# ATMOSPHERIC PHASE SHIFT IDENTIFICATION FOR INDIVIDUAL DATES BASED ON MULTI-REFERENCE DINSAR OR PSI DATA

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## ABSTRACT

Measurement of the Earth's surface motions with both Differential Interferometric Synthetic Aperture Radar (DInSAR) and Persistent Scatterer Interferometry (PSI) is often handicapped by atmospheric errors. These errors are due to path delays of the electromagnetic wave, e.g. caused by local changes in the water vapour amount of the atmosphere. As a result, spatial correlating phase shifts in differential interferograms occur, which can be mixed up with ground motions easily.

In this paper an easy way is shown to identify atmospheric phase shifts based on a multi-reference stack of interferograms. The derived results show the atmospheric phase shift for every single acquisition, not the superposition of the effects of two acquisition dates. The interferometric input data can be both raster-based and point-based. One big advantage is that the input data doesn't need to be unwrapped beforehand, which is often problematic for areas of low coherence.

A qualitative comparison and plausibility checking was done using optical ENVISAT MERIS data, acquired simultaneously with ENVISAT ASAR data. The results cannot be applied as correction values to the input differential interferograms yet, for they contain also portions of long lasting ground motions. But nevertheless the results assist very well in choosing the best reference scene for an interferometric analysis and in deciding whether an observed deformation signal is due to atmosphere or not.

## 1. ATMOSPHERIC EFFECTS IN SAR DATA

### 1.1. Introduction

Atmospheric effects in SAR data result from path delays of the electromagnetic waves on their way through the Earth's atmosphere and back to the SAR sensor. These path delays amount to a total of several meters and are nearly the same for all acquisitions. Critical for SAR interferometry are especially local inhomogeneities of the path delays due to variability of the refractive index of the troposphere. These contributions can show up as linear trends in the phase values of differential interferograms, but often they are also highly variable in the spatial domain by ranges of hundreds of metres to tens of kilometres. Especially they are caused by changes in the water vapour amount, e.g. in the case of clouds or rainfall, or due to air pressure changes.

### 1.2. Impacts on interferometric deformation measurements

As a result of variations in troposphere, spatial correlating phase shifts occur in differential interferograms which can be mixed up with ground motions easily. Two examples are shown in Fig. 1.

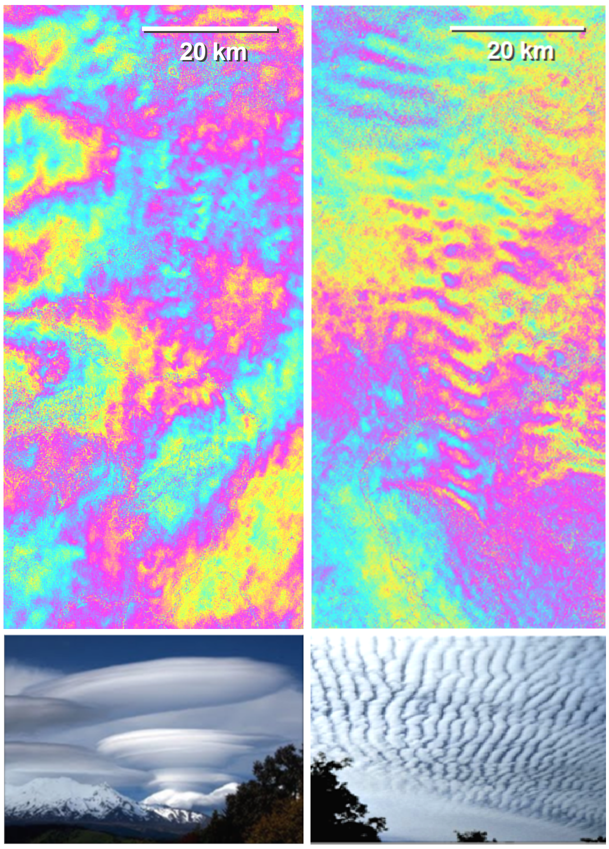



*Figure 1. Examples of atmospheric influences in ENVISAT ASAR differential interferograms (Argentina). Photographs below show* probable *weather conditions (left: lenticularis clouds, right: altocumulus clouds)*

In Central Europe this problem predominantly occurs during summer acquisitions between June and August. Thereby atmospheric phase shifts of slightly more than $2\pi$ (accordingly ca. 3 cm of vertical ground deformation using data in C band) could be observed. In an area of southern Argentina with arid weather conditions we observed phase shifts of up to $6\pi$ (both in ERS and ENVISAT C band SAR data); see left part of Fig. 1.

To compute an interferogram the SAR data of at least two acquisition dates is needed (using two-pass interferometry). Hence an interferogram always shows the superposition of the atmospheric effects of both dates simultaneously. This fact often complicates the determination of the acquisition date affected by atmosphere, although it becomes easier when there are strong atmospheric effects. By examining all interferogram combinations it is possible to manually identify the stronger atmospheres in the majority of cases.

Problems arise if the deformation signal searched for is very small, for example deformation rates of below 3 cm per year only produce deformation phase shifts of few millimetres in typical interferometric time intervals (e.g. 35 – 105 days). In this case deformation signals are much smaller than typical atmospheric signals, and even very light atmospheres can conceal the information searched for.

