Determination of the Long-Term Ground Surface Displacements Using a PSI Technique—Case Study on Wrocław (Poland)

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Abstract: Wrocław is a major city located in the southwestern part of Poland in an aseismic tectonic fault zone. Slow, long-term, vertical displacements have been observed there from the 1930s based on the levelling network measurements with the use of a precise levelling method. Due to the high cost of classic surveys, these were performed at intervals of several decades and the most recent measurement of ground surface displacement was performed in 1999. The main aim of this study is to determine the ground surface displacements on the area of Wrocław in the 1995–2019 period, the spatio-temporal analysis of deformations and the identification of the potential factors causing these deformations. To determine the ground movements, an advanced PSI technique and data from ERS-2, Envisat, and Sentinel-1 sensors were used. Application of SAR technology for the first time in this area, provided new knowledge about the process of deformation in short time intervals over the entire area of the city. The results verify the hypothesis on the linearity of displacements obtained from historical geodetic observations. The obtained results show that the displacements, which continue to occur in the area of Wrocław have a cyclic character with 4–5 year long period of subsidence and 2–3 year long periods of stabilization or uplift. The displacement trends indicate that the area of the city gradually subsides in relation to the reference area located on the Fore-Sudetic Block.

Keywords: PSI technique; multi-SAR sensors; subsidence; urban area; the Middle Odra Fault Zone

1. Introduction

Satellite SAR (Synthetic Aperture Radar) interferometry (InSAR) is a modern technique used for generation of digital elevation models (DEM), deformation estimation using differential interferometry (DInSAR) and estimation of surface deformation applied to time series analysis using multitemporal InSAR techniques (PSI, SBAS). It has the potential to provide ground surface deformation rate with millimetre accuracy [1]. The DInSAR technique is suitable in the analysis of single deformation episode caused by rapid movements of the earth’s crust [2] and has limitations related to temporal and geometric decorrelations, estimation of phase unwrapping, estimation of phase ambiguity and reduction of the atmospheric component. Because of the need to process many SAR images and the above-mentioned limitations, more advanced InSAR techniques are used. These techniques also
known as advanced differential interferometry synthetic aperture radar techniques (A-DInSAR) [3] use two main categories of backscatter [4]: Persistent Scatterers (PS) and Distributed Scatterers (DS). PS is characterized by high signal-to-noise ratio and usually occurs as a single pixel. Most often, it is the dominant scatterer (e.g., trihedral engineering object, plane, rock) in the resolution cell. Persistent scatterers exhibit stable amplitude and signal phase in all images [5]. Persistent scatterers (PS) are typically infrastructure objects and buildings and therefore their spatial distribution is usually irregular and might show high and low density values in different parts of urban area. DS have mean or low signal-to-noise ratio and are analyzed if they form a homogeneous group of pixels. DS are a sufficiently large group of adjacent pixels having a similar scattering mechanism and noise can be statistically mitigated. Usually, these are pixels with many small scatterers or similar size (e.g., natural scatterers like forests, agricultural fields, arid areas with low vegetation). The term Persistent Scatterers Interferometry (PSI) is used to refer to various techniques based on PSs, DSs and other hybrid approaches [6]. The main outcomes of a PSI are time series of displacement values and velocities of displacements over the analysed PSs or DSs. In the PSI technique, the interferograms are formed between one common image (master image) and each of the other images (slave images) in the stack. However, it is related to the extension of temporal baseline and the temporal decorrelation. The first PSI algorithms were developed by Ferretti et al. [1,7], which were patented under the trademark PSInSAR. In the following years, further modifications of this technique were created and adapted to various applications. Among the various modifications, new solutions such as the STUN algorithm developed by Kampes [8] and an approach adapted to monitor volcanoes and other natural areas called StaMPS (Stanford Method for PS) developed by Hooper et al. [9] can be mentioned. StaMPS allows joint processing of PS and DS. In 2011, Ferretti et al. also proposed an extension of the PSInSAR(TM) algorithm under the name SqueeSAR(TM) including DS processing. Berardino et al. [10] proposed a different approach assuming the formation of possible combinations of interferograms from SAR images stack. Datasets characterized by relatively small spatial distances between orbits referred as small baselines (SB) separated by large baselines form a common system of equations solved by the Singular Value Decomposition (SVD) method and the criterion of the minimum norm of the displacement velocity vector.

The InSAR method is commonly employed to investigate ground surface displacements due to tectonic movements [11–13], volcanic activity [14,15], mining and post mining activities [16,17], landslide processes [2,11,18,19] as well as land subsidence due to intensive groundwater extraction [20,21]. The displacements caused by the above processes are significantly greater than their calculation errors and they can be determined on the basis of a small number of images acquired at relatively short time intervals[15]. Displacement measurements in urban areas require precision on the order of millimeters and thus a significant number of publications focus on verifying the results of InSAR measurements with the use of classic in-situ methods. Hanssen et al. [22] researched the possibility of employing PSI in the area of Amsterdam to monitor the changes in elevation differences along a new underground line. In their study, elevation differences proved consistent with ground truth (tachymetry) data within the range of standard deviation up to 3 mm/yr. Precision on the order of millimeters was also obtained for the LOS (Line of Sight) displacement measurements performed with PSI in the area of Bucharest [23]. The displacements were compared with the displacement vectors obtained in the GNSS measurements along the vector consistent with the LOS direction. Ground surface displacement trends in the area of Bucharest were determined with the use of multi-temporal and multi-sensor InSAR. A detailed analysis of the accuracy of the InSAR method was carried out by Casu et al. [24] in the area of Los Angeles by comparing vertical displacements determined by InSAR (SBAS approach), GPS and levelling methods. Standards deviations of the difference between SAR and LOS—projected levelling and LOS—projected GPS measurements were 4.3 mm and 5.6 mm, respectively. A completely different approach based on qualitative assessment was proposed by Nicodemo et al. [25] using the compliance of displacement direction test obtained from SAR (LOS projected along vertical direction) and leveling measurements.
The compliance obtained in the area of Schiedam (The Netherlands) was 80% with a sample of 180 benchmarks.

