# Satellite-based Radar Monitoring of Vertical Deformations Caused by Tunnelling

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**The contribution presents the settlement monitoring from a TerraSAR-X satellite using the Persistent Scatterer Interferometry (PS-InSAR), a radar interferometric technique. The method is applied to the intra-urban tunnelling project Wehrhahn-Linie in Düsseldorf, Germany, where area-wide measurements are performed along about 1,000 m of a subway tube, build with a tunnel boring machine (TBM). Comparisons to classical terrestrial measurements prove accuracies in a millimeter range. Settlement data, accuracy analyses and illustrations of coupled effects of tunnelling works to the behavior of surface buildings are visualized in a virtual reality environment showing details of the complex transient processes and interactions.**

## 1 Introduction

Safety and structural integrity of surface structures are of major interest in intra-urban tunnelling. Depending on the specific type of a building, structures possess different sensitivities to settlements caused e.g. by shield driven tunnelling or different excavation types. They depend on the size of the deformations imposed, the structural type and its inner stiffness as well as on extent and position of the building area relative to a settlement trough. To prevent or at least reduce damages of sensitive or important structures usually various complex remedial measures – e.g. compensating injections – are applied. However, those measures are often expensive and designed based on expert´s knowledge rather than elaborated calculations. To investigate the interactions between tunnel driving and overlying buildings in a more detailed way, it is necessary to gain area-wide and precise settlement data in the chronology of the driving process. Typically, terrestrial methods are applied that require enormous time and cost efforts. In the framework of the Collaborative Research Centre 837 named Interaction Modelling in Mechanized Tunnelling at the Ruhr-University of Bochum, Germany – founded by the German Research Foundation (DFG) – an alternative monitoring technique, namely the radar interferometric method is elaborated and applied at a subway project. It uses data from the TerraSAR-X Satellite – kindly provided by the German Aerospace Centre (DLR) – to attain area-wide and accurate measurements at the construction site of the shield tunnelling project Wehrhahn-Linie in the capital city of North-Rhine Westfalia, Düsseldorf, Germany. Combined to local terrestrial displacement data the space borne radar measurements are verified and checked with respect to their achievable accuracy.

Furthermore this paper illustrates what accuracy satellite-based monitorings can reach and shows methods to visualize settlement and corresponding process data in a virtual reality (VR) environment.

## 2 Radar interferometry based monitoring

### 2.1 Basics of the applied radar interferometric method (SAR)

Since the German radar satellite TerraSAR-X has been launched in 2007, optical remote sensing has become viable for settlement monitoring due to an increased geometrical ground resolution of the installed radar systems down to about 1 m in square. Additional data of the satellite applied here and the specific radar system are given in **Figure 1** and **Table 1**.

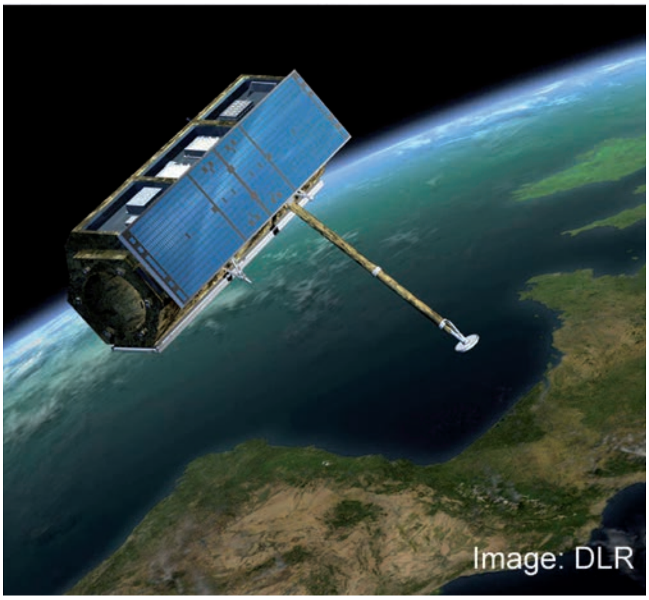

Figure 1: Technical data of TerraSAR-X radar satellite
(Source: German Aerospace Centre (DLR))