Apart from possible confusions of atmospheric phase shifts with height changes in raster-based differential interferograms, atmosphere is also a serious problem in point-based Persistent Scatterer Interferometry (PSI). The reference scene for PSI should be free of any atmospheric phase shifts. Indeed, the occurrence of atmosphere in the reference scene is often overlooked or even ignored during processing. For the further acquisitions in the PSI time series, atmosphere remains in the residual phase values and decreases deformation measurement accuracy of single dates. For this reason atmospheric influences are commonly reduced by spatial filtering. But such filtering can also affect real ground motions with non-linear behaviour over time which also remain in the residual phases. Therefore such filtering should preferably be avoided.

Applying DInSAR stacking algorithms atmospheric phase shifts are a severe topic to consider. The first and the last scene of the stack should be mostly free of atmospheric effects. Atmosphere within the stack only has impact on single dates. By summing up the whole stack atmospheric signals within the stack are eliminated, because they occur always twice in the interferograms. For example in the stack A-B-C-D-E, the atmosphere to date D occurs both in interferogram C_D, and in interferogram D_E (with opposite sign). Only the atmospheres A and E will remain unchanged in the stacked sum and should therefore be carefully chosen to be as negligible as possible.

### 1.3. Typical recent approaches for the reduction of atmospheric effects

Calculation of absolute correction values by using additional information is an ambitious task. Commonly it is tried to model atmospheric effects mathematically or geostatistically. Since atmosphere can be very varying for different acquisition dates it is necessary to adopt model parameters individually for every interferogram. Modelling works best, if additional (secondary) information is available.

This secondary information can be measured data of differential GPS networks. This data is a reliable source for atmospheric path delay in the surrounding of D-GPS stations. However heterogeneity of atmosphere can be very high and isn't described very well by wide measurement grids like SAPOS® in Germany.

Other secondary information is often not available at the exact SAR acquisition time (e.g. from polar orbiting weather satellites like MetOp AVHRR). Other satellites like METEOSAT Second Generation (MSG, acquisition interval every 15 minutes) possess spatial resolutions much coarser than SAR data (more than 1 km versus 2 – 20 m of typical SAR data).

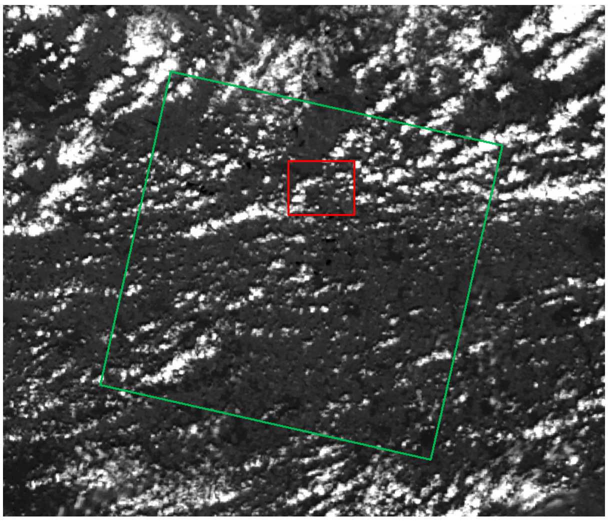


*Figure 2. ENVISAT MERIS full resolution swath band 9 image from July 16th, 2009 showing few scattered clouds. Green square depicts extend of ENVISAT ASAR image mode scene (ca. 100 x 100 km²). Red box marks extend shown in Figures 7 – 8*

Another approach for removing atmospheric effects by spatially averaging differential phases has been presented by us previously at Envisat Symposium 2007. Although this approach has proven quite well, it has disadvantages if the atmospheres are of very small scale or if there are large areas of slow deformation. Additionally, if the atmospheric influences in both SAR scenes of the interferogram are strong and heterogeneous, the resulting superposition becomes difficult, making it complicated or even impractical to average correctly. For these reasons a new approach has been developed, depicted in chapter 2.

In this paper ENVISAT MERIS full resolution swath data with a ground resolution of approx. 250 m is used (cf. Fig. 2 and 3). MERIS has the advantage that it is acquired simultaneously with ASAR data. We use this data only for qualitative comparison and plausibility checking.

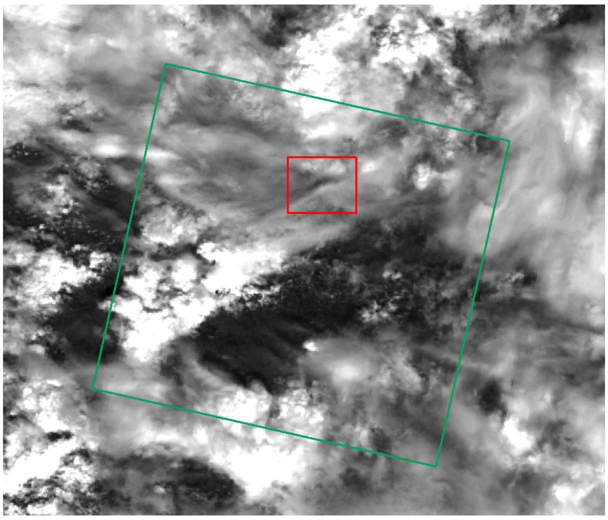


*Figure 3. ENVISAT MERIS full resolution swath band 9 image from June 11th, 2009, almost completely overcasted with clouds. Fig. 3 shows same extend as Fig. 2. Red box marks location shown in Fig. 6 – 10*

## 2. APPROACH

In this paper we show an easy way to determine atmospheric phase shifts based on a multi-reference stack of interferograms. The derived results show the atmospheric phase shift for every single acquisition, not the superposition of the effects as seen in an interferogram. The interferometric input data can both be raster-based (DInSAR) and point-based (PSI). One big advantage is that the input data doesn't need to be unwrapped beforehand, which is often problematic for areas of low interferometric coherence.