Bakon et al. [26] presented the results of ground deformation survey performed for the area of Bratislava (Slovakia), over a period of 24 years, with the use of several SAR platforms (ERS-1/2, Envisat, Radarsat-2, Sentinel-1A, TerraSAR-X). The publication also included a proposal to integrate results from the multi-sensor InSAR for the monitoring of engineering objects. Karila et al. [27] performed a detailed comparison of building displacement velocities obtained using PSI with the displacements determined using precise levelling method for the area of Turku in Finland. The authors demonstrated the applicability of PSI in establishing building displacement trends with the use of data provided by the ERS and ENVISAT satellites. However, they also pointed to the problem of determining and identifying the PS accurately and the need to verify PS results with classic measurements. Displacements and velocities obtained with InSAR methods are also used in cause-effect models. Peduto et al. [28] developed a multi-scale analysis of building damage based on DInSAR data on densely urbanized areas of southwestern portion of the Netherlands including geo-lithological properties, building in-situ damage survey and building characteristic. In turn, Cigna et al. [20] presented the use of InSAR data to assess the risk of geological hazard in combination with tectonic movements, Quaternary sediment compaction, and groundwater extraction.

The main aim of the study is to determine the ground surface displacements on the area of Wroclaw in the 1995–2019 period, the spatio-temporal analysis of deformation and to identify the main factors causing deformations. To determine the displacement, an advanced PSI technique was used to develop data from ERS-2, Envisat and Sentinel-1 sensors. This work is a continuation and development of research conducted in the area of the city. It provides the first results on the process of deformation in short time intervals based on the use of SAR technology. The obtained results verify the hypothesis on the linearity of displacements obtained from historical geodetic observations.

2. Characteristics of the Research Area

The city of Wroclaw is situated in southwest Poland (Figure 1) on the Silesian Lowlands and covers an area of 293 km². The Odra River flows through the centre of the analyzed area.

Figure 1. Location of the research area.
The Odra river valley is parallel to the main tectonic dislocations in Lower Silesia, i.e., the Sudetic Marginal Fault, the main dislocation zone of the middle Odra and the Hamburg–Kraków fault (Figure 2). In the southern part of the Wrocław area, in the sub-Cenozoic bedrock, the main fault of the middle Odra runs in the NW-SE direction [29]. The drop of metamorphic rocks on this fault exceeds 1500 m. It is assumed that in the Neogene the amplitude of downthrow exceeded 150 m [30]. Metamorphic rocks on the Fore-Sudetic block belong to several units: Middle Odra Complex, Kamieniec Ząbkowicki Unit, and Śleza Ophiolite Complex [29]. The boundaries between these metamorphic complexes are generally in the direction of NNE-SSW. In the western part of Wrocław, the Lower Permian sandstones and siltstones are exposed in the sub-Cenozoic bedrock. Sandstones of lower and middle (unseparated) triassic age occur also in the eastern part up to the Fore-Sudetic Block. They dip towards the north at an angle of 5 degrees. Triassic rocks are strongly dislocated, creating small tectonic horts and grabens. Elevation differences of these structures exceed 50 m. In the SE part, beyond the boundaries of Wrocław, Upper Cretaceous formations occur in a tectonic graben. In the area of Brzeg, under the Cenozoic deposits, there is a horst made of Triassic sediments. In the Neogene, the area of Wrocław was in the axis of the Central European Subsidence Zone [31].

Inferring from the difference in the thickness of the Neogene deposits lying on the Fore-Sudetic Block and on the Fore-Sudetic Homocline, it can be concluded that vertical movements in the Middle Odra Fault Zone had an amplitude of 50 to 180 m. These movements had greater amplitude in the eastern part, and smaller in the western.

Figure 2. Sub-Quaternary topography with location of faults determined by Cymermann [29] and modified by Badura et al. [30].

In the Tertiary sediments, a pentagon-shaped graben with a 40 to 60 m thick glacial deposits is clearly marked (Figure 2). It partially coincides with the structure named by [32] the Wrocław Through.

On the basis of a small number of boreholes, Różycki [32] placed this structure only in its SE part. The genesis of this structure, which looks like a tectonic graben, is not unequivocally explained. Undoubtedly, the unit’s SW frames are closely related to the Middle Odra Fault, whereas, its northern
end is located in the zone of the presumed fault of Trzebnica [33]. The eastern boundaries of the Wrocław basin reach the Mosina–Oleśnica–Brzeg fault, which to the north of Trzebnickie Hills, is already a narrow tectonic fault. There is a subglacial gutter (Oleśnica tunnel) up to 160 m deep in the zone of this fault. In the western part of Wrocław, the boundary of the sub-quaternary basin does not coincide with known faults. It cannot be ruled out that this is because of interpretation based only on differences in height of stratigraphically different Triassic sediments with sub-quaternary morphology. Indirect hydrographic evidence confirms the possibility of increased subsidence in Wrocław. These include the so-called Wrocław water node, where four tributaries flow into the Odra River on a small stretch. Another indication is a strong tendency of the Odra River to create many channels indicating the anastomosing character of this river in Wrocław, an increased subsidence rate related to the exploitation of underground waters has been demonstrated in [34]. Research carried out later showed that, after changes in industrial processes that reduced demand for water, the rate of subsidence caused by the depression cone decreased [35].

