DEFORMATION MONITORING WITH SEMI-AUTOMATIC PROCESSING OF INSAR ARTIFICIAL REFLECTOR DATA

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Abstract

InSAR is a method allowing to monitor Earth-surface deformations using satellite data. In our project, we use this method to monitor deformations in the area of Northern-Bohemian coal basin (between the Most and Chomutov cities). Due to a significant decorrelation of the area, there were 11 corner reflectors installed in the area, in order to provide a coherent reflection back to the satellite.

However, due to the fact that the reflectors are about 3-5 kilometers far away from each other, the problem of phase unwrapping (ambiguity resolution) is not trivial. In our project, we have 15 TerraSAR-X scenes available up to now, with the interval of about 33 days. We process only the reflector information, with interpolated coordinates and phase. The processing is performed partially manually, partially automatically.

Software packages developed for InSAR are not suitable for our problems due to various reasons; we use them only for certain auxiliary tasks.

Keywords: synthetic aperture radar, interferometry, persistent scatterers, artificial reflectors

INTRODUCTION

Synthetic aperture radar (SAR) interferometry (InSAR) is becoming a well-known technology for deformation mapping. Instead of in-situ measurements, often performed for each point independently, it uses satellite radar data to process a whole area of interest at the same time. However, the method gives reasonable results only in city areas where there are many artificial objects. In the countryside, we often encounter the decorrelation effect: the microproperties of the surface change between the two acquisitions (in the order of the radar wavelength, i.e. a few cm).

Conventional InSAR allows to process two radar images, with the result of deformations estimated to occur between the two dates of acquisition. This is often considered as insufficient, and therefore the persistent scatterers (PS, or PSInSAR) method was developed, processing a series of scenes, resulting in the deformation series or estimated deformation velocity (more often). In order to deal with the limited amount of computational memory, disc space and also computational time, not all pixels of the scenes are processed, only those that are considered more precise or coherent (in the first iteration, pixels with high intensity and low intensity variability are selected).

A key problem of the InSAR method is phase unwrapping. The principle is that the deformations are estimated as a difference in phase between the two scenes (corrected for other influences, such as flat-Earth and topography, both computed for the known orbit parameters and a given digital elevation model (DEM)). However, phase is (by definition) wrapped in the $(-\pi,\pi)$ interval, though the deformation is a real number. Therefore, the phase must be unwrapped in order to stand for the deformation, and the multiple of 2π to be added to the phase is ambiguous.

Phase unwrapping is the method for estimating the phase ambiguity. The problem is relative, reference both in space and time must be specified. Then, it is usually assumed, that the unwrapped phase difference between two neighbouring points and two consecutive scenes is always in the $(-\pi,\pi)$ interval. This statement makes a limitation to the maximum detectable deformation and depends both on the scene resolution (resp. density of the processed points) and the interval between the particular acquisitions.

In addition, due to noise, the condition of phase difference between two neighbouring points cannot be always fulfilled. Different methods (and implementations) of the phase unwrapping problem differ in the way of dealing with this problem. Usually an independent information (such as coherence) is used to make cuts, prohibiting the phase unwrapping path to cross them.

In our project, we are monitoring deformations in the Northern-Bohemian coal basin, between the cities of Most and Chomutov. There is a huge open-pit mine in the area, with some villages and industrial zones around it. Most of the processed area of interest is decorrelated due to vegetation (the open-pit mine and the Ore mountains). Therefore, there were 11 artificial reflectors installed in the area, providing a strong reflection back to the radar, and therefore expected to be coherent.

By misunderstanding, the reflectors were not designed as trihedrals, but as dihedrals, and therefore the requirements for orientation accuracy are stronger. Also, the intensity of the reflected signal varies by two orders, and also the accuracy of the estimated deformations varies a lot.

METHODOLOGY

For processing, we use data acquired by the TerraSAR-X satellite (operated by DLR), in the StripMap mode with resolution of approx. 3x3 m. The scenes are acquired usually once per 33 days, with some exceptions, on the descending track, early in the morning. The acquisitions have been performed since June 2011, so up to now, there are 15 scenes available. The incidence angle is the lowest possible - about 30 degrees.

