Remote sensing monitoring of influence of underground mining in the area of the S3 Express Road

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Abstract. Land subsidence is strongly associated with the activities of underground mines. Direct influence of exploitation lead to the formation of subsidence troughs, which are a common phenomenon in the Legnica-Glogow Copper Belt, in southwest Poland, where copper ore is currently intensively mined. As a result, the process of creating troughs may cause significant deformations in the surrounding urban infrastructure, including highways, bridges and railways. Satellite radar interferometry (InSAR), as a remote sensing method, appears to be a useful tool for detecting this type of extensive terrain surface change. Aim of this research was to detect the occurrence of displacements of the S3 Express Road section between the Glogow West Node and the Glogow South Node. For this purpose 29 images provided by European Space Agency (ESA) over descending orbit 22 was obtained from the Sentinel-1A satellite for the period from May 14, 2019 to April 26, 2020. Open source softwares has been used – GMTSAR to generate differential interferograms using the Persistent Scatterer Interferometry (PSI) method and Stanford Method for Persistent Scatterers (StaMPS) to process Persistent Scatterers (PS). The express road, as an anthropogenic object, is characterized by relatively high radar backscatter, thanks to which subsidence of the area are clearly noticeable and indicate the trend of long-term deformations.

1. Introduction

Intensive development of the methods of satellite radar interferometry over the past twenty years has enabled them to be used to observe surface displacements, including phenomena of both anthropogenic and natural origin. Especially the application of Persistent Scatterer Interferometry (PSI) or Small Baseline Subset (SBAS) techniques has contributed to advanced analyzes of existing displacements in time series and setting patterns that allow forecasting their future occurrence. Impact of the wide distribution of the applicability of the InSAR methods was also the expansion of the universe rich in new satellite missions. Increasingly shorter revisit time of the satellite and meter or sub-meter spatial resolution of SAR images has enabled more accurate research.

There are many examples in the literature of monitoring the behavior of urban areas using InSAR, in particular the Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) technique. The idea of PSInSAR is based on stable Persistent Scatterers, understood as permanently identifiable points on the Earth’s surface that have the ability to return much more energy than other objects. This means that the stable diffusers reflect most of the electromagnetic rays, and the amplitude and wave phase recorded after returning to the radar...
with a synthetic aperture show high stability compared to non-permanent scatterers. PS points are most often anthropogenic objects, such as roofs of buildings (reflecting rays directly back to the radar sensor) or linear structures such as bridges, roads, highways, railways, dams (causing double signal reflection - from each other and from the Earth’s surface). For this reason, the PSInSAR technique finds the widest application in built-up urban areas (see Table 1, the “Type of infrastructure” column).

Table 1. The use of Persistent Scatterer Interferometry to study the displacement of urban areas, depending on the type of infrastructure.

| Author and Data of Research | Type of Infrastructure | Location | Examples in Literature |
|-----------------------------|------------------------|----------|------------------------|
| Delgado Blasco et al., 2019 | road, bridge, airport runway | Rome, Italy | [1] |
| Milillo et al., 2019        | bridge                 | Genoa, Italy | [2] |
| Huang et al., 2018          | bridge                 | China     | [3] |
| Zhang et al., 2019          | railway                | China     | [4] |
| North et al., 2017          | road, railway          | UK        | [5] |
| Ciampalini et al., 2014     | building               | Sicily, Italy | [6] |

Satellite radar interferometry, including PSInSAR technique, is also a good alternative or complement to classical methods, including total stations geodetic levelling or the Global Navigation Satellite System (GNSS), used to determine changes in the terrain in areas of influence of underground mining. It can be used to detect ground displacements, as well as predictions of future impacts of exploitation, due to the ability to identify trends in the occurrence of deformation by long-term observation of the area. Many cases of PSI application in this type of mining area can be found in the literature, both for mines that actively exploit underground resources [7,8,9,10,11], as well as for those that have ceased operations and in whose areas secondary deformations occur [12,13].

In Poland, due to the intensive mining of copper ore in southwest Poland, a large part of the deformation in this region is its derivative. This, in turn, affects the subsidence of the surface and the formation of displacements and distortions of the above-mentioned objects such as buildings and infrastructure networks. For this reason, the area of Legnica-Glogow Copper Belt (LGOM) is constantly monitored with the use of, among others, precision leveling and satellite leveling. Research is also ongoing to implement remote sensing methods, including InSAR, into the surface deformation monitoring system. Great emphasis is placed on the analysis of long-term development of the subsidence troughs as well as displacements correlated with the seismic activity induced by underground mining activities. Induced tremors, which are relatively common in the LGOM area, lead to disturbances in the structure of the rock mass deep underground, which in turn results in deformation of the terrain surface. Both traditional Differential Synthetic Aperture Radar Interferometry (DInSAR) [14-17] and the techniques of the time series PSInSAR [18] and SBAS [19] were used to study the phenomena of occurrence of deformation in the area of LGOM.