The southeastern part of Poland is an aseismic region with vertical ground surface displacements in the range of a few millimeters per year. The displacements were determined on the basis of levelling performed at intervals of several years. The oldest documented levelling measurements from 1879–1882 and 1948–1956 in this part of Poland showed large-scale vertical movements up to +1 mm/yr [36]. Another historical study based on measurements from 1953–1958 and 1974–1975 [37] showed values from −2 mm/yr to +0.5 mm/yr, while the last vertical velocity map developed on the basis of levelling measurements from 1974–1975 and 1998–1999 shows values of approx. −3 mm/yr [38]. In turn, the vertical movement velocity map of the Earth’s crust in the area of Poland based on the GNSS data in the 2008–2012 period shows values of approx. +1 mm/yr [39].

In Wrocław, the levelling control network has been measured with the use of precise levelling method since the 1930s, at 30-year intervals. These measurements constituted a basis for establishing the ground surface displacements, which occurred in the area of Wrocław between 1930 and 1998 [34,40]. Vertical displacements in the area of the city were measured against the adjacent geological structures between 1956 and 1999 [41] on the basis of national precise levelling lines. The research revealed that the whole city area is subjected to subsiding movement in relation to the adjacent geological structures. The purpose of the current research is to evaluate ground surface displacements in the area of Wrocław after 1999, to determine the time series. The first research on ground surface displacements in the Middle Odra Fault Zone investigated vertical displacements observable in the area of Wrocław and covered the 1930–1968 [40] and 1968–1998 [34] periods. The results of these studies revealed that the relative vertical displacements in the area of the city reach −9 cm in the 1930–1998 period. During 68 years, the structure and area of the local levelling network underwent changes, so these studies were based on independent groups of points only partially overlapping. In the following research [42], an analysis of relative vertical displacements in the 1930–1998 period was conducted. It was based on a set of 319 common benchmarks. In the 1930–1968 period, the maximum displacement between points in the central, southern and northeastern part of the city compared to points in the southwestern part reached −34 mm (Figure 3). In the 1968–1998 period, this value reached −76 mm (Figure 4), and over the entire 68-year period −93 mm (Figure 5). Based on previous studies, it was assumed that the specified parts of the city undergo relative displacements with a mainly linear trend.
Figure 3. Relative vertical displacements in the 1930–1968 period [42].

Figure 4. Relative vertical displacements in the 1968–1998 period [42].
Therefore, the scope of research was expanded to include the areas outside the city and outside the Middle Odra Fault Zone. Based on the changes of the elevation differences in the national precise levelling lines for the period of 1956–1999, a conclusion was made that the whole area of Wrocław subsides in relation to the adjacent geological areas marked by the tectonic fault lines [43]. The borders of the subsiding trough are consistent with the north and south borders of the Middle Odra Fault Zone. Due to a relatively limited number of measurement points (benchmarks) and limited measurement frequency, determining a spatial model for vertical displacements was impossible.

Between 2008 and 2012, another research project focused on horizontal displacements in the network of 12 GNSS points in the Middle Odra Fault Zone (Wrocław is located in the center of a network of GNSS points). The estimated horizontal displacements in the area of Wrocław are approximately $-0.5 \text{ mm/yr/100 km}$ in the SW-NE direction and $+0.5 \text{ mm/yr/100 km}$ in the perpendicular [43–45]. Preliminary research on the application of PSI to a fragment of the Wrocław area was performed by [46] as part of the GEO-IN-SAR project, which covered selected areas in Poland. Mean LOS displacement values in the analysed fragment of the area of Wrocław were calculated at $-2 \text{ mm/yr}$ for the 1992 to 2001 period.

3. Data and Methodology

3.1. SAR Data

To determine the surface displacements in the research area, SAR images acquired by the ERS-2, Envisat and Sentinel-1A satellites were used (Table 1).

Figure 5. Relative vertical displacements in the 1930–1998 period [42].
Table 1. Characteristic of the SAR data used in calculations.

| Satellite | Track | Pass     | Years        | Master Image | Number of Scenes | Spatial Baseline (m) | Time Baseline (Days) |
|-----------|-------|----------|--------------|--------------|------------------|----------------------|----------------------|
| ERS-2     | 36    | Ascending| 1995–2004   | 22.04.1999   | 55               | <800                 | <365                 |
| Envisat   | 186   | Descending| 2002–2008   | 11.01.2004   | 21               | <700                 | <365                 |
| Sentinel-1A| 73    | Descending| 2014–2019   | 09.10.2016   | 52               | <150                 | <180                 |

InSAR stacks from the longest observation period of nine years was selected from ERS-2 data. Observation period for the Envisat data set is seven years, while, for the Sentinel-1A satellite, it is 5 years. Over the past 24 years (1995–2019), SAR sensors (ERS, Envisat, Sentinel-1A) and the method of data acquisition were changed, which resulted in the increase of SAR images quality. For the ERS-2 and Envisat satellites, the spatial baseline is no larger than 800 m, while the time baseline is not greater than 365 days. The frequency of SAR images acquisition by Sentinel-1A is much higher and has a timespan of no longer than seven days. In the research, a time baseline of no more than 90 days was assumed and a spatial baseline no greater than 150 m, which was sufficient to achieve the objectives. The data were made available by European Space Agency.

3.2. PSI Technique and Data Processing

The approach proposed by Hooper et al. [9] can increase the number of PS in natural areas by identification based on phase characteristics and finding points of low amplitude with a stable phase. This algorithm also uses the spatial correlation of the phases rather than phase history. The residual phase value of pixel \( x \) and the interferogram \( i \) contain the sum of five components:

\[
\phi_{x,i} = \phi_{def,x,i} + \phi_{\alpha,x,i} + \phi_{orb,x,i} + \phi_{\epsilon,x,i} + n_{x,i}
\]  

where:

- \( \phi_{def} \)—phase change due to terrain deformation,
- \( \phi_{\alpha} \)—phase change due to atmospheric contribution,
- \( \phi_{orb} \)—phase due to orbit inaccuracies,
- \( \phi_{\epsilon} \)—the residual topographic phase due to error in the DEM,
- \( n \)—phase noise.