In the image, the reflector looks as a group (with a shape of a cross or rectangle, depends on the strength of the reflected signal) of very bright pixels and can be usually found by the naked eye. This is not the case of reflector no. 9, which is situated in an area affected by layover. Here, the reflector cannot be found by the naked eye, but its position can be estimated using the *ptarg* script, enclosed in the GAMMA software (GAMMA, 2012).

The *ptarg* script enables to estimate the position of the reflector with a subpixel precision. Better position precision allows better evaluation both of the phase (which is interpolated) and other phase influences (flat-Earth phase and topographic phase), which are then subtracted. The interpolated intensity reaches from approx. $1 \cdot 10^6$ (reflector 8) through $6 \cdot 10^7$ (reflectors 1, 6) to $1 \cdot 10^8$ (reflector 9, situated in the layover area). The interpolated positions of each reflector also vary among the images: standard deviations reach from 0.08 to 0.15 px in the range direction, and are a bit smaller in the azimuth direction. It can be said that the lower the intensity, the higher position standard deviation. The variability can be caused either by inaccurate orientation of the reflector, or by the surroundings of the reflector.

The layout of the particular reflectors in the area of interest is shown in figure 1.

Reflector 1 is situated in the industrial area Komořany, among buildings. Reflector 2 is situated right inside the open-pit mine, near a small house desgined for various measurements. Reflector 3 is situated in a built-up area near the industrial zone Záluží, reflectors 4 and 5 are situated in villages Horní Jiřetín and Černice. Reflector 6 is situated at the edge of the open-pit mine. Reflector 7 is in the Jezeří castle, more than 100 m above reflector 6. Reflector 8 is - similarly to reflector 6 - at the edge of the open-pit mine. Reflector 9 is in the forest near the Jezeří dam, reflector 10 is in the village of Vysoká Pec and reflector 11 is in the industrial zone near the Vrskmaň village.

The DEM used

InSAR method can be used either for DEM generation (if there are no Earth-surface deformations in the area of interest), or for deformation monitoring. In the latter case, a DEM is neccessary for estimation and subtraction of the topography phase component. Its value depends significantly on the orbit setout (perpendicular baseline) between the two scenes.

First, we tried to use ASTER GDEM V1 (ASTER, 2012), but the resulting interferograms were very noisy due to the noisy DEM. Therefore, we use the SRTM (Shuttle Radar Topography Mission) DEM acquired in X-band (processed by DLR) (Farr, 2012). However, this DEM does not cover the whole area at our latitude.

Fortunately, there are no reflectors in such a 'hole', but the 'hole' is in the bottom-left corner of the area of interest (figure 1), covering the (coherent) city of Most. In future, we plan to use ASTER GDEM V2, known to be more precise.

In addition, the SRTM DEM was acquired in 2000 using interferometric technique. Since that time, there have been many changes in the area of the open-pit mines, resulting in false 'DEM-error phase changes'. In order to avoid these errors (in order to be able to estimate atmospheric contribution), the SRTM-X DEM was combined with a DEM acquired using aerial photogrammetry (available only for the area of open-pit mines) received from the Czech Coal company. Unfortunately, the photogrammetry DEM is not available for the 'hole' in the SRTM-X DEM.

