SAR scenes were processed with the temporal baseline of 70 days.

However, such a small amount of data does not allow to draw even qualitative conclusions. This time we process four data stacks with relatively short perpendicular baselines, in order to find out something about the geological processes happening there. The actual area of the open mines cannot be investigated by radar interferometry due to huge changes causing decorrelation, and the same holds for large areas in the reclamation process.

On the other hand, the last InSAR project showed that the decorrelation in the investigated area is not as bad as expected, and new scenes acquired also in summer and spring are ordered. The area contains several cities, undermined in last centuries, and therefore coherence is expected to be good in these areas even in the cases of large temporal baselines.

The interferometric results are then compared with in situ measurements.

Introduction

Synthetic aperture radar (SAR) interferometry (InSAR) processes a pair of satellite SAR images. The result may be a digital elevation model (DEM) or a map of Earth-crust deformations in the processed area.
The north-Bohemian coal basin is a largely unstable area. In addition to many huge open mines, it contains also deep mines, and some of them are very old and abandoned and may possess a potential danger for the people living in the area.
However, as a result of the previous ESA project, it is not reliable to estimate a deformation (or even its velocity) from one pair of SAR images, especially if the time between their acquisitions is rather short. On the other hand, if the time is long, the interferogram created from the images gets decorrelated due to many effects (most often the vegetation change) and the information gets lost.
The purpose of the ESA project nr. 3423 is to estimate the velocity of the subsidences in the area of north Bohemia using a stack of SAR images from different seasons within the 1996-2004 period.
Due to the fact that the processing is time and memory requiring, we do not process the whole scene, only specific areas (usually towns and cities). These areas were selected as coherent in an interferogram of about 13 months long temporal baseline. In some other interferograms, these areas are not coherent -- these

interferograms were excluded from the postprocessing. In addition, the urban areas are the most important to be monitored for subsidences.
The stack method involves processing of several interferograms with a common master, with respect to which the deformations are related. In order to achieve a larger number of interferograms, some of the slave scenes are resampled in order to correspond exactly (i.e. with subpixel accuracy) to the master. Then, any of these resampled scenes can be used as a master for creating other interferograms, although the baseline parameters etc. do not change by resampling.
The larger number of interferograms is not only usable in the case when some interferograms must be excluded due to a bad coherence (the bad coherence may be also crop-depending, i.e. different for different crops of the scene), but also for reducing errorneous influences in the deformation adjustment and for ambiguity resolution, which is an important part of the postprocessing.
In the InSAR method, all measurements are relative. In deformation mapping, a reference point (or area) must be said to be stable. The deformations can only be assessed with regard to a reference point. We do not know the areas in detail, and therefore are not able to determine the stable point; on the other hand, it may be decorrelated in some of the interferogram. That is why we select the stable point as the most coherent point in all interferograms. In this case, if an unstable point is selected, it looks stable but the surrounding, which really is stable, looks unstable. However, because we do expect subsidence, not the uplift, these two cases can be easily distinguished.
Another feature of the InSAR method is that the measured interferogram phase corresponds to the line-of-sight direction only. The deformation in the perpendicular direction cannot be assessed in any way.
On the other hand, if the deformations are computed independently from a stack of scenes acquired during descending passes of a satellite, and another stack is acquired during ascending passes of the satellite, the resulting 3D deformation may be computed if the scenes are geocoded properly.

Data

The master of this stack is the image acquired from track **23428**. The following locations were processed: Louny (supposed to be stable), Komořany and Most (supposed to be unstable).
Out of the data listed in table 1, many interferograms were created for each of the selected location. In order to create interferograms with non-master images, all images are resampled with regard to the master scene. However, not all of the interferograms were coherent. This may be caused by processing (inadequately estimated coregistration polynom between the two scenes), by acquisition in inappropriate season or by a long temporal baseline. These interferograms cannot be processed furthermore.
The topography was subtracted from the interferograms and the interferograms were filtered using adaptive spectral filtering.

track no.	***satellite***	***date***	***perp. bas.***
23428	ERS-1	1996-01-07	0
3755	ERS-2	1996-01-08	-69
24430	ERS-1	1996-03-17	77
4757	ERS-2	1996-03-18	100
25933	ERS-1	1996-06-30	6
9266	ERS-2	1997-01-27	26

track no.	*satellite*	*date*	*perp. bas.*
10268	ERS-2	1997-04-07	254
15779	ERS-2	1998-04-27	91
16280	ERS-2	1998-06-01	155
40963	ERS-1	1999-05-16	107
28304	ERS-2	2000-09-18	130
29306	ERS-2	2000-11-27	171
31811	ERS-2	2001-05-21	81

Table 1: The data used. However, the scene 31811 had to be excluded becaused it formed no coherent interferogram, maybe due to a problem with gyroscopes at this period (although Doppler centroid looks OK).