For the mean phase value in the radius \( L \) for pixel \( x \), it can write:

\[
\bar{\phi}_{x,i} = \bar{\phi}_{def,x,i} + \bar{\phi}_{\alpha,x,i} + \bar{\phi}_{orb,x,i} + \bar{n}'_{x,i}
\]  

The difference of Equations (1) and (2) give:

\[
\phi_{x,i} - \bar{\phi}_{x,i} = \phi_{\epsilon,x,i} + n_{x,i} - \bar{n}'_{x,i}
\]  

where \( \bar{n}' = \pi + (\bar{\phi}_{def} - \phi_{def}) + (\bar{\phi}_{\alpha} - \phi_{\alpha}) + (\bar{\phi}_{orb} - \phi_{orb}) \).

The residual topographic phase is proportional to the perpendicular component of the baseline \( B \)

\[
\phi_{\epsilon,x,i} = B \perp_{x,i} \cdot K_{\epsilon,i}
\]  

where \( K \) is a proportional constant estimated in the sense of least squares. For each pixel, \( x \) is defined as a measure based on temporal coherence:

\[
\gamma_x = (1/N) \left| \sum_{i=1}^{N} \exp(j(\phi_{x,i} - \bar{\phi}_{x,i} - \phi_{\epsilon,x,i})) \right|
\]
At the beginning of the algorithm, candidates for PS are identified on the basis of amplitude dispersion with a high threshold value of 0.4. In the neighborhood of each candidate, the mean phase values (Equation (2)) of the other candidates are calculated and estimate $K$ and $\gamma_x$. In subsequent iterations, candidates with low $\gamma_x$ are removed and are recalculated the means based on the remaining candidates and $\gamma_x$ for each candidate. The $\gamma_x^*$ threshold that maximizes the number of PS is determined statistically. More details are contained in the Hooper et al. [9].

The ERS-2 and Envisat data were processed with the StaMPS scripts [15], in the DORIS and Matlab environments [47,48]. Phase unwrapping was performed with the Snaphu ver. 1.4.2 application [49]. Wave phase correction in relation to ground surface was performed with the SRTM-C (3") model [50]. To process Sentinel-1A SAR data, the GMTSAR software [51] was used to calculate the interferograms, whereas the calculation of displacements using the PSI technique was carried out with the StaMPS.

The processed series of radar images provided mean values of displacement velocities for persistent scatterers in the direction towards the satellite (LOS velocity in mm/yr). The reference system was adjusted to a set of points having similar displacement values. Without the use of SAR corner reflectors integrated with the GNSS station, it is not possible to determine a reliable absolute reference system. Displacements are determined in a relative system, in which relative movements between individual parts of the research area can be determined or the regions of the largest gradients of change can be indicated. Relative displacements can be determined in reference to point or reference location (points inside the given circle radius) with assumption of zero displacements [20] in the sense of least squares. The relative values of the calculated LOS velocity were determined in relationship to the PS points located within the circle of 2.5 km. These points were selected near the benchmarks of national levelling lines analyzed in previous studies [41]. These area were stable in the 1956–1999 period. The distance between benchmarks outside the built-up area is in the range of 1.5–2.5 km. It was assumed that at least three benchmarks should be included in the reference area, which after next levelling network measurement will allow comparison of results obtained from SAR. It was aimed at finding the changes, which occur in the area of Wroclaw, located in the Middle Odra Fault Zone, in relationship to the reference area of the Fore Sudetic Block.

4. Results

For all the analyzed sets of SAR images, the number of PS points is proportional to the urban density. PS density is the highest in the city center and gradually decreases with increasing distance from the city center. The highest density of PS points on the research area was obtained for the Sentinel-1A stack, while the smallest for the ERS-2. This is due to the lower quality of ERS-2 SAR images, as well as the long observation period of nine years. With the increase in the length of the observation period, there are factors affecting the decorrelation of radar signal, which lead to a reduction in the number of PS.

Mean displacements velocities (LOS) calculated for ERS-2 stack for the period 1995–2004 ranged from $-3.5$ to $+1.3$ mm/yr (Figure 6). For most of the area, negative displacements prevailed, while positive displacements occurred in a compact sub-area in the southern and central parts of the city and are dispersed in the northeastern part.
Figure 6. LOS velocities determined on the basis of ERS-2 data for the period 1995–2004.

In the next period of 2002–2008, displacements velocities (LOS) determined from the Envisat InSAR stack ranged from $-5.5 \text{ mm/yr}$ to $+0.9 \text{ mm/yr}$ (Figure 7). Positive displacements were recorded in several places in the northeastern part, while negative displacements occurred on the remaining area.

Figure 7. LOS velocities determined on the basis of Envisat data for the period 2002–2008.
For the Sentinel-1A SAR stack in the period 2014–2018, the average LOS displacement velocities ranged from \(-2.9\) mm/yr to \(+2.4\) mm/yr (Figure 8). Positive movements occurred in the southern and southwestern part, while the remaining area was subjected to negative movements.

**Figure 8.** LOS velocities determined on the basis of Sentinel-1A data for the period 2014–2018.

The presented maps of displacement velocities indicate subsidence of the prevalent city area and periodic uplift in the southern part. The results confirm the continuation of the subsidence process documented by classical measurements [41]. In order to describe the ground surface deformation process in time for each InSAR stack, LOS displacements were determined for every epoch of data acquisition. Based on historical maps of displacements (Figures 3–5) and taking into account the coverage with PS points, several characteristic places marked from P1 to P10 (in Figures 6–8) were selected. In these places, the average value of LOS displacements for PS points inside a circle with a radius of 250 m were calculated and presented in Figures 9–11. Points P1–P10 have been selected in representative locations in the city, the selection criteria included: the history of displacements in the period 1930–1998 (Figures 3–5), the occurrence of benchmarks of the levelling network, and the presence of PS points for all the analyzed periods and sensors. The radius of 250 m is connected with the distance between benchmarks in Wrocław, which is in the range of 150–250 m. It was assumed that at least three benchmarks should be included in the reference area, which, after the next levelling network measurement, will allow comparison of results obtained from SAR. Calculating average values for persistent scatterers located in the surface units has been suggested by Bakon et al. [26] for development of displacement map on the basis of data obtained from the multisensor InSAR for the area of Bratislava.