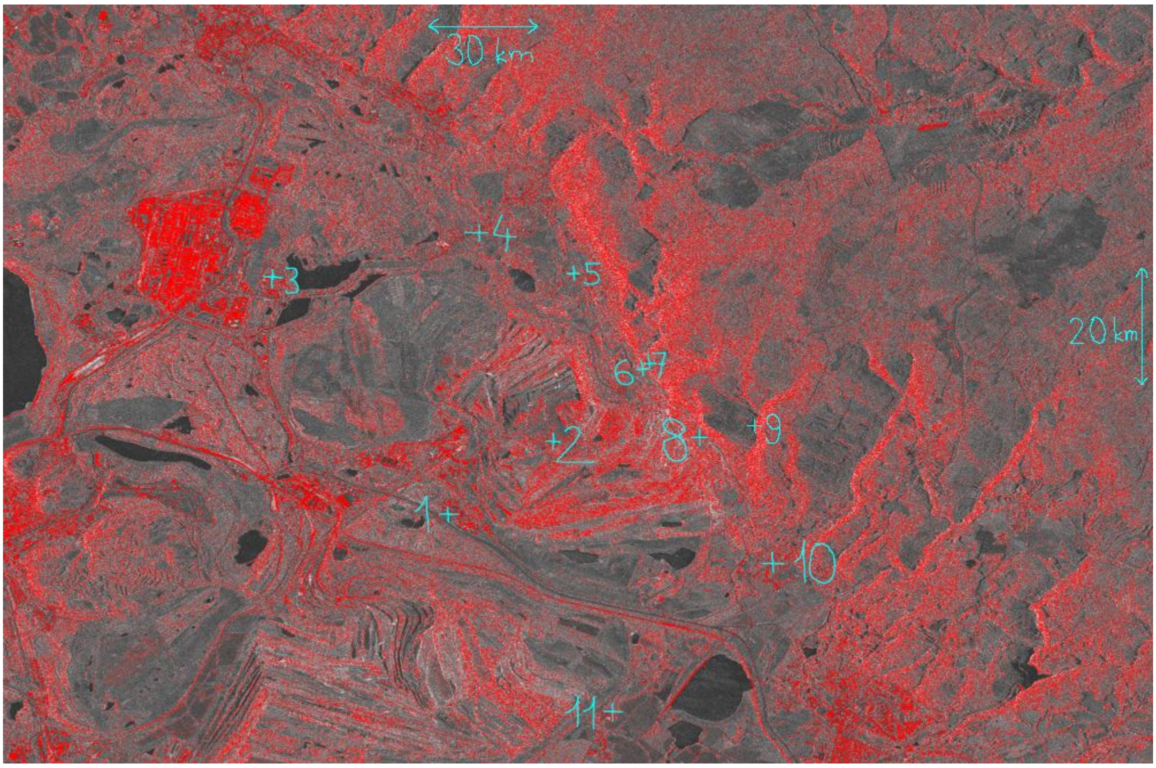

Fig. 1. The area of interest with the positions of the individual reflectors (1-11). The image is flipped by the vertical axis and a bit rotated. Red points signify higher intensity, and therefore lower probability of decorrelation. (c) DLR.

Results from PSInSAR processing

There are several software packages for PSInSAR processing. We use two of them: the GAMMA software, which does not give reasonable results for 15 scenes (too noisy), and StaMPS (Hooper, 2012). StaMPS gives reasonable results in our case since the time we have had more than 8 scenes available; however, it has some disadvantages: the corner with no DEM data is processed as the altitude was 0; and although the reflectors were selected in the first step to have enough quality, they were excluded during consecutive processing, so we do not have the results for the reflectors.

Figure 2 shows the deformation estimated by the StaMPS package in the area of interest: as expected, the most area with highest subsidence is the Ervěnice corridor, with approximate deformation of about 1-2 cm/year.

Semi-automatic processing

In order to get the deformations for the particular reflectors, we were forced to perform manual processing; however, due to its time demands, some parts of it were automatized.

First, the coordinates of the reflectors are estimated in the GAMMA *ptarg* script, together with the interpolated phase and intesity. It is expected that the interpolated values are more accurate than the values for the whole pixel (Ketelaar, 2008). Then, these values are imported into MATLAB, where the phase corrections (flat-Earth phase, topographic phase) are computed (baseline legth is also interpolated from values computed by GAMMA *base_perp* script) and subtracted for all possible scene pairs (with 15 scenes, there are 105 interferograms).

A reference scene (for temporal referencing) is selected as a scene approximately in the middle of the time series, a scene with no visible atmospheric effect and a scene without significant problems (will be dealt below). In our case, it is the April 2012 scene (the tenth in the series).

For each reflector pair, automatic adjustment is performed, together with ambiguity corrections. First, all phase differences (for all reflector pairs) are wrapped into the ($-\pi,\pi$) interval. A set of 4 scenes is then picked up, around the reference scene, and the adjustment is performed, interferograms with high residues are corrected for 2 π multiples. In the next iteration, one more scene is added to the current set, the adjustment is performed again, with high residues only belonging to the interferograms with the new scene. This way, all scenes are added to the set step by step, and the adjustment is performed for all of them.