Initially all interferometric combinations (with the same direction in time, e.g. from past to future) need to be computed. These result in a total of n*(n-1)/2 interferograms for n acquisition dates. Our approach has shown to work very well with a total number of 20 to 60 scenes. With 80 – 120 scenes it would be better to split up the stack in two separate stacks. The usability with less than 20 scenes has to be investigated individually.

All interferometric combinations relating for example to acquisition C also contain the phase shift signal of atmosphere C, either with negative (–) or positive (+) sign (see also Fig. 4). By simply calculating the mean of these interferograms we get the atmospheric phase shift caused to the date C. All other atmospheric signals only appear once and are spatially random, thus their mean results in zero in the averaging result for date C. After averaging n times we get n results (either raster or point based) containing the atmospheric phase shifts to every single date A .. $X_n$.

It is important to note, that the mean function has to consider phase ambiguities (–π .. +π) correctly. Therefore calculation takes place in complex space (using a program written in IDL programming language). This has the additional advantage, that there's no need for phase unwrapping beforehand. Afterwards the phase shifts of the derived atmospheric results can be unwrapped to get absolute phase shifts if needed.

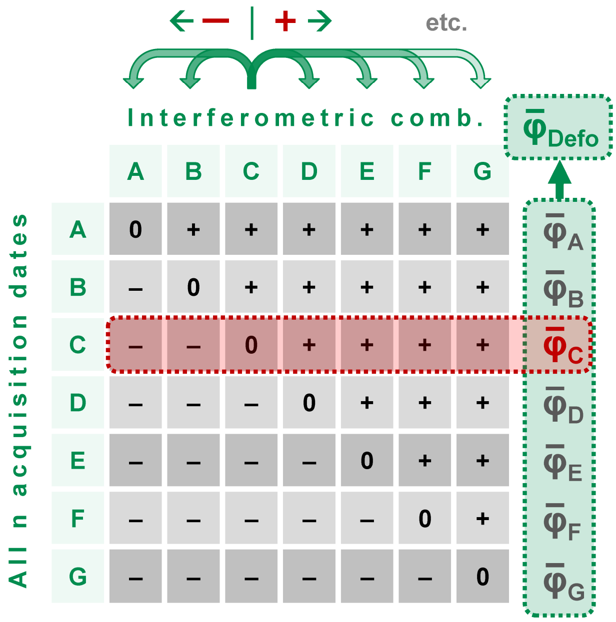



*Figure 4. Illustration of the analysis approach for n = 7 dates (cf. chapter 2 for detailed explanation)*

When using PSI differential interferometric data as input, is has shown helpful to estimate a height correction for every PS point by regression analysis initially. After this step the results get much "clearer" and less noisy. Additionally the regression analysis allows decreasing the number of points by eliminating "bad" points with high standard deviation.

Admittedly the resulting atmospheric signal for every scene also contains more or less portions of long-lasting ground motions, which can also be depicted, but not separated yet. For phase ambiguities in the input data due to higher deformation rates the deformation cannot be determined absolutely, nevertheless the boundaries of deformation areas (with very low deformation rates) can be seen very clearly. For this reason the results cannot be applied as correction values to the input interferometric data yet. But nevertheless the results assist in choosing a suitable reference scene or to distinguish a deformation signal from an atmospheric signal.

Subsequently it is possible to average all the derived atmospheric results. Because of all atmospheric signals should be spatially random their average is zero and only the deformation signals remain. Although giving no absolute values this deformation result has shown helpful to get hints about long-lasting deformation regions (see Fig. 15). Additionally this deformation result allows the inspection of larger areas to get information about very slow ground movements.

## 3. RESULTS

### 3.1. Areas of investigation

The main area of investigation is situated south the city of Leipzig in Germany. In this very rural area (except for Leipzig, a city with approx. 500.000 inhabitants) many abandoned open pit mines are located in spatially close neighbourhood along with two active lignite open pits. These cause only little ground motions of below 1 cm per year due to changes of the ground water level.

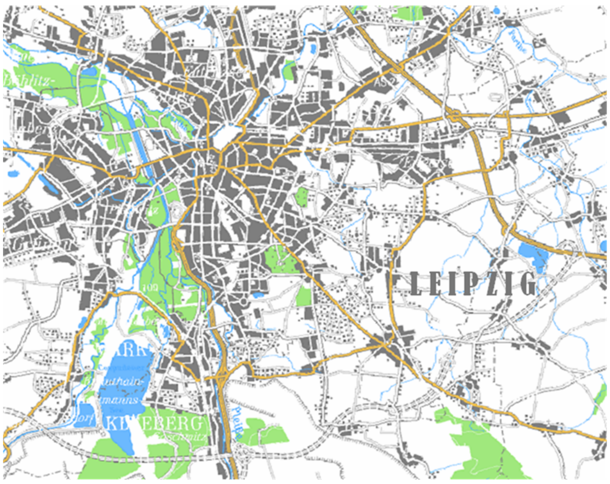



*Figure 5. Map of Leipzig showing the same extend as Fig. 6 – 10. Urban areas and villages show best applicability due to high interferometric coherence*

Additionally results of an underground potash mining area in the European part of Russia are shown. The potash mine is located below the city Berezniki with approx. 170.000 inhabitants. In this area a mining accident occurred resulting in very high deformation rates due to the unintentional flooding of the mine. In this paper a subarea of the city with deformation rates up to 7 cm per year is shown.