The processing of ERS-2 observations in the period 1995–2003 revealed increasing negative LOS displacements in the period 1995–2000 for the most of analyzed elementary fields and change to positive in 2000–2002 period (Figure 9). After 2002, LOS displacements are varied.
In the next period, 2002–2006 results of Envisat data analysis indicated increased negative LOS displacements and after 2006 displacements probably stabilized or changed trend to positive (Figure 10). There is no possibility of unambiguous assessment due to the end of observation of this area carried out by the Envisat satellite in 2008.

Relatively short period of displacements of Sentinel-1A observations show negative value increments in the 2014–2016 period (Figure 11). In the period 2016–2018, processing of satellite data revealed positive displacements in the southern part of the city.

Figure 9. LOS displacements in the 1995–2003 period—ERS-2.

Figure 10. LOS displacements in the 2002–2008 period—Envisat.

Figure 11. LOS displacements in the 2014–2019 period—Sentinel-1A.

5. Discussion

The presented results of analyses spanning the years 1995 to 2019 show 4–5 year periods of negative displacements and 2–3 year period of stabilization or positive displacements. After periods of relative stability, there are longer periods with relatively higher values of negative displacements. Therefore, analysis of levelling network epoch measurements performed every few decades presented in Ferenc [40], Grzempowski and MAKOLSKI [42], and Grzempowski et al. [41] show mainly subsidence in the city area. Due to the possible oscillatory nature of these movements, mean values of LOS displacement velocities may change in particular periods of observation. Periodic oscillations are
mainly visible in the development of ERS-2 SAR images, while the data from the other sensors give only partial information, as they cover relatively short periods of 4 and 6 years. In addition, there is a gap of six years between Envisat and Sentinel-1A observations. The values of displacements in the overlapping observation periods of ERS-2 and Envisat show some differences, which are the result of different reference systems. The observations of these sensor were developed independently, so each of the InSAR stacks has a different spatial and temporal reference. Vertical displacements are assumed to have the greatest influence on the obtained results. However, the signal is deflected from surfaces inclined at various angles (e.g., squares, building roofs, chimneys, etc.) and, as a result, displacements of different directions have been obtained for the selected surrounding area. Some studies described in literature have been aimed at identifying PS points with regard to spatial information, which includes data on buildings, road infrastructure, etc., as well as at classifying and interpreting these points with regard to the types of objects identified as PS points [52]. Interpreting the velocities of PS points is problematic due to various types of scatterers and deformations. The determined displacement of PS points may be the consequence of the displacement of the subsoil and movement of the building structures, which are the sources of reflection [53]. Proposal for detailed interpretation of the PSI data in combination with geospatial data was presented by Gehlot et al. [52]. This approach requires access to detailed GIS databases. Additional problems may occur when attempting to unambiguously identify the PS points and to find their precise location [27].

Potential factors causing deformations in the studied area include: slow, large-area deformations associated with tectonic movements covering the region of southwestern Poland, compaction of Cenozoic deposits, and local factors related to development of large constructions projects. The geodynamic research in the region of south-western Poland [45] indicates intraplate horizontal displacements causing compression in the SW-NE direction, tension in the NW-SE direction and negative vertical displacements on the most part of the area. The GNSS epoch observations were carried out in the network consisting of several dozen of points, while geometric levelling measurements were done in the National Levelling Network at intervals of at least 25 years. The relatively small number of these points on the research area and its surroundings made it impossible to accurately assess the surface deformation process of individual parts of the city with results of geodetic measurements. Until now, a constant rate of horizontal intra-plate displacements and deformations at the 0.5 mm/yr/100 km and a mean vertical displacements rate of approx. −2 mm/yr were assumed on the city area. The presented current measurements of displacements using InSAR technique made with higher temporal and spatial resolutions indicate predominant periods of ground surface subsidence with periodic 2–3 year stabilization or uplift. The deformations of the ground on the city area have continuous character. There are no significant increases in the value of displacements in the surroundings of tectonic faults. However, it should be noted that possible movements on tectonic faults can be suppressed by 250 m thick cover of Cenozoic deposits. The sediments in the majority of the research area are alternating layers of clays, sands and boulder clays, which may undergo compaction processes. The displacements can also be affected by complex ground-water conditions. Cenozoic sediments include the 10–20 m thick sands layers that constitute confined aquifers whose condition is not monitored.

Historical data on vertical displacements in the area of Wroclaw [42] for the period of 1930–1998 (Figure 5) and changes in Polish precise levelling lines [41] for the period of 1956–2000 show noticeable differences in displacements between the southwest and the northeast parts of the city.

The past 20 years saw an intensive development of new road infrastructure and residential housing projects in the city outskirts. Corine Land Cover change [54] database for the periods of 1990–2000, 2000–2006, 2006–2012 and 2012–2018 was used to identify potential causes of man-made displacements that may influence results of SAR data processing (Figure 12). The CORINE Land Cover (CLC) is a systematized data set. It comprises the borders of areas classified into five main classes and three levels of hierarchy. In urban areas, ground surface deformations are significantly influenced by new of anthropogenic areas in the CLC database are shown in Table 2.
Table 2. Classes of anthropogenic areas with codes according to CORINE Land Cover.