| **Description** | **Unit** | **Item** |
|---|---|---|
| Length (approx.) | [m] | 5.00 |
| Diameter | [m] | 2.40 |
| Weight during start (approx.) | [kg] | 1,230 |
| Radarfrequence | [GHz] | 9.65 |
| Resolution | [m] | |
| ▪ Scan-Mode | | 1.00 |
| ▪ Stripmap-Mode | | 3.00 |
| ▪ Spotlight-Mode | | 16.00 |
| Launch | [-] | 15th June 2007 |
| Launch site | [-] | Baikonur/Kasachstan |
| Height of orbit | [km] | 514 |
| Inclination angle | [deg] | 97.4 |
| Lifetime, minimum | [y] | 5 |
| Operationscenter | [-] | DLR, Oberpfaffenhofen (GER) |

Table 1: Technical data of TerraSAR-X

Essentially, radar based deflection measurements from satellites base on the following principle: Presented in a simplified way, radar waves from an active radar sensor are sent to the earth's surface, reflected pointwise to a radar echo and finally received back by the antenna of the satellite (**Figure 2**). Depending on e.g. the strength of the signal received, Synthetic Aperture Radar images can be derived. To achieve a high geometric resolution, a special recording and analysis method is used, the so-called Synthetic Aperture Radar technique (SAR) [1]. Here the length of the antenna artificially is enlarged by employing a specific combination of a number of pictures from successive satellite locations. If a settlement of a reflecting ground location occurs between 2 overflights, it causes a shift in the radar phase. So the main task is to calculate for the phase-shift or interferometric phase φ, compute deflections in the spatially inclined "line of sight" (LOS) of the satellite to the reflecting points observed and finally to derive the vertical components of the deflections yielding the settlement data looked for. This calculation is influenced by the return period of the satellite – TerraSAR-X passes every 11 days the same orbit – and uncertainties like deviations caused by weather or climatic conditions and the stability in the reflections of the single points. Thus, with nowadays techniques, deflection controls can only be given after a few weeks of delay and within a certain (impressively small) scattering range.

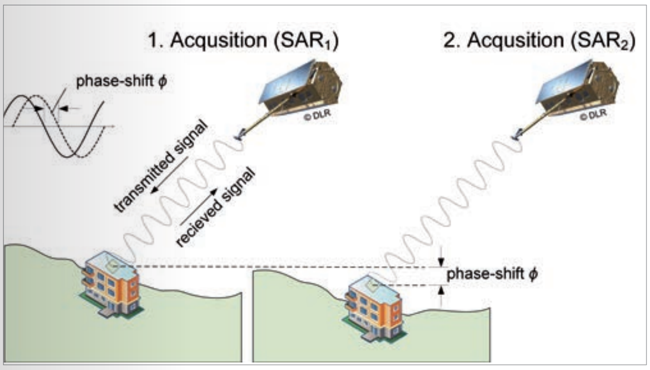

Figure 2: Principle of Interferometric SAR in displacement monitoring, acc. to [2]

Today, measuring and evaluation methods usually take about 20 to 50 single radar images to achieve the favored high accuracies from stochastic evaluations. Then, atmospheric disturbances can be eliminated to a large extent – weather conditions are often separately input – in order to generate a complete time series of settlements [3, 4]. Furthermore, stable reflection properties (coherence) are required over the total period of observation. As such requirements are often not fully satisfied, Ferretti et al. [5] have developed a remedy, namely the so-called persistent scatterer technique, often referred to by the Permanent Scatterer Interferometry (PSInSAR$^{TM}$). Here, local points with stable backscattering properties, so they behave geometrically stable as well as over time, are called persistent scatterers (PS). Such points usually lie on facades, roofs, window borders, steel elements etc. Areas of vegetation and moving objects (e.g. vehicles) make interferometric analysis difficult or even impossible.

### 2.2 The monitoring project Wehrhahn-Linie, Düsseldorf

For the radar interferometric monitoring at the subway construction site Wehrhahn-Linie, 24 records of TerraSAR-X radar images were provided by the DLR for scientific use. These images were recorded during the major shield tunnelling activities and made available by raw data in the period from January till December 2011 using the so called descending mode, orbit 63, characteristic strip mode and recorded with HH-polarization. They achieved a ground resolution of up to 3 x 3 m.

