Nonuniform Ground Motion Monitoring With TerraSAR-X Persistent Scatterer Interferometry

Urs Wegmüller, Senior Member, IEEE, Diana Walter, Volker Spreckels, and Charles L. Werner, Senior Member, IEEE

Abstract—In the past, the application of Persistent Scatterer Interferometry (PSI) was primarily possible in the case of slow (less than a few centimeters per year) uniform movements. In this paper, we show how PSI permits the monitoring of relatively fast (including rates up to > 50 cm/year) and nonuniform movements using TerraSAR-X repeat observations over deep-level mining. To enable this, parts of the PSI methodology were adapted to the special characteristics of the example studied. Apart from a description of the methodology used and the result achieved, error considerations and a validation of the result with *in situ* measurements are included.

Index Terms—Differential SAR interferometry (DINSAR), land deformation, mining, persistent scatterer interferometry (PSI), TerraSAR-X.

I. INTRODUCTION

O VER the last years, the mapping and monitoring of coherent displacements at *centimeter* to *millimeter* resolution with spaceborne synthetic aperture radar (SAR) interferometry reached some maturity. Spaceborne SAR interferometry benefits from the already existing SAR data archives covering more than 15 years. The required interferometric SAR data are available from a number of spaceborne SAR sensors including the European Remote Sensing Satellite (ERS)-1, ERS-2, the Environmental Satellite Advanced SAR (ENVISAT ASAR), Radarsat-1, Radarsat-2, the Japanese Earth Resources Satellite, the Advanced Land Observing Satellite Phased-Array L-band SAR, TerraSAR-X, and Cosmo-Skymed. Additional and subsequent missions are also being planned. For a more extensive introduction to the principles of SAR interferometry, the reader is referred to [1]–[3].

In the mining sector, there exists a significant demand for deformation information for legal obligation, safety, and environmental reasons. Existing non-Earth-observation (EO) techniques such as leveling and GPSs are operationally used. In

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U. Wegmüller and C. L. Werner are with Gamma Remote Sensing AG, 3073 Gümligen, Switzerland (e-mail: wegmuller@gamma-rs.ch; cw@gamma-rs.ch).

D. Walter is with the Institute of Geotechnical Engineering and Mine Surveying, Clausthal University of Technology, 38678 Clausthal-Zellerfeld, Germany (e-mail: diana.walter@tu-clausthal.de).

V. Spreckels is with the RAG Aktiengesellschaft, RAG Deutsche Steinkohle, Geschäftsbereich Geoinformation/Vermessung BG G, 44623 Herne, Germany (e-mail: volker.spreckels@deutsche-steinkohle.de).

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spite of this, there is a high interest in potential complementary or alternative techniques.

In spite of advanced SAR interferometric processing techniques and numerous very convincing results, there remain limitations to the utility which can be summarized as "partial unavailability of the EO-based information." The most important reasons include information gaps for low-coherence areas and the difficulty to resolve high-phase gradients [4]. The main improvement achieved using Persistent Scatterer Interferometry (PSI) was that uniform deformation at low rates could more accurately be assessed. However, the spatial coverage could not significantly be improved because very few scatterers were typically found in rural areas. Furthermore, PSI is typically not successful in the case of higher deformation rates and nonuniform deformations [5]. In the case of underground coal mining, this limitation typically results in large information gaps in the area above and near the mining panels where the highest deformation occurs [6].

A significant improvement to the applicability of the interferometric technique for coal-mining-related surface deformation is achieved by using data at the longer L-band wavelength. For intervals up to 92 days, the coherence remained high enough to retrieve deformation information even over forests [6], and the applicability is significantly improved in the case of high deformation rates [6]. Nevertheless, a major disadvantage is that temporal coverage achieved with ALOS PALSAR repeat observations is not fully sufficient for a monitoring at monthly or bimonthly intervals.

Other possibilities to improve the applicability of SAR interferometry for the monitoring of fast ground movements are to move to higher spatial resolutions and shorter repeat intervals. The higher spatial resolution improves the spatial sampling of the deformation pattern. The shorter repeat interval reduces the amount of deformation occurring between two acquisitions. Both effects reduce the complexity of the phase unwrapping.