| Level 1                          | Level 2                               | Level 3                                      |
|----------------------------------|---------------------------------------|----------------------------------------------|
| 1 Artificial surfaces            | 11 Urban fabric                       | 111 Continuous urban fabric                  |
|                                  |                                       | 112 Discontinuous urban fabric               |
| 12 Industrial, commercial and    | 121 Industrial or commercial units     |                                             |
| transport units                  | 122 Road and rail networks and         |                                             |
|                                  | associated land                       |                                             |
|                                  | 123 Port areas                        |                                             |
|                                  | 124 Airports                          |                                             |
| 13 Mine, dump and construction   | 131 Mineral extraction sites          |                                             |
| sites                            | 132 Dump sites                        |                                             |
|                                  | 133 Construction sites                |                                             |
| 14 Artificial, non-agricultural  | 141 Green urban areas                 |                                             |
| vegetated areas                  | 142 Sport and leisure facilities      |                                             |

Land use change in the area of Wrocław has been predominately the result of development and expansion of housing. Land cover changes in the period 1990–2018 within the city limits occurred only on the area of about 7%. Construction of the Wrocław Motorway Bypass was realized in the 2010–2013 period and could not affect the calculated displacement velocities. SAR images of the required quality are not available for the 2009–2013 period. Operation of the ERS-2 and Envisat satellites came to an end in 2011 and 2012 respectively, while Sentinel-1A was launched in April 2014.

Figure 12. Corine Land Cover (CLC) and land cover change in 2000–2018 on the Wrocław area.

6. Conclusions

The results of this research show the continuation of displacements in the area of Wrocław after the last levelling measurements in 1999. Based on previous research, the results are interpreted to be mainly vertical displacements, which were recorded since 1930, and are estimated at a velocity of up to 3 mm/yr. To a limited degree, the results may also be affected by horizontal displacements, whose intraplate velocities do not exceed 1 mm/yr. The calculated displacement values do not exceed
measurement accuracy estimated by other authors at 3 mm [22,27]. However, due to a relatively long observation period (1995–2002 and 2002–2008), as well as to a significant number of persistent scatterers and a standard deviation of 0.5–0.7 mm/yr, the following conclusions are justified:

- the displacements, which continue to occur in the area of Wrocław have a cyclic character with 4–5 years long period of subsidence and 2–3 years long periods of stabilization or uplifted.

- the displacement trends indicate that the area of the city gradually subsides in relation to the reference area located on the Fore-Sudetic Block.

In previous studies [34,41,43], it was assumed that, in the city area, there are subareas with permanent subsidence or uplift. Current research, in contrast to these assumptions, indicates periodic changes in direction of displacements.

Potential causes of the ground surface displacements include large-scale and long-term cyclical deformation and compaction of Cenozoic sediments. Surface displacements resulting from new infrastructures investment can influence deformation values locally, but their range and duration could not significantly affect the obtained results for the entire area. The cause-effect model development must be preceded by modelling and removal of periodic displacements.

For a detailed interpretation including tectonic factors, further research covering the entire area of southwestern Poland is required. This will demand solving several problems related to the conversion of LOS displacements into vertical displacements, integration of results from neighboring scenes, and integration of results from different sensors.

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**References**

1. Ferretti, A.; Prati, C.; Rocca, F. Permanent scatterers in SAR interferometry. *IEEE Trans. Geosci. Remote Sens.* **2001**, *39*, 8–20. doi:10.1109/36.898661.

2. Crosetto, M.; Gili, J.; Monserrat, A.; Cuevas-Gonzalez, M.; Corominas, J.; Serrah, D. Interferometric SAR monitoring of the Valcelebre landslide (Spain) using corner reflectors. *Nat. Hazards Earth Syst. Sci.* **2013**, *13*, 923–933. doi:10.5194/nhess-13-923-2013.

3. Mohammed, O.I.; Saeidi, V.; Pradhan, B.; Yusuf, Y.A. Advanced differential interferometry synthetic aperture radar techniques for deformation monitoring: A review on sensors and recent research development. *Geocarto Int.* **2014**, *29*, 536–553, doi:10.1080/10106049.2013.807305.

4. Even, M.; Schulz, K. InSAR Deformation Analysis with Distributed Scatterers: A Review Complemented by New Advances. *Remote Sens.* **2018**, *10*, 744. doi:10.3390/rs10050744.

5. Ferretti, A.; Savio, G.; Barzaghi, R.; Borghi, A.; Musazzi, S.; Novali, F.; Prati, C.; Rocca, F. Submillimeter accuracy of InSAR time series: experimental validation. *IEEE Trans. Geosci. Remote Sens.* **2007**, *45*, 1142–1153. doi:10.1109/TGRS.2007.894440.

6. Crosetto, M.; Monserrat, O.; Cuevas-Gonzalez, M.; Devanthery, N.; Crippa, B. Persistent Scatterer Interferometry: A review. *ISPRS J. Photogramm. Remote Sens.* **2016**, *115*, 78–89. doi:10.1016/j.isprsjprs.2015.10.011.
7. Ferretti, A.; Prati, C.; Rocca, F. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. *IEEE Trans. Geosci. Remote Sens.* **2000**, *38*, 2202–2212.

8. Kampes, B. *Radar Interferometry: Persistent Scatterer Technique*; Springer: Dordrecht, The Netherlands, 2006.

9. Hooper, A.; Zebker, H.; Segall, P.; Kampes, B. A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers. *Geophys. Res. Lett.* **2004**, *31*, doi:10.1029/2004GL021737.

10. Berardino, P.; Fornaro, G.; Lanari, R.; Sansosti, E. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Trans. Geosci. Remote Sens.* **2002**, *40*, 2375–2383. doi:10.1109/TGRS.2002.803792.

11. Colesanti, C.; Ferretti, A.; Prati, C.; Rocca, F. Monitoring landslides and tectonic motions with the Permanent Scatterers Technique. *Eng. Geol.* **2002**, *68*, 3–14.

12. Kutoglu, H.; Kemal dere, H.; Deguchi, T.; Berber, M. Discovering a pull-apart basin using InSAR in Bursa, Turkey. *Nat. Hazards* **2014**, *71*, 871–880. doi:10.1007/s11069-013-0938-x.