After processing the data a list of intensively reflective pixels, the so called active Persistent Scatterers (PS), is derived [5]. **Figure 3** illustrates about 16,000 such PS which are detected in the sphere of influence for the TBM drive in the eastern branch from the starting shaft at the Corneliusplatz near the center of Düsseldorf to the destination at the Wehrhahn, located in westerly direction after about 1,000 m of drilling. The observation area is characterized by classical 2 to 4 storage houses built of masonry for living, administrative or business purposes, mostly erected in the last 4 to 10 decades, whereas the actual tunnel with a diameter of almost 10 m and about the same amount of overburden lies under a main street and crosses several initially prebuild stations with lateral concrete walls. The colors of the PS in **Figure 3** correspond to the maximum value of a settlement during the overall process. Observed deflections in LOS remain small in a range of -10 to +10 mm. So settlements (positive signs) as well as uplifts (negative signs) were detecting, the latter arising e.g. intentionally from local compensation injections performed in advance to the TBM actions.

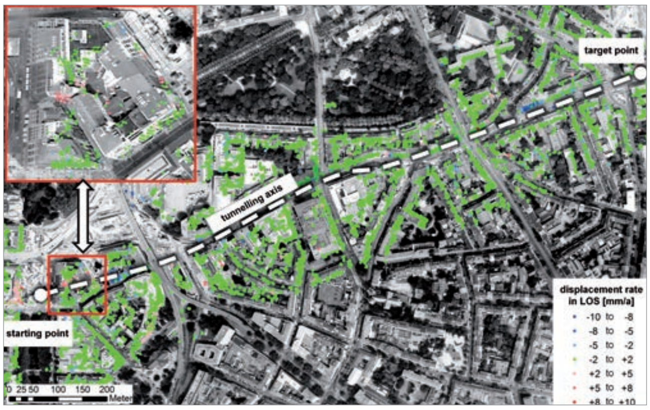

Figure 3: Aerial map of the eastern branch of the Wehrhahn-Linie in the state capital city of North-Rhine Westfalia Düsseldorf, Germany with displacement-rates in LOS (mm/year), acc. to [6]

Disruptions and temporary disturbances, such as conflicts with other commercial or scientific TerraSAR-X users in the area of interest created unwanted, but unavoidable gaps in the time series. Generally, increases in data gaps also increase the risk of possible de-correlations. For the present example, this implies that at the 24 recorded scenes in Düsseldorf the time intervals between 2 data points in the time series do not necessarily correspond in all the cases to the 11 day satellite repetition rate, giving rise to at least minor de-correlation effects due to data gaps.

### 2.3 Accuracy analysis of settlement data

To verify and to validate the measures [7] a comparison of radar-based and terrestrial measurements is suggested. Terrestrial methods (TER) at the Wehrhahn-Linie include distributed tube level measurements at buildings at their foundations as well as classical greenfield evaluations using levelling techniques. For the sake of simplicity, terrestrial data with proven accuracies in a submillimeter range are considered to be of true value without calculative deviations or scatter [8]. So deviations are only addressed to space-born values.

Generally, PS and TER differ in their exact ground coordinates, height as well as in their time of record. So strictly speaking, there are no comparable couples or pairs at all. To overcome this, corridors in space (ground coordinates) and time (record within a given time period) are introduced. Couples within a given ground range (2 by 2, 5 by 5 or 10 by 10 m) that do only slightly differ in their time of record (2 days, 5 days) are then considered to have the "same" place and time. The analyses are implemented in spreadsheet form applying VBA (Visual Basic for Applications) in Microsoft Excel.

Doing so, the number of identified pairs along 1 km of tunnelling varies between about 23,000 (10 m and 5 days) and 1,900 (2 m and 2 days). Altogether, approximately 400,000 readings, both terrestrial and satellite-based, were recorded throughout the shield drive of 11 month [7]. **Figure 4** illustrates 2 results of the extended stochastic evaluations by normalized frequency distributions with space corridors of 10 x 10 m (left, I.) and 5 x 5 m (right, II.) and corresponding time corridors of 5 days (I.) and 2 days (II.), respectively. The distributions already visually shape like normal distributions and cluster around a difference of 0 between PS and TER. As expected, scatter increases with an increase of corridors [8] resulting in a more compact shape within the second graph. A standard deviation of about ±1.5 mm can be derived there underlining a remarkable accuracy of the space-born measurements having in mind the assumed simplifications within the analyses.