TerraSAR-X is one of the recent satellite SAR sensors that can provide data suited for interferometry at high spatial resolution. TerraSAR-X is furthermore operated with an 11-day repeat interval which is significantly shorter than the 35-day intervals of the ERS and ENVISAT satellites. In spite of its shorter wavelength, the temporal and spatial sampling of deformation patterns is significantly better than for these C-band SARs. Consequently, there is an interesting potential to resolve faster deformation as it is occurring in the case of mining. TerraSAR-X differential interferograms derived over a German mine confirm this potential [7].

The focus of our work presented in this paper is on the assessment of the potential of PSI over a mine. In PSI, the

date	Baseline [m]	Interval [days]	Ambiguity height [m]
11-Feb-2008	0	0	-
22-Feb-2008	161	11	42
04-Mar-2008	-10	22	-677
15-Mar-2008	-35	33	-193
06-Apr-2008	273	55	25
28-Apr-2008	77	77	88
09-May-2008	2	88	3385
31-May-2008	175	110	39
11-Jun-2008	69	121	98
03-Jul-2008	138	143	49
14-Jul-2008	105	154	64
25-Jul-2008	-13	165	-520
05-Aug-2008	-38	176	-178
16-Aug-2008	252	187	27
27-Aug-2008	84	198	81
07-Sep-2008	38	209	178
18-Sep-2008	54	220	125
29-Sep-2008	94	231	72
10-Oct-2008	-35	242	-193
21-Oct-2008	75	253	90

TABLE I TERRASAR-X ACQUISITION DATES, PERPENDICULAR BASELINES RELATIVE TO FIRST ACQUISITION, AND TIME INTERVALS RELATIVE TO FIRST ACQUISITION

interferometric phase is only analyzed for scatterers that are selected in an early processing step. There exist a number of different PSI approaches including those in [8]–[12]. For the work presented in this paper, we used the Interferometric Point Target Analysis (IPTA) Software, which is GAMMA's implementation of PSI. For an overview on IPTA, the reader is referred to [13]–[16]. The IPTA software should not be understood as a single "standard" PSI processing sequence. It is rather a toolbox that can support many different methodologies including different methodologies for scatterer candidate selection, spatial and temporal phase unwrapping, and supporting approaches for single- as well as multireference stacks.

The methodology that we used has some similarity to small baseline approaches applied to single pixels presented in [9] and [11]. While, in [9] and [11], an important criterion is to use short baselines to have good coherence, the relevant condition in our case is to have short temporal intervals to avoid too much phase change between observations. As pointlike scatterers are used in our approach, short spatial baselines are not required, which permitted one to always consider pairs of consecutive acquisitions. The specific PSI methodology used will be described in more detail in Section II.

The colliery considered is located in the German Ruhr area. The area investigated includes urban as well as rural parts. The area includes parts with strong deformation (> 30 cm over 253 days, > 12 cm over 55 days, and > 4 cm over 11 days). The deformation results from deep-level hard-coal excavation of coal seams of about 1.6-m thickness at an average mining depth of 1400 m, and therefore, high spatial deformation gradients are present, and the deformation is nonuniform in time.

For our investigation, we used a significant series of TerraSAR-X repeat observations in fine-resolution single-polarization stripmap mode, Strip 012R, with an incidence-angle range of $39^{\circ}-42^{\circ}$ at HH polarization. Until November 2008, more than 20 scenes were acquired over our area of interest. Table I lists the acquisition dates as well as the perpendicular baselines and the time intervals relative to the first

acquisition. The interferometry activities were complemented by leveling and GPS measurements, permitting a validation of the results. For the selected site, there is a real monitoring demand, and SAR interferometry shall play an important role in the integrated monitoring concept. SAR data of other sensors (ASAR and PALSAR) are also acquired over this site, offering possibilities for comparisons.