13. Reale, D.; Fornaro, G.; Member, S.; Pauciullo, A.; Zhu, X.; Member, S.; Bamler, R. Tomographic Imaging and Monitoring of Buildings With Very High Resolution SAR Data. *IEEE Geosci. Remote Sens. Lett.* **2011**, *8*, 661–665.

14. De Zeeuw-van Dalfsen, E.; Pedersen, R.; Hooper, A.; Sigmundsson, F. Subsidence of Askja caldera 2000–2009: Modelling of deformation processes at an extensional plate boundary, constrained by time series InSAR analysis. *J. Volcanol. Geothem. Res.* **2012**, *213*, 72–82. doi:10.1016/j.jvolgeores.2011.11.004.

15. Hooper, A.; Segall, P.; Zebker, H. Persistent scatterer InSAR for crustal deformation analysis, with application to Volcan Alcedo, Galapagos. *J. Geophys. Res.* **2007**, *112*, B07407, doi:10.1029/2006JB004763.

16. Samsonov, S.; d’Oreye, N.; Smets, B. Ground deformation associated with post-mining activity at the French-German border revealed by novel InSAR time series method. *J. Appl. Earth Obs. Geoinf.* **2013**, *23*, 142–154. doi:10.1016/j.jageo.2012.12.008.

17. Gee, D.; Sowter, A.; Novellino, A.; Marsh, S.; Guylas, J. Monitoring land motion due to natural gas extraction: Validation of the Intermittent SBAS (ISBAS) DInSAR algorithm over gas fields of North Holland, the Netherlands. *Mar. Pet. Geol.* **2016**, *77*, 1338–1354. doi:10.1016/j.marpetgeo.2016.08.014.

18. Peduto, D.; Ferlisi, S.; Nicodemo, G.; Reale, D.; Pisciotta, G.; Gullà, G. Empirical fragility and vulnerability curves for buildings exposed to slow-moving landslides at medium and large scales. *Landslides* **2017**, *14*, 1993–2007. doi:10.1007/s10346-017-0826-7.

19. Wasowski, J.; Bovenga, F. Investigating landslides and unstable slopes with satellite Multi Temporal Interferometry: Current issues and future perspectives. *Eng. Geol.* **2014**, *174*, 103–138. doi:10.1016/j.enggeo.2014.03.003.

20. Cigna, F.; Osmano, B.; Cabrál-cano, E.; Dixon, T.H.; Ávila-olivera, J.A.; Garduño-monroy, V.H.; Demets, C.; Wdowinski, S. Remote Sensing of Environment Monitoring land subsidence and its induced geological hazard with Synthetic Aperture Radar Interferometry: A case study in Morelia, Mexico. *Remote Sens. Environ.* **2012**, *117*, 146–161. doi:10.1016/j.rse.2011.09.005.

21. Bawden, G.W.; Thatcher, W.; Stein, R.S.; Hudnut, K.W.; Peltzer, G. Tectonic contraction across Los Angeles after removal of groundwater pumping effects. *Nature* **2001**, *412*, 812–815.

22. Hanssen, R.; Van Leijen, F.; Van Zwieten, G.; Dortland, S.; Bremmer, C.; Kleusbens, M. Validation of PSI Results of Alkmaar and Amsterdam within the TERRAFIRMA Validation Project. In Proceedings of the FRINGE 2007 Workshop, Frascati, Italy, 26–30 November 2007.

23. Armas, I.; Gheorghe, M.; Lendvai, M.; Dumitru, P.; Badescu, O.; Calin, A. InSAR validation based on GNSS measurements in Bucharest. *Int. J. Remote Sens.* **2016**, *37*, 5565–5580. doi:10.1080/01431161.2016.1244367.

24. Casu, F.; Manzo, M.; Lanari, R. A quantitative assessment of the SBAS algorithm performance for surface deformation retrieval from DInSAR data. *Remote Sens. Environ.* **2006**, *102*, 195–210. doi:10.1016/j.rse.2006.01.023.

25. Nicodemo, G.; Peduto, D.; Ferlisi, S. Investigating building settlements via very high resolution SAR sensors Investigating building settlements via very high resolution SAR sensors. In *Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure*; Taylor & Francis Group: London, UK, 2017.

26. Bakon, M.; Papco, J.; Perissin, D.; Sousa, J.; Lazecky, M. Multi-sensor InSAR Deformation Monitoring over Urban Area of Bratislava (Slovakia). *Procedia Comput. Sci.* **2016**, *100*, 1127–1134. doi:10.1016/j.procs.2016.09.265.
27. Karila, K.; Karjalainen, M.; Hyypia, J.; Koskinen, J.; Saaranen, V.; Rouhiainen, P. A comparison of precise leveling and persistent scatterer SAR interferometry for building subsidence rate measurement. ISPRS Int. J. Geo-Inf. 2013, 2, 797–816.

28. Peduto, D.; Nicodemo, G.; Maccabianii, J.; Ferlisi, S. Multi-scale analysis of settlement-induced building damage using damage surveys and DInSAR data: A case study in The Netherlands. Eng. Geol. 2017, 218, 117–133. doi:10.1016/j.enggeo.2016.12.018.

29. Cymerman, Z. Tectonic Map of the Sudetes and the Fore-Sudetic Block 1:200 000, 2nd ed.; Polish Geological Institute: Warsaw, Poland, 2010. (In Polish)

30. Badura, J.; Przybylski, B.; Zachowiecz, W. Cainozoic evolution of Lower Silesia, SW Poland: a new interpretation in the light of sub-Cainozoic and sub-Quaternary topography. Acta Geodyn. Geomater. 2004, 1, 7–29.