### 3.2. DInSAR results

Fig. 6, 7, and 9 show atmospheric phase shift results of raster based ENVISAT ASAR input data for the area of Leipzig. For the area of Berezniki only one DInSAR example based on TerraSAR-X is shown in Fig. 11. No deformation result has been depicted for DInSAR data for lack of space.

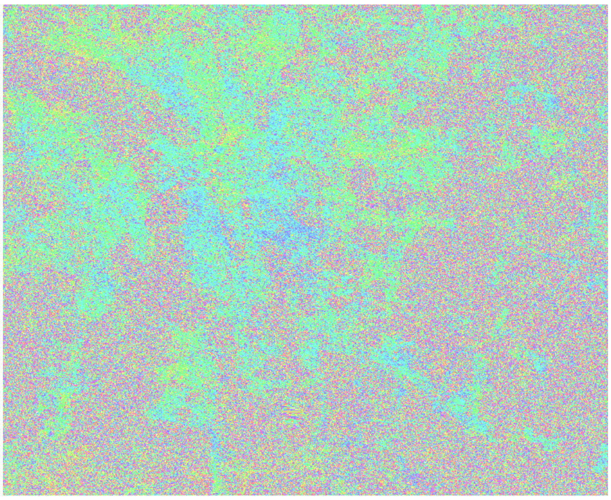


*Figure 6. Atmospheric result for August 20$^{th}$, 2009 (Leipzig area) showing remarkable few phase shifts for an acquisition during August due to completely cloudless weather condition*

### 3.3. PSI results

Atmospheric phase shifts derived from PSI interferometric data are shown in Fig. 8 and 10 (based on ENVISAT ASAR data in the area of Leipzig), and Fig. 12 – 13 (based on TerraSAR-X data in the area of Berezniki). The resulting phase values are still wrapped and can be unwrapped e.g. using a multi cost flow (MCF) approach. This is advantageous for displaying and analysing the data in a GIS.

Subsequently the unwrapped phase shifts have been spatially interpolated with an inverse distance weighting (IDW) algorithm. Note that due to locally sparse point density the IDW result is doubtful in a few places. These areas have been marked by hand in Fig. 8 (b) and (c) by grey dashed ellipses.