II. APPROACH

A. Preprocessing

The TerraSAR-X data used were single-look complex (SLC) data with pixel spacings of 1.36 m in slant range and 1.90 m in azimuth. As SLC reference geometry, we used the first scene that was acquired (February 11, 2008). Geocoding was performed on the multilook intensity image of the reference scene. As part of the geocoding, we also transformed the digital elevation model (DEM) heights into the SAR geometry. These terrain heights were then considered in the SLC coregistration. The coregistration approach included a refinement step using actual offset estimates between the data sets, and it provided error statistics. Offsets determined in a test for the coregistered SLCs showed very low standard deviations below 0.05 SLC pixel.

B. Persistent Scatterer Candidate Selection

From the coregistered SLC, we estimated two sets of persistent scatterer candidates using complementary criteria. The first set was estimated based on a low spectral diversity [13]. In this method, pixels with a dominant pointlike scatterer are selected. Such scatterers are particularly well suited if the stack used later on includes pairs with long baselines because pointlike scatterers are not much affected by geometric decorrelation. The second set was determined based on the temporal variability of the backscattering. Pixels with very low variability were selected. For these pixels, it is again expected that they are well suited for the PSI analyses. The two candidate sets were then combined into one list, which was then used for the analysis. From these pixels, 5.7% qualified as candidates. Given the 240 000 pixels/km², this corresponds to more than 10 000 candidates/km², which is dramatically more than what is found at the C-band data of ERS or ENVISAT, particularly when considering that much of the area considered is of rural character. Nevertheless, the spatial distribution of the candidates is very inhomogeneous with high densities for built-up areas (villages and other infrastructure such as railways) and low densities over forests and fields.

C. Multireference Stack Methodology

Using the coregistered SLC, the related DEM heights in SAR geometry, and the persistent scatterer candidate list, we can then calculate point differential interferograms. For each persistent scatterer candidate, the topographic and orbital phases are simulated and subtracted from the pointwise complex-valued interferogram. The main phase components of the initial point differential interferograms are residual orbital phase, residual topographic phase, deformation phase, atmospheric phase, and phase noise. Most of these phase terms are spatially correlated; the exceptions are the phase noise and the residual topographic phase. Given that the candidate selection was adequate, the phase noise should be small (< 1 rad) for most scatterers. The topographic phase depends linearly on the point height correction necessary and the perpendicular baseline of a specific pair. At least for pairs with relative short baselines (e.g., < 100 m), the topographic phase should be reasonably small. Because of the strong deformations in this areas, deformation phases become very significant over longer intervals. To keep the deformation phases as small as possible, we therefore worked with a multireference stack. Only pairs with intervals up to 44 days were considered.

D. Phase Unwrapping

For the pairs with relatively short intervals, spatial unwrapping was possible. Based on the unwrapped phase, orbitalphase corrections were estimated, considering only areas which were expected to be stable. The residual phase was then spatially filtered. The filtered phase contains the spatial lowfrequency deformation and atmospheric phases, and the highfrequency residual phase which is obtained by the subtraction of the spatially filtered phase contains the residual topographic phase, the phase noise, as well as the high-frequency parts of the deformation and atmospheric phases. Using a 1-D regression on this residual phase permitted one to determine point height corrections. Depending on the quality of the initial point heights and on the baselines present in the multireference stack, it may be necessary to iterate this approach. Initially, spatial unwrapping may only be successful for pairs with relatively short baselines. Based on these, a height correction can be estimated. Using the improved point heights, it is then typically also possible to unwrap the point interferometric phases of pairs with longer baselines. This methodology is better applicable in the case of strong and nonuniform deformation. In the

present TerraSAR-X study, the spatial unwrapping was actually not very challenging because of the good spatial sampling provided by the dense candidate network and the high quality of the candidates selected. The main output of these steps is the unwrapped point differential interferometric phases of the selected short interval pairs.

Quality checking of the unwrapped phase is very important. The quality of the individual points is checked by the consideration of the phase standard deviation in the regression used to estimate the point height correction. Points with standard deviations above a certain threshold are discarded from the result. Furthermore, the spatial and temporal consistency of the phases is carefully checked to identify potential phase unwrapping errors. Errors identified are either corrected or the corresponding pair is discarded from the result.