## 3 Visualization in 3D space

Amount and complexity of the available data ask for suitable techniques for illustration and displaying the transient process of settlements as well as interactions to existing buildings or the TBM data (**Figure 7**). Chart forms appear uneconomic and ineffective. A visualization technique within the virtual lab of the chair of Computing in Engineering at the Ruhr-University Bochum, Germany was therefore chosen. The visualization brings together a 3D city model of the adjacent building area of Düsseldorf, geometric as well as material data of soil, tunnel and machinery, process and simulation data as well as mea-

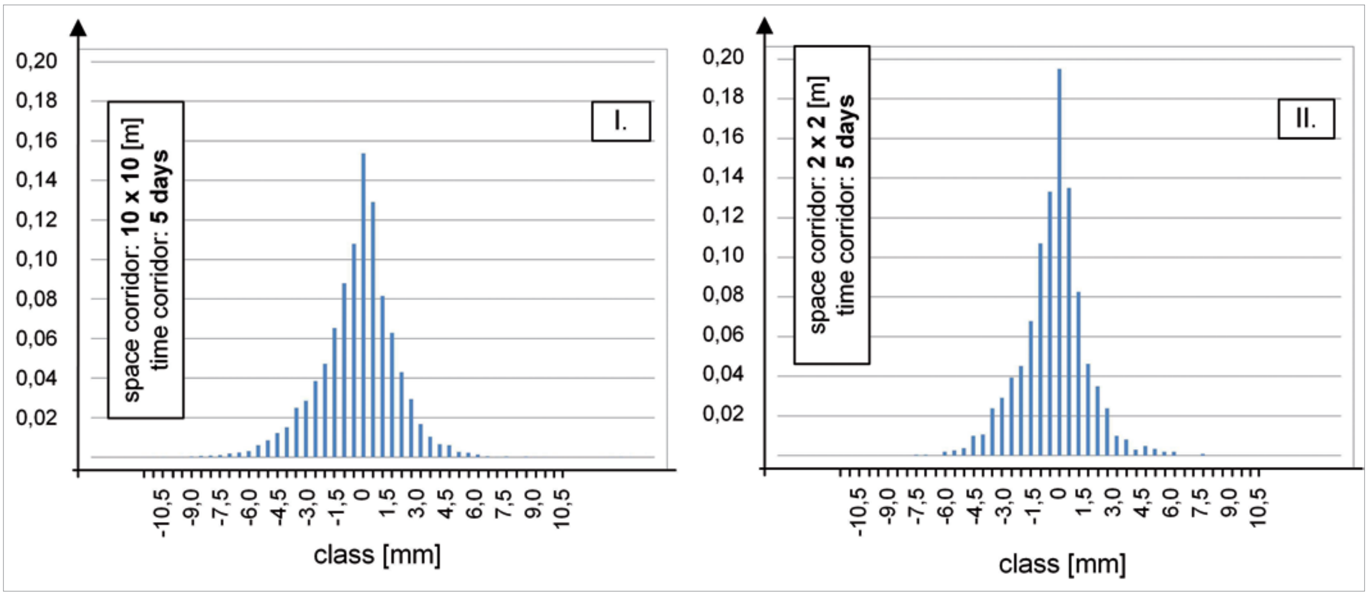

Figure 4: Frequency distributions of differences between PSI and terrestrial measurements, acc. to [9]

sured data like settlements, climatic influences and others. One major aspect of this overlapping is an initial assimilation of row data in their overall type, coordinate and specification systems as well as data format. Second, suitable ways of displaying must be identified, usually using point-oriented and color-coded settlement visualizations [10, 11].

**Figure 5** shows a typical example viewing in the direction of the TBM drive, where the PS can be easily recognized by single spheres in their spatial location predominately at the facades. It represents one point in time of the drive. Colors describe the extent of actual settlements ranging from blue (uplifts) to red (settlements) ones.