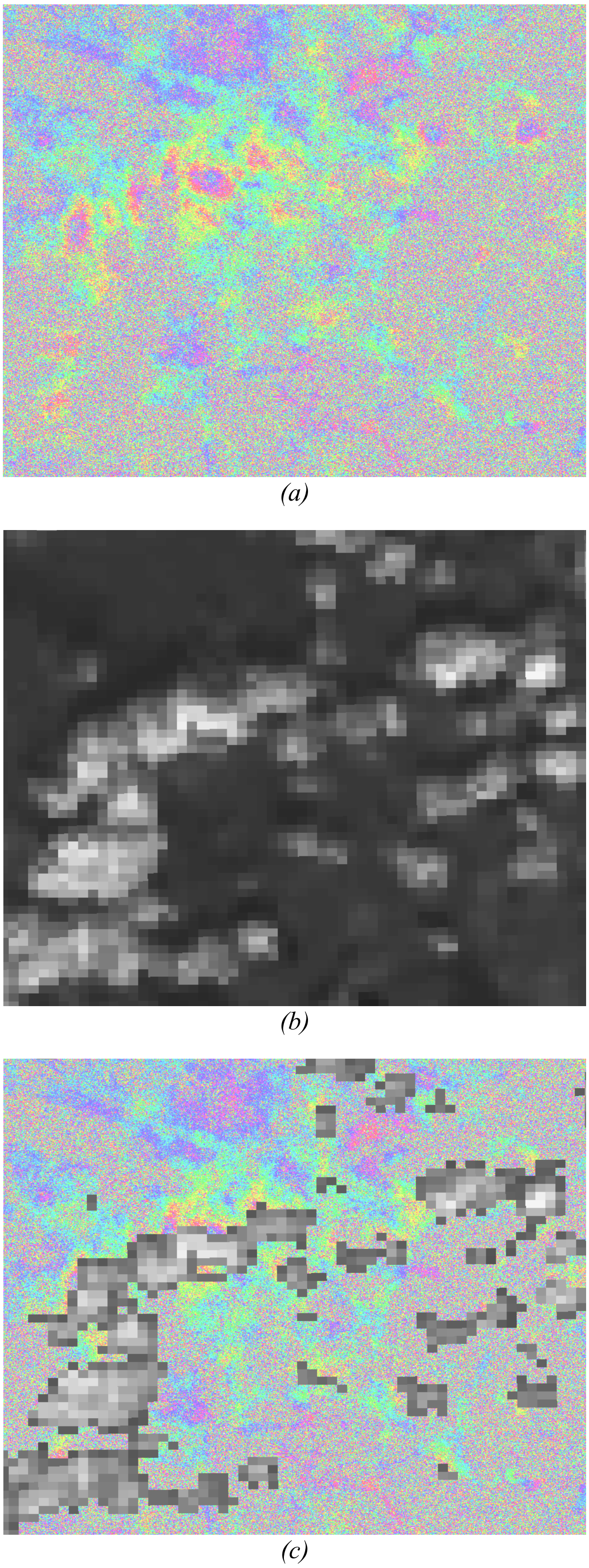



Figure 7. Atmospheric phase shifts for July 16th, 2009 in Leipzig area. (a) DInSAR atmospheric phase shifts, (b) MERIS FRS (cf. also Fig. 2), (c) MERIS level 2 product "cloud albedo" overlaid on (a)

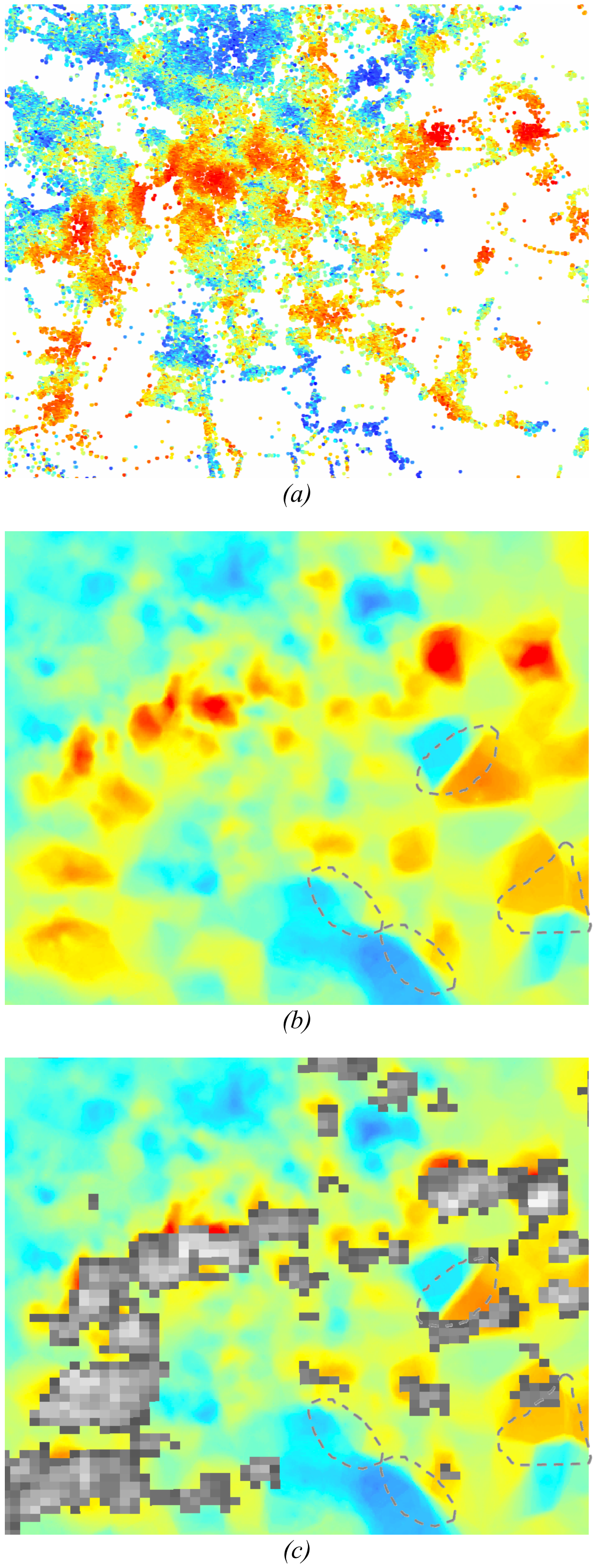
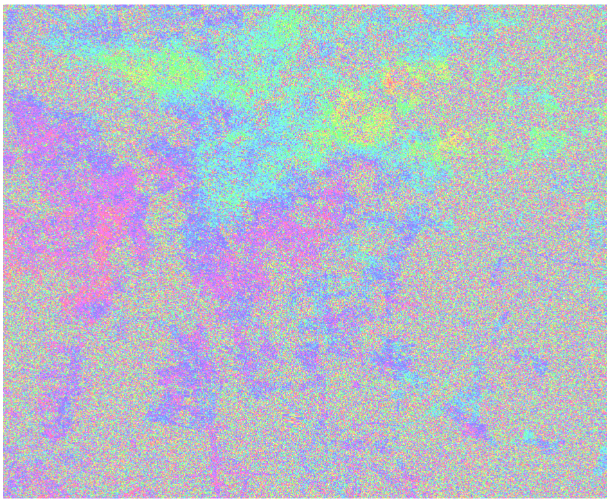
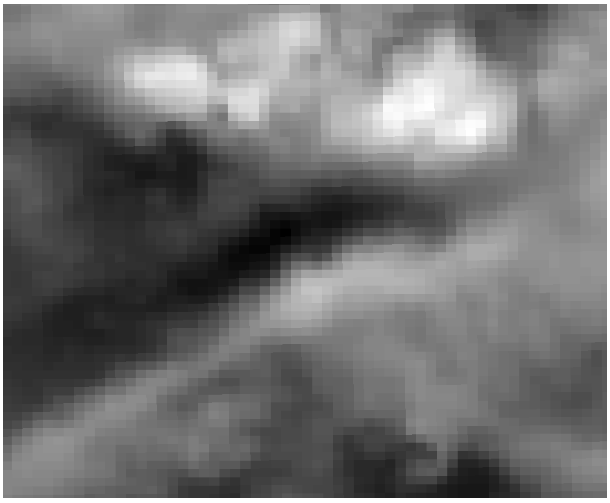