E. Phase Interpretation

Starting from the multireference stack, we derive a single reference time series using singular value decomposition (SVD) to obtain the least squares solution for the phase time series. A similar approach was proposed in [17]. A complete series is obtained for the times connected by the multireference pairs. Based on the ten pairs, namely, A-B, A-C, B-C, B-D, B-E, C-D, C-E, C-F, D-E, and E-F, we obtain for example, the time series for the six times, i.e., A, B, C, D, E, and F. Redundancy in the differential interferogram input data reduces uncorrelated errors in the time series. Uncorrelated errors include residual topographic phase errors and phase noise. Atmospheric phase, on the other hand, is not reduced by this estimation procedure. For a given acquisition date, there is a well-defined atmospheric phase delay pattern which is present in all the pairs including this date. The same applies for nonuniform deformation phase. Consequently, the obtained time series of unwrapped phases still includes the atmospheric phases as well as nonuniform deformation phase.

Apart from the phase time series, the *rms deviation of the* values from the SVD is calculated as a quality value, permitting one to identify unwrapping errors which remained undetected.

Assuming uniform motion only, we can now derive linear regressions to these time series, spatially filter the phase deviations from the linear regressions, and interpret these as atmospheric phase delays. In the areas with significant nonuniform subsidence, this results in very high residual "atmospheric delays" which are suspects as they show a significant temporal correlation as well as a strong spatial correlation with the deformation pattern itself—i.e., the shape of the atmospheric delay correlates strongly with the deformation pattern. Of course, the assumption of a uniform deformation is not adequate in this case, and therefore, we have to use better suited methods to discriminate atmospheric phase delay, nonuniform deformation phase, and phase noise.

An important characteristic of the atmospheric phase delay is that it is temporally uncorrelated for the considered time intervals of 11 days and more. Temporal filtering can be used to separate temporally correlated (nonuniform deformation) and uncorrelated (atmospheric delay and phase noise) components [8]. In our specific case, we determined the temporally



Fig. 1. (a)–(c) Examples of residuals to temporally filtered phase history and (d)–(f) corresponding phases after subtraction of the phase component which correlates with the deformation pattern. One color cycle corresponds to a 2PI.

correlated phase of each acquisition time by applying a linear regression to the acquisition within an interval of plus and minus 45 days around this date. The residuals to this temporally filtered phase were then calculated. Examples of such residual phases are shown in Fig. 1. Comparison with the total deformation shows that these residual phases correlate in the area of the main deformation pattern strongly with the total deformation (see Fig. 3). No spatial correlation between the atmospheric delay and the deformation pattern is expected in this relatively flat area. Consequently, we should not just interpret this phase which correlates spatially with the deformation as atmosphere. As a model, we assume a linear relation between the total deformation and the temporal nonlinearity. To discriminate the nonlinear deformation part of the residual phase in areas with strong deformation, we calculated a linear regression between this residual phase and the total deformation. The thus determined spatially correlated part of the residual phase was then added to the temporally filtered phase and interpreted as deformation phase. The remaining atmospheric phase now correlates much less with the deformation pattern, as also shown in Fig. 1.

The resulting phases were combined again to obtain a deformation-phase model without phase noise and atmosphere, a deformation-phase model with phase noise, and a deformation-phase model with phase noise and atmosphere. The deformation phases were then transformed into lineof-sight displacements and geocoded to the selected map geometry.

F. Error Analysis

Subtracting the phase model (= linear and nonlinear motion) from the point differential interferograms, we obtain the final residual phase which includes the atmospheric phase as well as phase noise. Estimating, for each date, the spatial statistics of this final residual phase, we find values between 0.27 and 0.85 rad. To calculate the error of deformation estimates, we consider that a deformation estimate requires two acquisitions and that the deformation estimate is relative to a spatial reference point which is also affected by the same errors. The root sum square of the four error terms is consequently between 0.54 and 1.70 rad. This corresponds to line-of-sight displacement estimation errors between 1.3 and 4.1 mm. These are conservative error estimates in that the entire atmospheric phase was interpreted as error, in spite of estimating and subtracting the atmospheric phase. Considering the residual phase after subtraction of the atmospheric phase, the corresponding error estimates are between 1.3 and 2.7 mm.