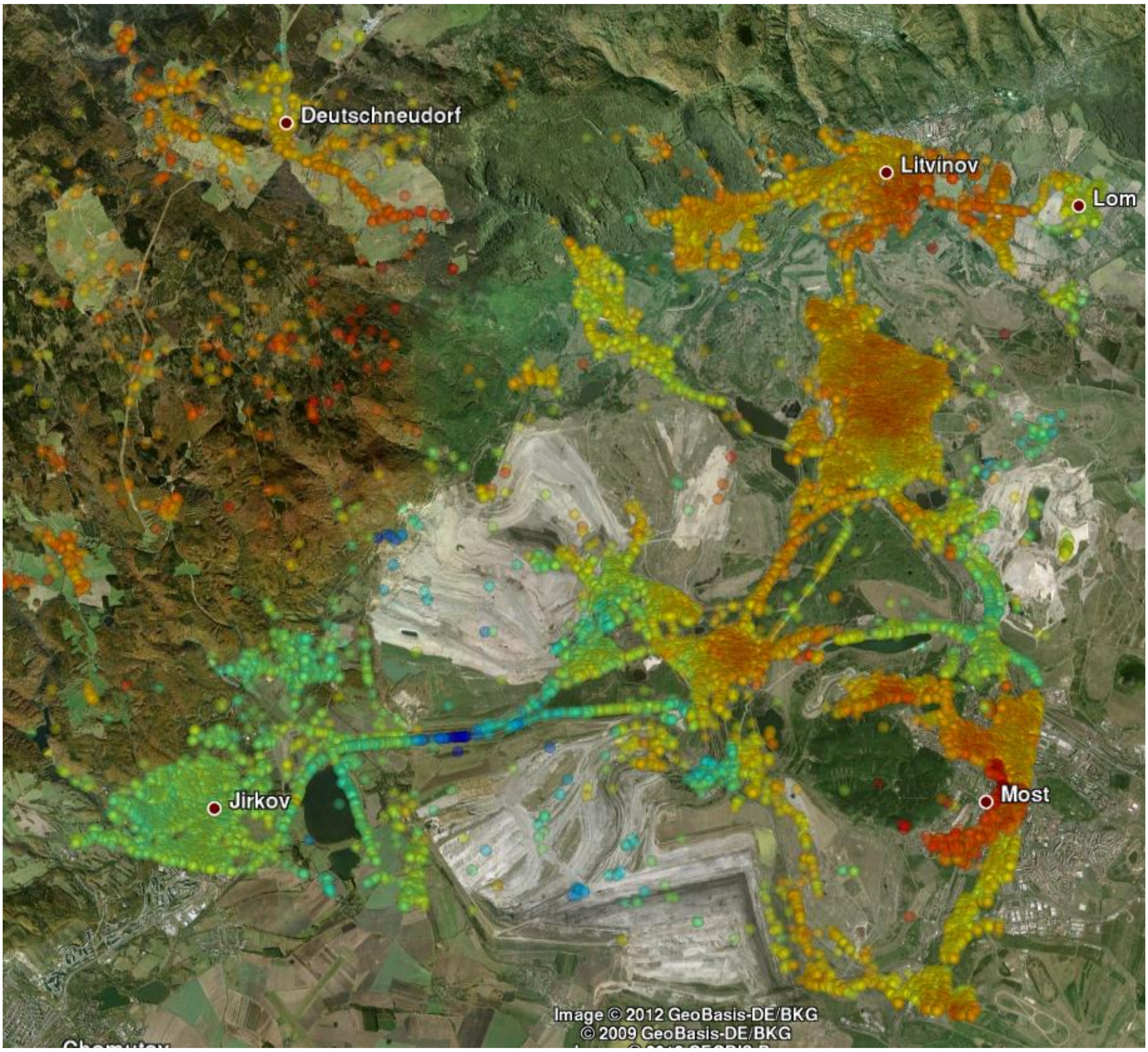

Fig. 2. Estimated deformation velocities for the area of interest using the StaMPS software. Dark blue corresponds to subsidence of 13 mm/year, dark red corresponds to uplift of 8 mm/year. The bottom-right corner (image is geocoded) corresponds to no DEM data, i.e. irrelevant results. (c) DLR and Google Earth.

Then, spatial consistency is enforced. From all reflector pairs, triangles are constructed, and within each triangle, the estimated deformations are summed up: the expected sum is zero for all acqusition times. The real sums are either zero, or a multiple of 2 π. The process of estimation which reflector pairs are to be corrected for which scenes, is still performed manually; we plan to do it automatically, but it has not been implemented yet.