Figure 8. Atmospheric phase shifts for July 16th, 2009 in Leipzig area. (a) PSI unwrapped atmospheric phase shifts, (b) PSI result interpolated with IDW, (c) MERIS "cloud albedo" overlaid on (b). See also chapter 3.3

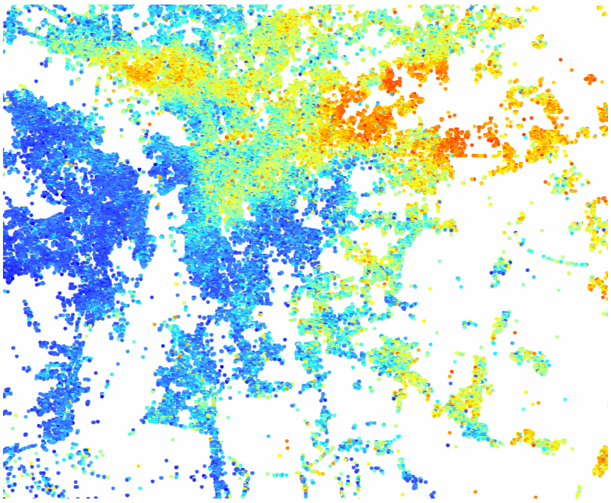


*(a)*

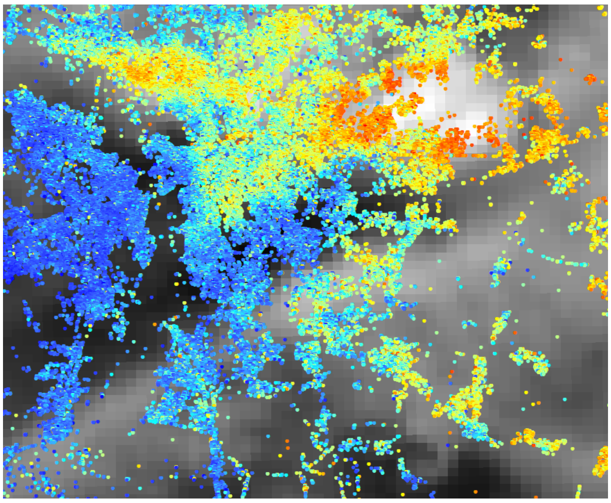


*(b)*

*Figure 9. Atmospheric phase shifts for June $11^{th}$, 2009 (Leipzig area). (a) DInSAR result, (b) MERIS FRS band 9 image (cf. also Fig. 3)*



*(a)*



*(b)*

*Figure 10. Atmospheric phase shifts for June $11^{th}$, 2009 (Leipzig area). (a) PSI result, (b) result (a) overlaid on MERIS FRS band 9*

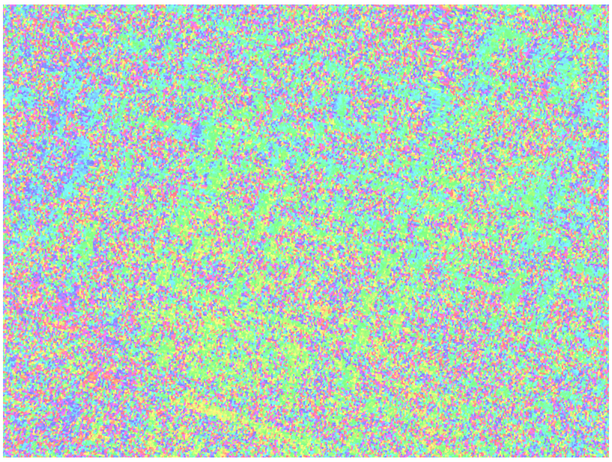


*Figure 11. Atmosphere phase shift for Aug. $21^{st}$, 2008 based on TerraSAR-X DInSAR data (Berezniki area)*

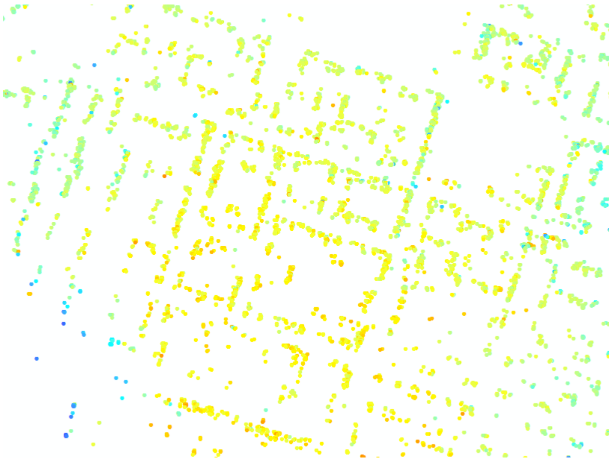


*Figure 12. Atmosphere phase shift for Aug. $21^{st}$, 2008 based on TerraSAR-X PSI data (same area as Fig. 11)*