For an 11-day observation interval, a deformation error of 2.7 mm results in a deformation rate error of 0.25 mm/day. For the 253-day interval between the first and the last acquisitions considered here, it results in a deformation rate error of 0.01 mm/day, i.e., 3.9 mm/year. This value is significantly higher than the submillimeter-per-year rate typically indicated for deformation rate estimates derived from C-band series. The reason for this is that we did not consider here the accuracy of a slope estimate for a linear regression to a large number of observations but we considered here the error of the



Fig. 2. Line-of-sight surface deformation between February 11 and October 21, 2008 derived from TerraSAR-X data series in an IPTA processing over an active mining area in Germany.

individual deformation estimate without assumption on its temporal behavior.

G. PSI Result

The total deformation between the first and the last date considered is shown in Fig. 2. The size of the area shown is 3.7 km times 3.2 km. For this small area, a solution is found for more than 100 000 points. Nevertheless, the spatial distribution of these points is not at all homogeneous, and therefore, there are significant spatial gaps in spite of the large number of points. In the center of the area shown, there is significant subsidence with maximum values > 30 cm over the 253-day period. For each point, a deformation time series is available. For examples of pointwise deformation histories, the reader is referred to Section III. The main deformation pattern in the center clearly shows a nonuniform behavior. In the beginning, subsidence rates around 1 mm/day are observed. Then, the subsidence accelerates to 2 mm/day before slowing down to rates below 0.5 mm/day. These temporal variations correlate well with the mining of a specific panel between January and September 2008. Each of these phases is covered by multiple observations which increase the confidence in the result. To visualize the changes in the deformation rate, we show, in Fig. 3, the average deformation rate between subsequent TerraSAR-X acquisitions. In spite of the relatively short intervals, the rates



Fig. 3. Line-of-sight deformation rates for subsequent intervals between February 11 and October 21, 2008 derived from TerraSAR-X data in an IPTA processing over an active mining area in Germany.

look spatially and temporally consistent, maybe with the exception of the last interval where more severe localized atmospheric distortions are apparent.

III. VALIDATION

Validation of the SAR interferometric results was an important part of our project. A significant effort was spent to acquire in-site reference data. Leveling campaigns were conducted several times along the SAR data acquisitions, preferably on dates corresponding to SAR data acquisitions. Considering the effort needed, it was not possible, however, to conduct a largearea leveling campaign for each TerraSAR-X acquisition along many leveling lines. The height measurements were performed every two to three months with high-precision leveling instruments with a root-mean-square accuracy of 1–2 mm/km for a loop line leveling. The leveling starts and ends on the same height reference point located in a stable region that is not influenced by mining-induced ground movements. Additionally, for this mine, corner reflectors were installed, and their positions were measured several times by GPS methods and leveling.

The area of the PSI TerraSAR-X result (Fig. 2) is covered by two leveling lines. The leveling lines and a few selected leveling points for which time series were compared with the PSI TerraSAR-X results are shown in Fig. 4.



Fig. 4. Overview map showing (red) leveling lines used in this study, (green cross) leveling reference, and locations of selected leveling points further analyzed (with point number indicated). The background image shown displays the line-of-sight surface deformation between February 11 and October 21, 2008 derived from TerraSAR-X data series in an IPTA processing over an active German mine using a cyclic color scale with 10 cm displacement per color cycle.



Fig. 5. Comparison of leveling (+) and PSI vertical deformation time series for selected locations. (a) Point 74 117. (b) Point 74 154. (c) Point 74 141.