Methodology

The first step of the processing is the interferogram creation. Then, topography is subtracted using SRTM DEM and filtered using an adaptive filtering algorithm implemented in the GAMMA software and coherence is computed.
The phase of the interferograms is then reduced so that a reference point (in our case, the most coherent point) has zero phase in all the interferograms. Actually, due to an unsufficient knowledge of the area this is not a stable point – in future, we plan to use a stable point for this purpose.

Interferogram consistency check

According to (Usai 2003), the phase of three interferograms , , , created from three scenes *A*, *B*, *C* must satisfy the following condition:

$$+ \quad + \quad = \quad ,$$

the signs may be altered with respect to the sequence of master and slave.

As verified in the case of a randomly selected three interferograms, this condition is approximately verified for most of the pixels.

We can now distinguish two cases of not-fulfilling this condition:

- the sum is (at least approximately) an integer number of cycles, in this case one or more of the phases must be shifted by an integer number of cycles,
- the sum has a different value, this case cannot be resolved without changing on of the values, and may be cause by two influences:
    i. the coregistration of the three interferograms was performed independently, i.e. there may be small coregistration errors,
    ii. the phase was filtered, and the phase value may change significantly in decorrelated areas; in this case, the phase quality is so low that it cannot enter the final deformation adjustment.

The process of consistency check has three steps:

1. Construction of interferogram triples. All interferogram triples are selected and then tested, if they cover only three scenes and are therefore to be summed to 0. In fact, also longer graph cycles may be selected, but this task is too time requiring due to the number of arcs (interferogram) -- between 30 and 50. In the future, tetragons may be implemented too, if the number of triangles is found not to be sufficient.

   A matrix *C* is constructed in this step: the number of columns corresponds to the number of interferograms, and the number of lines corresponds to the number of cycles. Each lines contains three non-zero elements: 1 means that the phase of the interferograms must be added, -1 means that the phase must be subtracted in order to give 0.

2. Check for the coregistration/filtering errors. In this step, the phases are not sum up, but complex numbers with a unique amplitude are constructed and multiplied (in the case of a negative sign, the complex number is conjugated before multiplication). The interferograms in triples, in which the product phase is near zero, are considered to be all OK. The tolerance is set considering the phase standard deviation to be a tenth of the cycle, although the interferogram phases are not independent.

   Some interferogram triples are considered bad. If two of the three interferograms are OK, the "corrected" phase of the third is computed from the other two. This corrected phase is then used to assess the quality of the other interferograms; however, it does not enter the final deformation adjustment.

3. Ambiguity resolution. We only process the interferograms evaluated to be OK in the last step. The phase sums *r* for all interferogram triples are computed, divided by the phase cycle and rounded in order to give integers. Now, the equation may be constructed:

   $$ = \, , $$

   where *x* is the vector of ambiguities for each interferogram. However, the *C* matrix is singular and an integer solution is required.

   The Singular Value Decomposition (SVD) technique allows to resolve a similar problem with *C* singular, but it does not give the integer solution. The additional condition of the SVD technique is that the solution fulfills the minimum norm condition for the *x* vector, which is in accord with the interferometry requirements.

   The problem of ambiguity resolution is not uniformly solved in the interferometric literature. We decided to compute the SVD solution iteratively: each time the interferogram phase with the (absolutely) largest value of *x* is shifted by one cycle in the appropriate direction and the absolute sum of the *r* vector is lowered. In all cases, a solution is found. This solution may not fulfill the minimum norm condition, which is not a problem in interferometry -- however, the problem may have more minimum-norm integer solutions which may be equivalent with regard to mathematics, but not with regard to the reality.

The interferogram triples are computed just once for each location (and the corresponding interferograms). However, the steps 2 and 3 are performed independently for each pixel. Although computationally requiring, the computation takes a reasonable time in MATLAB for small interferograms (approx. 200 by 200 pixels).

A disadvantage of performing the computations independently for each pixel is that the computed ambiguities may not be smooth spatially.

Adjustment model

The interferometric phase (after topography subtraction) contains the following components:

- DEM errors (this component is directly propotional to the perpendicular baseline),

- deformation signal (possibly split into linear and nonlinear components),
- atmospheric delay (i.e. the difference between the delay in the master and slave scenes),
- noise.

In the literature dealing with interferometric stacks, there are basically two models for deformation adjustments:

- *deformation model*, where the deformations in the times of acquisitions are searched for,
- *velocity model*, where the deformations are considered linear in time and their velocity is searched for, together with other parameters.

Both approaches have their advantages and disadvantages, which will be discussed below.