If a triangle has a non-zero sum, it is never clear which reflector pair is to be corrected. Or, the sum in a triangle can be zero and there may be two scenes to be corrected. To simplify the considerations, which reflector pairs should be corrected, all the triangles are 'decomposed' into the reflector pairs again and if a triangle sum is non-zero, such a sum is attributed to all reflector pairs in the triangle. Then, for each reflector pair, the number of non-zero triangles are summed up, and the reflector pair with the highest number of non-zero triangles is corrected. The process is iterative.

However, the process is not as simple as it looks. The process is performed independently for each acquisition time; and due to the fact that the set is referenced in time, it may happen that the reference scene is 'right' to be corrected, not the other ones. Also, for some scenes it is sufficient to correct a small number of scenes (easily identifiable), while for other scenes it is not easy to identify the scenes to be corrected (some must be just chosen) and the number of corrected reflector pairs may finally reach 15-20. In our project, this is the case of scenes acquired in July 2011, December 2011 and August 2011 (in a smaller scale). In a case of correction, the correction concerns all interferograms containing the one scene to be corrected and one reflector pair.

Expected deformations in the area of interest are lower than 1 cm per year (actually, levelling results show that one of the reflectors moved 2 cm up in three years, the other reflectors are moving more slowly).

The last step is to review the deformation time series for all reflector pairs, and in some cases, the phases are corrected for a multiple of 2 π; in this case, the corrections are performed for all interferograms containing the scene and all reflector pairs containing the reflector. This step is also performed manually, we also plan to automatize it, together with an evaluation of the hops in individual time series.

Phase ambiguity 2 π corresponds to 15 mm for the TerraSAR-X data. That means that 2 π corrections are by 15 mm deformations, which is relatively high value, considering the time between acquisitions, which is usually 33 days. Therefore no large hops in the time series are expected.

RESULTS AND DISCUSSION

Unfortunately, it is impossible to get rid of all hops higher than π, because of the spatial consistency condition. In addition, in some cases there are also hops up and down lower than π, which are also considered unreal. We have therefore decided to give away the estimated deformations for the most noisy acquisition times: July 2011 (heavy rain) and December 2011 (thin layer of snow, maybe also snowing; reflectors were cleaned except for refl. 7).

In some cases, the results are disputable. For example the end of the time series (June-September 2012) for reflector 8: it goes straight up with regard to reflectors 5,6,7 (which are situated close to it), but there are large hops with regard to reflectors 10 and 11, which are also situated close to it. If the hops were corrected, the situation would turn around and the hops would be in relation to other reflectors. In addition, it seems that reflector 8 is uplifting also at the beginning of the time series.

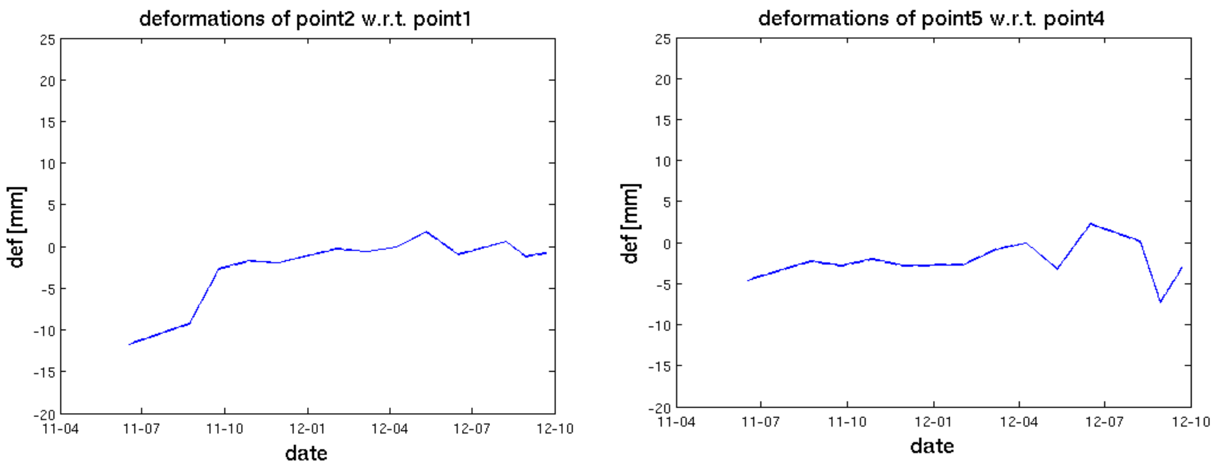

Fig. 3. Estimated deformations for reflector pairs 2-1 and 5-4. The dashed lines (if visible) stand for twice the estimated standard deviation.