The leveling measurements and the PSI results were compared for some points representing different parts of the subsidence trough. One or two points of the PSI result in the closer neighborhood of the leveling points were determined. For these selected locations, both the leveling and the PSI values were plotted versus the time. As temporal reference, March 4, 2008 had been specified because of the nearly coincident leveling measurements on March 5, 2008 (see Table I). Thus, the vertical displacement for both the leveling and the PSI result was set to 0.0 for this date. Furthermore, the spatial reference had to be defined. In the case of the PSI result, the spatial reference is indicated by a red +, and for the leveling data, the spatial reference is indicated by a green x; both points are located in the southwest of the area (see Fig. 4). Comparisons for three points are shown in Fig. 5.

The leveling line considered for the comparison traverses the main subsidence trough. The leveling point 74 117 is located at the border of the main subsidence area characterized by low deformation rates. At leveling point 74 117, the PSI result extracted at two IPTA points corresponds well to the leveling. The PSI result shows a point-to-point variability of a few millimeters, which is expected based on the error analysis discussed in Section II-F. At the last date, the PSI result shows a displacement value which is about 1.5 cm higher than for the previous dates. This significantly different value is not necessarily related to an unwrapping error as one might speculate, but rather to the corresponding uncompensated small-scale atmospheric phase delay which is clearly visible in Fig. 3 (last image).

Leveling point 74 154 is clearly located within the subsidence trough. For the first three leveling dates, the deformation values match well. For the last PSI value, there is an offset of about 1 cm between the leveling and the PSI results. Both the leveling and the PSI results show two main periods in the deformation: first, an almost linear subsidence followed by a period with an almost stable ground.

Leveling point 74 141 is located near the maximum subsidence observed. Here, the PSI result indicates around 40 cm of subsidence over the 253 days. Overall, the PSI result corresponds well to the leveling. There is an initial period with slower subsidence, then the period with fast subsidence (2 mm/day), and then, toward the end, the subsidence slows down again significantly. For the end of May measurements, we notice an offset of almost 5 cm between the leveling and the PSI results. We are not entirely sure about the origin of this offset. A phase unwrapping problem is not very likely as we find a much better match again later on. For this fast moving area, the small differences in the location and the time of the two measurements may explain a part of the difference, and a part may be related to uncompensated atmospheric delays. However, overall, the achieved accuracy is very satisfactory, considering that the subsidence is fast and nonuniform.

The leveling measurements were compared with the TerraSAR-X PSI results. Profiles showing the displacements after February 11, 2008 are shown in Fig. 6. For the selected times, both the leveling and PSI values are plotted versus distance relative to the first point of the leveling line in the southwest of the subsidence area. For some sections of the leveling line, there are no neighboring points of the PSI result. As a consequence, the subsidence trough is not well sampled everywhere. Overall, the profiles show results comparable to the time-series plots. For the first time period (February 11– March 4–5, 2008), the leveling and PSI results correspond well to each other. In this plot, the noise in the PSI results is more obvious due to the finer scale compared with the scale of the other plots. A few single points along the profile appear to be outliers of the PSI result. Such outliers are typically observed in areas with low spatial coverage in the PSI result. For the period between February 11, 2008 and March 28-31, 2008, the PSI-based subsidence estimates are higher than the leveling measurements by about 50 mm in the center of the trough and lower than the leveling by about 20 mm to the north of subsidence trough. For the time periods until July 16-14, 2008 and October 15-10, 2008, the PSI result corresponds well to the leveling. In the areas with high spatial deformation gradients, differences of up to about 20 mm could result from the different positions of PSI and leveling points. The underestimation of subsidence in the PSI result for the last period observed at distances above 2000 m was most likely caused by uncompensated atmospheric effects. Nevertheless, it is very positive that the entire subsidence trough was sufficiently well covered by the PSI results at all relevant times. The slight spatial offset observed



Fig. 6. Comparison of leveling (red) and PSI (green) vertical deformation profiles along the leveling line (see Fig. 4) from southwest to north relative to February 11, 2008. (a) Leveling of March 5, 2008 and PSI of March 4, 2008. (b) Leveling of May 28, 2008 and PSI of May 31, 2008. (c) Leveling of July 16, 2008 and PSI of July 14, 2008. (d) Leveling of October 15, 2008 and PSI of October 10, 2008.

between the maximum positions of the last two profiles shown may be related to the fact that the objects measured with PSI and the leveling benchmarks are not identical.