In these studies it was decided to investigate the impact of underground mining exploitation manifested in the form of subsidence troughs on a fragment of the S3 Express Road, particularly the section between the Glogow West Node and the Glogow South Node. The research is motivated by the fact that underground mining in this area may have a negative impact on the road running through it, which is reflected in mining damage - bulges and cracks formed on the asphalt road surface.
1.1. Study Area
The research area, located in southwest Poland, includes a fragment of the S3 Express Road section between the Glogow West Node and the Glogow South Node, which is also included in the international route E65. Geologically, it is situated in the Fore-Sudetic Monocline and most importantly, from a mining point of view, it also runs through Legnica-Glogow Copper Belt, specifically the Sieroszowice mining area (Figure 1). In the LGOM region, rich in copper ore deposits, this raw material has been exploited for many years with the retreat room and pillar method with hydraulic backfill. In contrast to the system of decommissioning mining excavations with roof collapse, filling it with a hydraulic backfill significantly decreases the deformation of the ceiling, and thus reduces its subsidence and consequently impact on the surface. However, even the use of the most modern methods of mining and liquidation of excavations cannot completely exclude the formation of continuous and discontinuous surface deformations. It should also be mentioned that in the LGOM region the extraction depth is still increasing (currently it reaches even 1200 m), and thus the range of the impact of exploitation is also expanding.

Figure 1. Area of interest and selected Sentinel-1A scene for descending (D022) tracks. Black polygons denote borders of the mining areas and red polygon represents area where the S3 Express Road section passes. NASADEM Merged DEM Global 1 arc second used as background.

In the LGOM area subsidence troughs, which are the result of continuous deformation, are a common phenomenon. The process of their creation can significantly affect a road located within the range of mining influences, and thus lead to a change in its longitudinal and transverse profile, change in the stiffness of layers or deterioration of the pavement [20]. They are characterized by five main geometric values, such as vertical displacement (W), tilt (T), extension (ε), horizontal displacement (u) and curvature (K). For roads, the most important are vertical and horizontal displacement and tilt [21].
2. Materials and Methods

2.1. Datasets

In this study satellite images provided by European Space Agency (ESA), obtained using an onboard Synthetic Aperture Radar SAR operating on the C band (4-8 GHz) from the satellite mission Sentinel-1 were used. The Sentinel-1 mission is an improvement on earlier projects of this type, such as ESA missions ERS-1/2 and ENVISAT or Canadian RADARSAT-1/2. Its undoubted advantage is the ability to acquire data regardless of weather conditions, both during the day and at night, which is a serious limitation of passive remote sensing methods. One of two independent satellites belonging to the constellation - Sentinel-1A (12-days repeat cycle) (Table 2) was used, moving in descending orbit (D022) (Figure 1), providing a large number of acquisitions over the area of interest.

| Satellite | Start Data | End Data | Orbit | Path | Frame | Sub-Swath | Polarization |
|-----------|------------|----------|-------|------|-------|-----------|-------------|
| S1A       | 2019/05/14 | 2020/04/26 | Descending | 22   | 420   | IW2       | VV          |

The use of PSInSAR technique requires an appropriate amount of satellite images apply in calculations. A sufficient number that gives reliable results is 20-30 images [22]. In this study we used 29 images with an annual range of time from May 14, 2019 to April 26, 2020. As the master scene the display from November 22, 2019 was selected, centrally in relation to the temporal and spatial baseline (Figure 2). The sizes of spatial baselines are small, because all the images were obtained from one path - 22. However, this is not so important because the dimensions of Persistens Scatterers are smaller than the resolution of the SAR image cell. This eliminates the negative impact of decorrelations, which is a limitation of the traditional InSAR method [23].

Figure 2. The spatial and temporal baseline configuration of interferometric pairs showing the SLC data in this study (29 images).
2.2. Methodology

In the calculations, three main stages can be specified - initial processing of data to obtain differential interferograms, preliminary selection of PS candidates (PSC) for persistent scatterers and their export and basic work on the processing of PS (Figure 3). Before processing, from prepared data (29 satellite images) the master scene was selected with the help of the European Space Agency (ESA) SentinEL Application Platform (SNAP) software to provide the best interferometric configuration. For each image, Precise Orbit Ephemerides (POE) files containing accurate information about the current satellite position were also downloaded. A Digital Elevation Model (DEM) containing information on topography of the terrain was also necessary - in this case SRTM1 (30 m resolution) [24].

To generate differential interferograms, open source GMTSAR software was used, containing a set of scripts written in C and Generic Mapping Tools (GMT) to visualize the results [26]. The most important work steps can be included:

(i) Coregistration – adjustment of the slave scene geometry to the master scene.
(ii) Master-slave network – creating a list of connections between each slave scene and master scene.
(iii) DEM to radar coordinates – DEM geometry matching to master scene (reverse geocoding).
(iv) Interferograms computation – determination of the equation in the phases of individual pixels of both images.
(v) Topography removal – removal of the estimated topographic phase component from the interferometric phase (creation of differential interferograms).
(vi) Area subset – cutting the generated interferograms to the study area in order to reduce the time-consuming calculations.