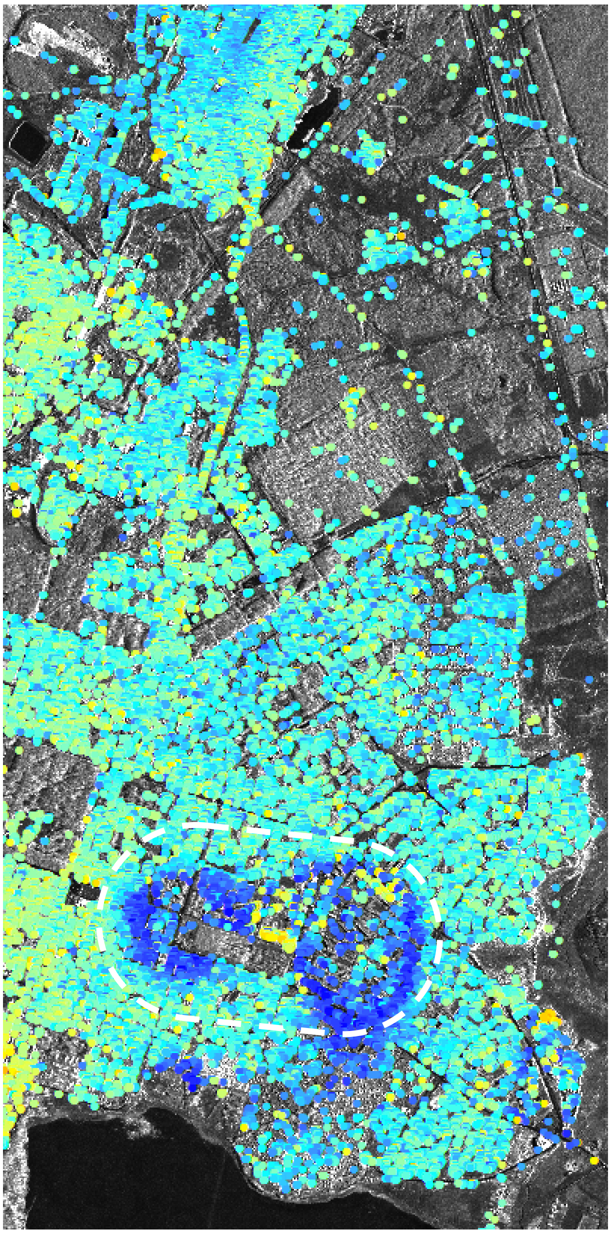


*Figure 13. Slight TerraSAR-X PSI derived atmospheric phase shifts for September 1st, 2008 in Berezniki. White dashed ellipse emphasizes main deformation area*

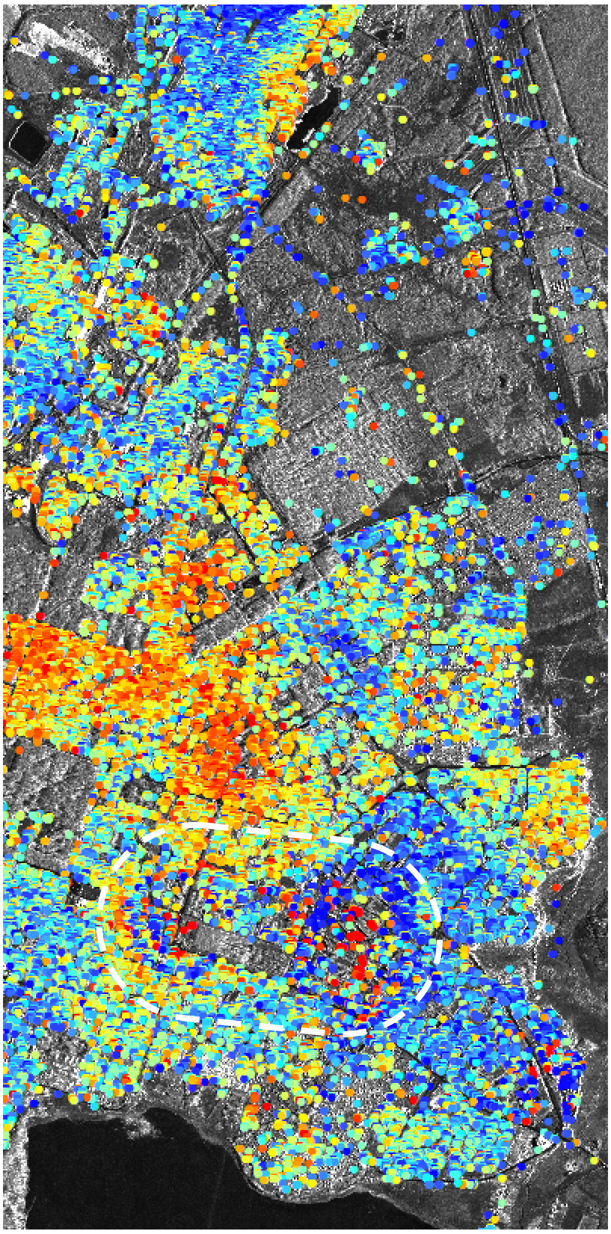


*Figure 14. Strong TerraSAR-X PSI derived atmospheric phase shifts for August 30th, 2009 in Berezniki. White dashed ellipse emphasizes main deformation area*

### 3.4. Comparison with ENVISAT MERIS data

For the purpose of a plausibility checking, the derived results have been qualitatively compared to optical MERIS data acquired simultaneous with the ENVISAT ASAR data. Although MERIS full resolution swath data possess much lower geometric resolution of approx. 250 m relatively to ASAR data with 20 m, the comparison shows good analogy (cf. Fig. 7, 8, 9, and 10). For TerraSAR-X results no optical comparison data were available.