IV. CONCLUSION

In the past, the application of PSI was primarily possible in the case of slow (less than a few centimeters per year) uniform movements. In this paper, we have discusses a case where we successfully applied PSI to monitor relatively fast (including rates up to > 50 cm/year) and nonuniform movements. This was possible, owing to two relevant factors. The first one was that we used high-resolution TerraSAR-X data acquired at relatively short 11-day intervals. Owing to the high spatial resolution, the number of persistent scatterers found was significantly higher than for ERS or ENVISAT data stacks. The high number of points found resulted in a significantly better spatial sampling of the present high phase gradients. Furthermore, the shorter 11-day interval resulted in less deformation phase per period. This strongly facilitated the spatial phase unwrapping. The second relevant factor was that we applied a special PSI methodology which was adapted to the special characteristics of this case. The deformation was not estimated in a linear regression to a single reference stack, but considering a multireference stack with short intervals. Spatial unwrapping of the point differential interferograms was an important step in this.

The spatial coverage achieved was sufficient to get most of the information on the main subsidence trough. Nevertheless, there remain important gaps in the spatial coverage. No results were obtained over agricultural fields and forests. Even local infrastructure such as a railway line was sufficient to provide persistent scatterers.

The PSI result achieved was validated using leveling data. The overall good correspondence confirmed the utility of the TerraSAR-X data and the applied PSI methodology. In the interpretation of the PSI result, we moved away from mainly interpreting the average deformation rate to rather interpreting the individual value. As discussed in the error analysis, the



Fig. 7. Comparison of leveling and PSI vertical deformation time series for two IPTA points (x, x) near (+) leveling point 74122, indicating an unwrapping error affecting the solution of the blue point.

remaining uncertainty of an individual value in the PSI result (value at a specific point for a specific date) is substantial. Statistically, we found a one standard deviation error of 2.7 mm. However, in the case of a turbulent atmosphere, uncompensated small-scale variations in the atmospheric path delay can also result in deviations larger than 1 cm. Consequently, it is important to consider rather several observations instead of an individual one for the interpretation.

One limitation in the reconstruction of the deformation history based on short intervals is that an individual unwrapping error may disturb the entire time series after its occurrence. During the validation work, we identified two neighboring IPTA points near leveling point 74 122 with deformation histories, as shown in Fig. 7. Up to early June 2008, the values of the two points correspond well to each other and to the nearby leveling point. Then, starting in July 2008, there is always an offset between the two points of about 1.5 cm, which corresponds to one phase cycle. This error in the result can be identified by comparison of the individual time series with the one of its spatial neighbors. When identified, we can either reject the inconsistent result or correct the phase unwrapping in a postprocessing.

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Urs Wegmüller (M'94–SM'03) received the M.S. and Ph.D. degrees in physics from the University of Bern, Bern, Switzerland, in 1986 and 1990, respectively.

Between 1991 and 1992, he was with the Jet Propulsion Laboratory, Pasadena, CA, and between 1993 and 1995, he was with the University of Zürich, Zurich, Switzerland. In 1995, he was a Founding Member of GAMMA Remote Sensing AG (GAMMA), a Swiss company active in the development of signal processing techniques and remote

sensing applications. As CEO of GAMMA, he has overall responsibility for GAMMA's activities. Currently, his main involvement is in the development of applications and the definition and implementation of related services in land surface deformation mapping, hazard mapping, land-use mapping, and topographic mapping. He is/was a Principal Investigator for projects supported by the European Space Agency and the European Commission Framework Programs.



Diana Walter was born in Meissen, Germany, in 1978. She received the Diploma degree in mine surveying and geodesy from the Technical University Bergakademie Freiberg, Freiberg, Germany, in 2004. She is currently working toward the Ph.D. degree at the Clausthal University of Technology, Clausthal-Zellerfeld, Germany, in the field of synthetic aperture radars (SARs).