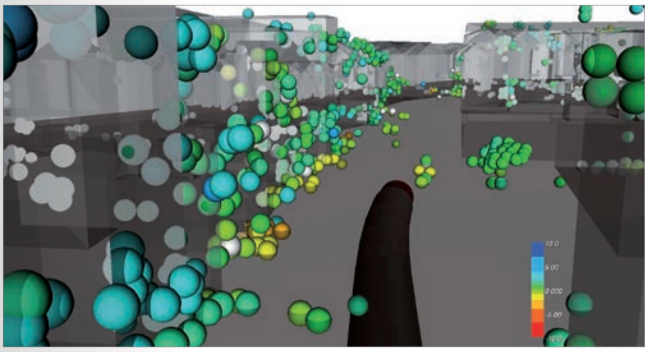

Figure 5: Point-oriented and color-coded settlement visualization of PSI data [10]

However, visualization techniques nowadays can go far beyond pure displaying purposes. They might also serve for detailed data analyses like accuracy controls or interaction checks.

**Figure 6** shows such an example for an accuracy analysis comparing PSI and TER measurements at a single building in their deviations relative to geometric locations in ground view [9]. The predefined TER points almost uniformly distribute over the ground slab, whereas the PS localize on front and roof of the building in the inclined LOS of the satellite. Deviations (Δps) mainly occur at front and right border of the building, where interactions of subsoil and building play a major role. TER close to the soil and PS high above at the facades also differ here due to additional solid body motions and stiffness effects of the building. However, deviations are still of small extent.

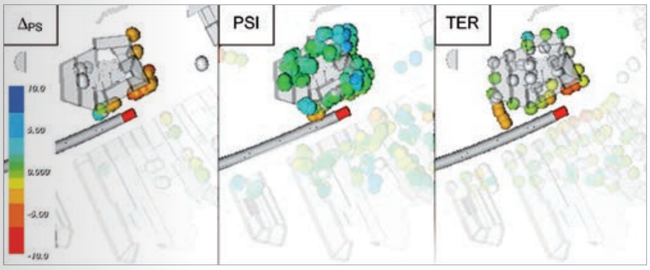

Figure 6: Example of a visual accuracy analysis, acc. to [9]

**Figure 7** gives an example for illustrated interactions. It shows a specific position of the TBM with strongly increased thrust forces – plotted within the grey-lined graph over the length of the drive (bottom left side) – and a slight heaving of the surface (zoom box with blue colored spheres). At the actual position – highlighted by the green line in the graph – a stiff, slurry injected concrete wall had to be overcome by the TBM giving rise to increased jack forces and small local surface heavings [10].

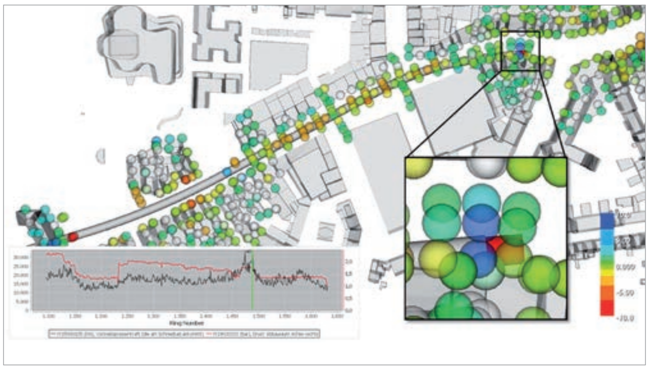

Figure 7: Settlement visualization correlated to TBM data: local surface uplifts (box) and corresponding increased thrust forces (graph), acc. to [10]

## 4 Conclusions

High-resolution radar monitoring from satellites, combined with controlling conventional terrestrial measurements, provide a very practical, economical and effective approach to observe settlements in large areas. They will surely increase their field of applications in the near future. Usual intra-urban buildings show a suitable back-scattering ability of the radar waves rather than vegetation, where supplemental reflectors need to be placed. So the method is very applicable for subway and tunnelling projects in cities. Due to the current repetition rate of

11 days, real-time monitoring is not (yet) implemented, but a subsequent and holistic control.

Visualization techniques are strongly needed to completely take advantage of the immense set of data. They can illustratively show transient processes like developments in settlements or tunnelling data, serve as an evaluation tool for accuracy analysis or even provide evidence for complex interaction behaviors like soil-structure-interactions or combinations of different data sets. Difficult interactive processes get easier to access, understand and finally to control yielding a safer tunnelling.

## 5 Acknowledgements

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