A similar case is with the scene acquired in August 2011 for reflector 9.

However, it seems that reflector 2 (w.r.t. the others) uplifts at the beginning of the time series (June-September 2011) and then it stays approximately constant. It is also possible that it subsides at the same time period (the subsidence would be a little smaller, with a small uplift in September). It is also possible that the August 2011 scene should have been also excluded from the adjustment due to problems with spatial consistency (as the scenes acquired in June and December 2011 were).

It also seems that reflector 7 subsides at the beginning of the time series (June 2011 - March 2012) by a centimeter (approximately), but at the end of the time series, it goes back up to the original level. Reflectors 3 and 4 (close to each other) seem to oscillate up and down at the end of the time series (w.r.t. refl. 1).

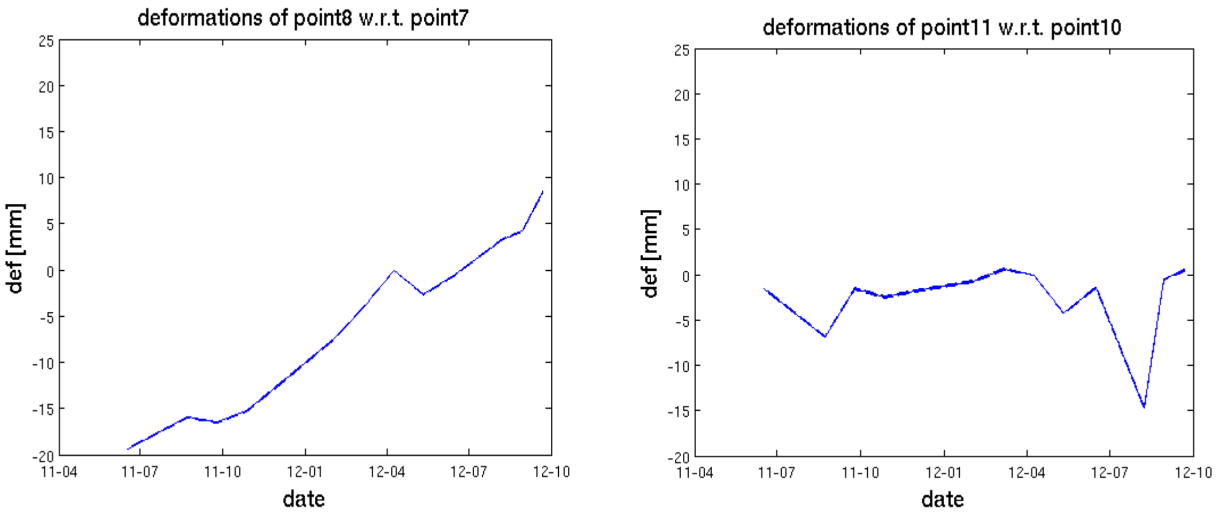

Fig. 4. Estimated deformations for reflector pairs 8-7 and 11-10. The dashed lines (if visible) stand for twice the estimated standard deviation.

The causes of subsidence/uplift are not known. Most of the reflectors are situated in areas expected to be stable: this is the case of reflectors 1, 3, 4, 5, 7, 9, 10, 11. However, levelling results (unfortunately, from a different time period than our measurements) show a slight uplift of reflectors 1, 11 (and a more significant uplift of reflector 2). Some deformations (especially reflectors 2, 6, 8) may be attributed to a changing soil humidity.