From 2003 to 2005, she was with the German Remote Sensing Data Center (DFD), German Aerospace Center (DLR), Wessling, Germany, in the

frame of her diploma thesis and as a Research Assistant with the TopoSAR group. Since 2005, she has been a Research Assistant with the Institute of Geotechnical Engineering and Mine Surveying, Clausthal University of Technology. Her main research interests are SAR interferometric processing and digital elevation models with main focus on deformation monitoring above underground mines using ENVISAT Advanced SAR, Advanced Land Observing Satellite Phased Array type L-band SAR, and TerraSAR-X.



Volker Spreckels was born in Hammah, Germany, in 1965. He received the Graduate Engineer (Dipl.-Ing.) degree in geodesy from the Leibniz University of Hannover, Hannover, Germany, in 1995, with main focus on photogrammetry and engineering surveys.

Between 1986 and 1988, he learned the profession of a Qualified Land Surveyor with the "Oeffentlich bestellte Vermessungsingenieure Clasen & Voss," Stade, Germany. Between 1995 and 1996, he was a Freelancer with PHOENICS, Service-Oriented So-

ciety for Digital Photogrammetry and GIS Ltd., Hannover. From 1996 to 1997, he was a Photogrammetry Engineer with Kirchner & Wolf Consult Ltd., Hildesheim, Germany. Between 1997 and 2002, he was a Research Assistant with the Institute for Photogrammetry and GeoInformation (IPI), Leibniz University of Hannover, in four successive R&D projects set up by the German hard-coal-mining company RAG Deutsche Steinkohle. The aim of the projects was to investigate the capability of different space- and airborne systems for the detection and monitoring of subsidence movements caused by underground hard-coal-mining activities. The projects dealt with digital elevation models (DEMs) derived from analytical and digital photogrammetry, three-line-scanner imagery, airborne LIDAR and radar data, and the use of differential synthetic aperture radar interferometry for the detection of relative subsidence movements. Since October 2002, he has been the Group Manager for Photogrammetry and Remote Sensing with the RAG Aktiengesellschaft, RAG Deutsche Steinkohle, Geschäftsbereich Geoinformation/Vermessung BG G, Herne, Germany. His domains concern the quality control and combination of terrestrial, aerial, and remote sensing data for the generation of DEMs and orthophotos, planning, construction, mapping, ground-movement detection in day-to-day business, and their improvement by R&D projects.



Charles L. Werner (S'75–M'79–SM'08) received the Ph.D. degree in systems engineering from the University of Pennsylvania, Philadelphia, in 1987, where he developed a fully polarimetric 3-D microwave holographic imaging facility operating over the range of 2–18 GHz.

At the Jet Propulsion Laboratory, Pasadena, CA, he worked on the digital processing and applications of airborne and spaceborne SAR. This included research in focusing algorithms, speckle reduction, scatterer classification, polarization signatures, de-

tection of moving targets, and absolute and relative radiometric calibration of polarimetric SAR data. He developed the system design and performed the system analysis of the Cassini Radar, a multimode radar incorporating SAR, altimeter, scatterometer, and radiometer modes for mapping Saturn's largest moon Titan. While he was with the University of Zurich, Zurich, Switzerland (1992-1995), he developed an interferometric SAR processing system for both airborne and spaceborne sensors. Phase unwrapping algorithms of interferometric SAR have been of continuing research focus, and he was responsible for the phase unwrapping algorithms used in the Shuttle Radar Topographic Mission Topographic Processing System and the GeoSAR Pand X-band airborne SAR systems. In 1995, he and Urs Wegmuller founded Gamma Remote Sensing AG, Gümligen, Switzerland. He has been responsible for the extension of the Gamma software to process data from the Japanese Earth Resources Satellite, Envisat Advanced SAR, Radarsat, and Advanced Land Observing Satellite Phased-Array L-band SAR and has participated in the development of a flexible terrain geocoding system for SAR data and the interferometric point target analysis system. He also led the development and construction of the Gamma Portable Radar Interferometer, a groundbased frequency-modulated continuous-wave radar interferometer operating at 17.2 GHz for producing in situ deformation maps.