31. Aizberg, R.; Garetzky, R.; Karabanow, A.; Kockel, F.; Levkov, E.; Ludwig, A.; Lykke-Anderson, H.; Ostaficzuk, S.; Palijenko, V.; Schwab, G.; et al. Neotectonic structural subdivision (beginning of Oligocene until the Recent). Supplement to Brandenburgische Geowissenschaftliche Beiträge, 8, 1, respectively to Abb. Naturwiss 2001, 35, 8. (In German)

32. Różycki, M. Geological Structure of the Vicinity of Wrocław; Bulletin of The Polish Geological Institute no. 214; Bulletin of The Polish Geological Institute: Wrocław, Poland, 1968; pp.181–230. (In Polish with English Summ)

33. Badura, J.; Przybylski, B. Application of digital elevation models to geological and geomorphological studies-some examples. Pol. Geol. Rev. 2005, 53, 977–983. (In Polish)

34. Grzempowski, P.; Cacoń, S. Analysis and interpretation of vertical ground movements in Wrocław. Acta Mont. IRSM AS CR 2003, 24, 1–9.

35. Grzempowski, P.; Cacoń, S. The cause analysis of benchmark movements in the city of Wrocław. Rep. Geod. 2005, 3, 271–281.

36. Woźniak, J. Geodetic Methods for Investigations of Present-Day Vertical Movements Earth Crust Taking into Consideration Multiple Levelling Network in SW Poland. Ph.D. Thesis, Wroclaw University of Technology, Wroclaw, Poland, 1976.

37. Wyrzykowski, T. Map of Gradients of Velocity of the Recent Vertical Movements of Earth Crust Surface on the Territory of Poland; Institute of Geodesy and Cartography: Wrocław, Poland, 1985.

38. Kowalczyk, K. Modelling the vertical movements of the earth’s crust with the help of the collocation method. Rep. Geod. 2006, 2, 171–178.

39. Kontny, B.; Bogusz, J. Models of vertical movements of the Earth crust surface in the area of Poland derived from leveling and GNSS data. Acta Geodyn. Geomater. 2012, 9, 331–337.

40. Ferenc, J. The Studies of Ground Surface Vertical Movements in the City of Wrocław. Ph.D. Thesis, Wroclaw University of Technology, Wroclaw, Poland, 1979. (In Polish)

41. Grzempowski, P.; Badura, J.; Cacoń, S.; Przybylski, B. Recent vertical movements in the Wrocław section of the Middle Odra Fault Zone. Acta Geodyn. Geomater. 2009, 6, 339–349.

42. Grzempowski, P.; Makolski, K. The problem of validity of benchmark elevations for general engineering tasks in urbanised areas on the example of vertical benchmark network in the city of Wroclaw. Rep. Geod. 2007, 1, 91–102.

43. Grzempowski, P.; Badura, J.; Cacoń, S.; Kaplon, J.; Rohn, W.; Przybylski, B. Geodynamics of south-eastern part of the Central European Subsidence Zone. Acta Geodyn. Geomater. 2012, 9, 359–369.

44. Bogusz, J.; Figurski, M.; Kontny, B.; Grzempowski, P. Horizontal velocity field derived from EPN and ASG-EUPOS satellite data on the example of south-western part of Poland. Acta Geodyn. Geomater. 2012, 9, 349–357.

45. Kaplon, J.; Kontny, B.; Grzempowski, P.; Schenk, V.; Schenkova, Z.; Balek, J.; Holeovsky, J. Geosud/Sudeten Network GPS Data Reprocessing and Site Velocity Estimations. Acta Geodyn. Geomater. 2015, 11, 65–75.

46. Perski, Z.; Mróz, M. Application of SAR interferometric (InSAR) methods for the study of natural Earth surface displacements in Poland. GEO-IN-SAR project. Arch. Photogramm. Cartogr. Remote Sens. 2007, 17, 613–624. in Polish.

47. Kampes, B.; Usai, S. Doris: The Delft object-oriented Radar Interferometric Software. In Proceedings of the ITC 2nd ORS Symposium, Enschede, The Netherlands, 16–20 August 1999.
48. Kampes, B.; Hanssen, R.; Perski, Z. Radar Interferometry with Public Domain Tools. In Proceedings of the FRINGE 2003, Frascati, Italy, 1–5 December 2003.

49. Chen, C.W.; Zebker, H.A. Network approaches to two-dimensional phase unwrapping: Intractability and two new algorithms. *J. Opt. Soc. Am.* **2000**, *17*, 401–414. doi:10.1364/JOSAA.17.000401.

50. Farr, T.G.; Rosen, P.A.; Caro, E.; Crippen, R.; Duren, R.; Hensley, S.; Kobrick, M.; Paller, M.; Rodriguez, E.; Roth, L.; et al. The Shuttle Radar Topography Mission. *Rev. Geophys.* **2007**, *45*, RG2004, doi:10.1029/2005RG000183.

51. Sandwell, D.; Mellors, R.; Tong, X.; Wei, M.; Wessel, P. GMTSAR: An InSAR Processing System Based on Generic Mapping Tools; Scripps Institution of Oceanography: San Diego, CA, USA, 2011.

52. Gehlot, S.; Perski, Z.A.; Hanssen, R.F. Web-based framework for PS-INSAR data interpretation assisted by geo-spatial information fusion. In Proceedings of the ISPRS Mid-term Symposium Enschede, Enschede, The Netherlands, 8–11 May 2006.

53. Perski, Z.; Ketelaar, G.; Mróz, M. SAR Persistent Scatterers: Targets Characterization in Urbanized Areas with Envisat Alternating Polarisation Data. *Arch. Photogramm. Cartogr. Remote Sens.* **2006**, *16*, 467–482. (In Polish)

54. Büttner, G., CORINE Land Cover and Land Cover Change Products. In *Land Use and Land Cover Mapping in Europe: Practices & Trends*; Manakos, I., Braun, M., Eds.; Springer Netherlands: Dordrecht, The Netherlands, 2014; pp. 55–74. doi:10.1007/978-94-007-7969-3_5.

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