## 4. SUMMARY

As could be shown, atmospheric phase shifts in interferometric data have high spatial variability to some dates, mainly in the summer months. They can be easily mixed up with vertical ground motions of more than 3 cm. Particulary regions with slow deformation rates can be concealed by atmosphere. Calculation of absolute correction values by using additional information is an ambitious task. Therefore we propose an extraction from the SAR data themselves.

Our approach works both with DInSAR and PSI data. Although no correction of interferometric data is possible yet in areas of deformation, the results have shown very helpful for interferometric analyses, for example when choosing a reference scene suitable for PSI or interferometric stacking algorithms. The results show good analogy to optical ENVISAT MERIS data.

It has to be noted that (as with interferometry in general) results can only be achieved for areas of high coherence, like villages and cities, or for persistent scatterer points when using PSI. Larger urban areas generally support an identification of atmospheric effects. Some of our atmospheric results appear noisy for single dates. This was caused either by a high perpendicular baseline of this acquisition in relation to the majority of all the other scenes (this also results in DEM related topographic errors in the results), or by a high doppler centroid frequency of the scene. Also snow coverage of a scene has shown to considerably increase the noise of the result.

For the design of future SAR missions we would like to recommend a SAR satellite with an optical sensor (like ENVISAT MERIS), for optical data acquired simultaneously with SAR data has shown very helpful. Potentially also a multispectral SAR sensor offering 2 or 3 bands (e.g. in the X and L band of the electromagnetic spectrum), which are acquired simultaneously would be very interesting for identification and possibly correction of atmospheric effects in differential interferometric data.

## 5. ACKNOWLEDGEMENTS

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The TerraSAR-X StripMap mode data was provided by German Aerospace Center (DLR) via TerraSAR-X AO project GEO 0348.

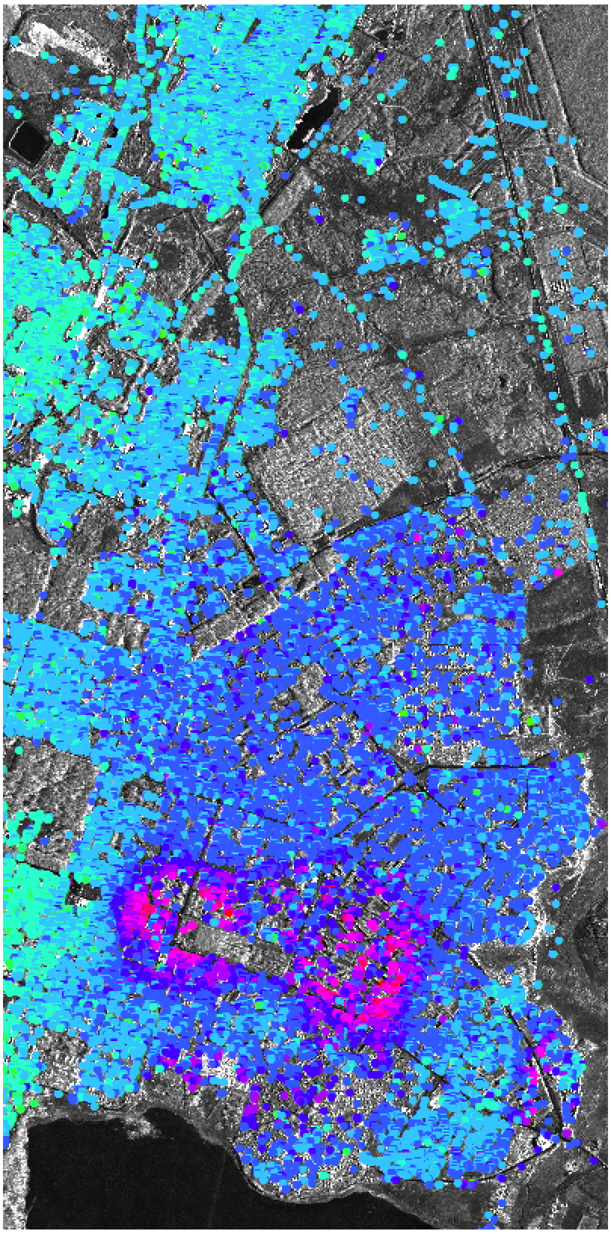

*Figure 15. TerraSAR-X PSI result for mean deformation signal computed from unwrapped atmospheric signals. Left side of image shows no deformation (cyan), whole lower right part of Berezniki shows slight subsidence. Boundaries of higher deformation areas are clearly visible, though inner parts were not correctly represented due to phase ambiguities in the averaging process (cf. also chapter 2 for details)*