For both approaches, let us introduce the following vectors and matrices:

- matrix A denoting which interferogram was created from which scenes: it has n columns (one for each scene) and m rows (one for each interferogram) and contains -1 if the corresponding scene was master for the interferogram, and 1 if it was slave.
- vector of acquisition times t, containing n rows, one for each scene. Due to the fact that the ERS-1/2 satellites are sunsynchronous and moving on the same orbit, the time of day of all the acquisition times is the same. Therefore, the values in t are integer multiples of days.
- vector of temporal baselines dt, containing m rows, one for each interferogram. Here, $dt = A \cdot t$.
- vector of perpendicular baselines B, containing m rows, one for each interferogram. The perpendicular baselines is used for assessing the DEM error and do not need to be precise. Although the perpendicular baseline significantly changes within an interferogram, the values computed for the scene center (i.e. the values are the same for all locations) are used. The ratio between the used and true baseline should be almost the same for all interferograms in a stack. The GAMMA software does not provide the perpendicular baseline length, so the baselines were computed in the DORIS software.
- vector of the measured phases f, containing m rows, one for each interferogram.

Let us note here that both models assume that the adjustment is performed independently for each pixel of the interferogram stack.

Deformation model

This deformation model is described and applied in (Usai 2003).

Before the processing itself, matrix A needs to be regularized, which may be performed by eliminating the column corresponding to the master scene, in which acquisition time the deformations are considered to be zero.

Then,

$$= + ,$$

where F is the vector of adjusted deformation in the time of acquisition of each interferogram and df is the phase noise to be minimized in the least-squares adjustment. Let us note here that this deformation model does not need any assumptions of the deformation linearity in time. However, it does not assess DEM errors. Atmospheric influence is said to be partially eliminated in the adjustment.

Due to a large number of unknows, there may be a problem of the regularity of the matrix . During the interferogram consistency check steps, some interferograms may be excluded from the adjustment, causing that some columns of the *A* matrix may be empty or there are more independent sets of scenes, which are not interconnected by any interferogram. In both of these cases, the matrix is singular and there are two ways of solving it:

- excluding the empty columns from the matrix *A*, eventually separating the independent sets of interferograms into more matrices and adjusting independently; however, some elements of the vector *F* are missing in the case of exclusion and the independent sets of vector *F*, computed by separate adjustment, may not be interconnected in any way without apriori information (e.g. from neighbouring pixels or by temporal interpolation).
- using the already noted SVD technique. However, this method has some disadvantages: it provides no weighted solution, so no weights cannot be introduced into the adjustment. The other disadvantage is that the results may not correspond to the physical reality, as noted in (Berardino 2002), where the SVD technique with the velocity model is recommended.

Velocity model

The velocity model, described and applied in (Berardino 2002), assumes that the deformations are linear in time, respectively the deformations may be represented by an explicit function of which the parameters are searched for.

The linear velocity model can be expressed in the following way:

$$= \quad + \quad + \quad ,$$

where v is the deformation velocity, r is the slant range and k_1 and k_2 are constants. dz is the DEM error, which influence does not depend on the temporal baseline dt, but on the perpendicular baseline B, and df is again the phase noise to be minimized by the least-squares adjustment.

A great advantage of this model is that the number of unknowns is small and therefore there are no problems with singularity. However, the problem is that the parametric expression of the deformations may not be known in advance and that the assumption of linearity may not be always satisfied.

Results

Three locations were mapped during the first phase of the project, and just about a fourth of the data were used. The results are following:
Figure 1: Deformation between January 1996 and November 2000 at the Komořany site computed using the deformation model.

Figure 2: Deformation velocities at the Komořany site. The points, where the velocity standard deviation exceeds 5 mm/yr, are displayed in black.

Figure 3: Deformation between January 1996 and November 2000 at the Most site computed using the deformation model.

Figure 4: Deformation velocities at the Most site. The points, where the velocity standard deviation exceeds 5 mm/yr, are displayed in black.

Figure 5: Deformation between January 1996 and November 2000 at the Louny site computed using the

deformation model.

Figure 6: Deformation velocities at the Louny site. The points, where the velocity standard deviation exceeds 5 mm/yr, are displayed in black.

Conclusions

There is a difference between the results of the deformation and the velocity models. In the case of Komořany site, which is very close to open mines, the November 2000 deformation array looks quite stable, while in the velocity array, there can be seen four unstable areas. On the other hand, the standard deviations are lower in the deformation model, although we received many warnings during the computation (inverting almost-singular matrix).

However, there is an area near the center of the Komořany site which looks deformed in both deformation maps. We suspect this area to be deformed.

In addition, some deformation areas can be seen on the velocity map of the Louny site.

The deformation maps look very colourful – such as that the velocity is different for each pixel. That is probably caused by an inexact solution due to the unsufficient number of processed interferograms and large standard deviation. In future, we plan to perform hypothesis testing on the results and exclude a part of them.

However, the deformation in the area is very slow and does not exceed a fringe in any of the processed interferogram. We plan to focus only on the velocity model in future.

References

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