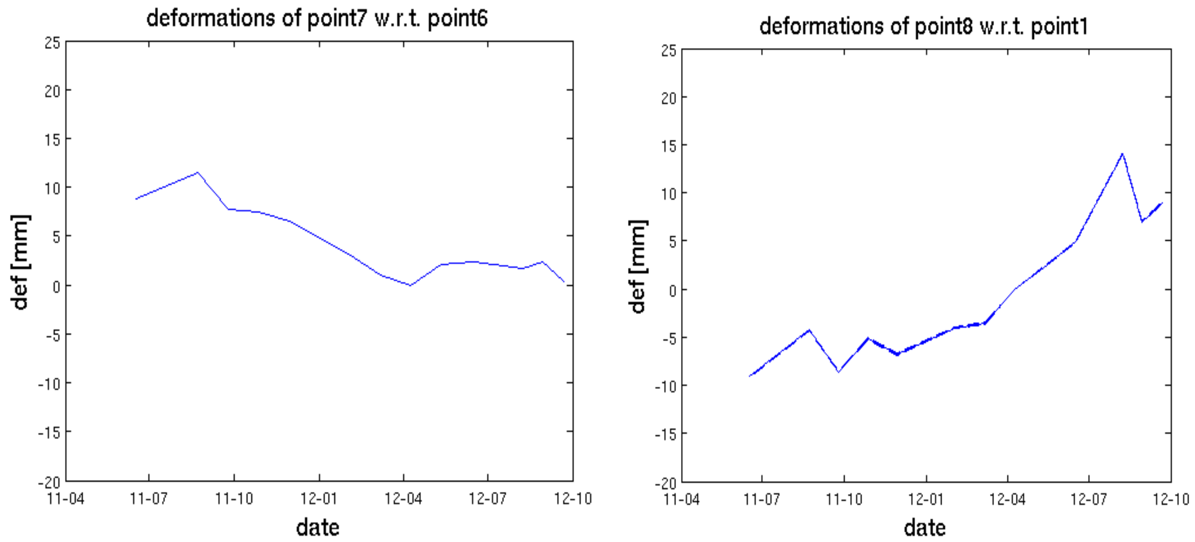

Fig. 5. Estimated deformations for reflector pairs 7-6 and 8-1. The dashed lines (if visible) stand for twice the estimated standard deviation.

The estimated deformations are still in satellite line-of-sight (LOS). The vertical deformations are expected to be lower by approx. 15% (incidence angle is 30 degrees).

CONCLUSIONS AND FUTURE WORK

The key problem of the InSAR technique is the ambiguity resolution. This is the case even in our project, with as many as 15 scenes, and with the expected deformations lower than 1 cm per year; with the radar wavelength of 3 cm, corresponding to the ambiguity cycle of 15 mm and temporal resolution of approx. 1 month. Still, there are some scenes which need to be excluded from adjustment due to high errors - they can make the ambiguity resolution process even more difficult.

We can never say that a point is stable w.r.t. another one. In all cases, there are some deformations detected, and they are much higher than their estimated standard deviations. However, the problem is the interpretation of the hops: if they are real (caused e.g. by soil humidity variations or other effects, which can be also detected by levelling), or not (caused e.g. by atmospheric delay variations, differences in orbit situations, or even by the fact that the center of the reflector was found at different coordinates and therefore interpolated for a different position).

Concerning the atmospheric delay variations, we found a significant (atmospheric) trend for two dates of acquisition: June 2011 and May 2012. During the spatial consistency enforcement, there were smaller problems with these two scenes, and therefore these scenes were not excluded. Much more significant problems were with scenes acquired in July 2011 (excluded), August 2011 (finally not excluded) and December 2011. Another problematic scene was the one acquired in August 2012 (here, we still wait for the scenes to be acquired in future, in order to decide whether to exclude it or not). During the December 2011 acqusition, there was a slight layer of snow (the reflectors were cleaned except for refl. 7, but they were cleaned few hours before the acquisition, not right before due to technical reasons). During the July 2011 acquisition, there was a heavy rain, possible to bring noise into the phase delay (with such a short radar wavelength).

For comparison, there are levelling results available. The reflectors were installed in 2008 and levelled approximately once a year. The accuracy is not known. But from levelling, it is known that reflector 2 uplifts approx. 2 cm per 3 years (the last levelling date is September 2011), reflector 11 uplifts by 5 mm per 3 years and the other reflectors uplift or subside in a smaller scale. These are much smaller amounts of deformation than estimated from InSAR, but their temporal resolution is also much smaller; so the results may be OK.

In future, we plan to automatize the process of ambiguity resolution, especially the step of the spatial consistency enforcement. However, it is not yet clear how the disputable cases will be solved: the automatic procedure will probably apply only for the simple cases.

Also, we plan to get into the StaMPS sottware in a way to be able to process the reflector information.

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