Based on the generated interferograms, Persistent Scatterer Candidates was then determined. PSC selection was performed using Amplitude Dispersion Index. It means that for a single imaging pixel amplitude dispersion was defined as the ratio of its standard deviation to the mean value, which can be written as follows:

$$D_A \triangleq \frac{\sigma_A}{m_A}$$ (1)

where:

$\sigma_A$ – standard deviation of the amplitude value,
$m_A$ – average amplitude value.

The value $D_A$ for each pixel was compared with the initial limit value threshold (in this case 0.4 was assumed). If the value for a point was less than the set threshold value of the indicator, it was qualified as a potential PS point. Then GMTSAR results were converted in order to be processed by the StaMPS software [27].

The last calculation stage included the proper processing in the Stanford Method for Persistent Scatterers software. Persistent Scatterers Candidates were initialized to the Matlab environment using an appropriate script. Then phase noise value was determined for each PS candidates, which was used to identify the final PS points. Selected points underwent cleaning process and were also corrected for spatially-uncorrelated look angle (DEM) error. Phase unwrapping and filter steps were applied. Finally, spatially-correlated look angle (SCLA) error, master atmosphere and orbit error were estimated. Each of steps is described in detail in the StaMPS User Manual [25].
Figure 3. Schematic diagram presenting data preparation, generation of interferograms (GMTSAR), conversion and export (GMTSAR into StaMPS) and processing of PS points (StaMPS) [25].
3. Results and Discussion
Based on the calculations, 850 021 PS points were obtained in the entire study area. In borders of the mining area the average displacement rate determined for them amounts to -48.6 to 23.1 mm/yr (Figure 4). The occurrence of terrain subsidence is closely related to the underground mining exploitation carried out in this region and its derivatives of subsidence troughs. Troughs in Figure 4 are well outlined and indicate the underlying deformation mechanism. The rate of displacement is fast considering that the study period is only one year. This means that changes occurring on the surface of the terrain can significantly affect the surrounding elements, cause deformations and lead to their damage, for example damage to the surface or structure of nearby roads. It should be noted that the results obtained using the InSAR methods should always be compared with the classic geodetic methods for determining displacements.

![Figure 4. Sentinel-1 average Line-Of-Sight (LOS) deformation rate map over the period May 14, 2019 – April 26, 2020. Red polygon represents area where the S3 Express Road section passes. NASADEM Merged DEM Global 1 arc second used as background.](image)

There is a definite density of PS points in urban areas such as cities (including Głogów, Polkowice, Lubin), where mainly buildings are an excellent basis for backscattering of radar signal, as well as well-observed patterns of roads, railways, paths, bridges along which PS points are evenly distributed. As the main area of interest is the S3 Express Road section between the Głogów West Node and the Głogów South Node, subsequently among all the PS points, the ones selected are on the primary and secondary roads in the area of research (Figure 5A). For this purpose, PS points and extracted OpenStreetMap shapefile layers (containing information about roads located in this area) available in [28] were imposed. This process made it possible to extract only the points corresponding to specific objects (in this case roads). The most significant surface subsidence was observed along the S3 Express Road, in particular in places where two
troughs occurred (marked in Figure 5 as B and C). Noticeably occurring terrain deformations resulting from mining operations interfere with the S3 Express Road and lead to its systematic lowering. The lower part of Figure 5 presents LOS displacements in these two main (B) and (C) areas in the time series. The largest displacement values reach up to about -30 mm/yr. On both of them can be seen a repetitive pattern of settling the road surface, which can be detected and observed using InSAR time series techniques.

![Figure 5](image)

**Figure 5.** Sentinel-1 average Line-Of-Sight (LOS) motion rates along primary and secondary road (A). LOS displacement time series on the S3 Express Road near the locations of the subsidence troughs (B, C).

Based on the obtained research results, it can be noticed that the PSInSAR time series technique can be successfully used in mining areas in order to detect mining damage on the ground or in construction. It makes it possible to register not only the subsidence or elevation of the ground surface caused by the downward movement of subsequent rock layers into the post-mining voids under the pressure of overlapping layers, but also their correlation with objects located in the mine’s area of influence and directly exposed to the impact of underground mining. Previous studies with the use of satellite radar interferometry in the LGOM area largely focused on the analysis of the occurring induced tremors using the differential satellite interferometry (DInSAR) method and thus determining the value and size of the displacement immediately after the event, which in fact has a great importance, but not fully illustrates the long-term changes that may occur in the infrastructure as a result of applied stresses. The nature of this research allows to determine the displacements undergone by a particular type of infrastructure.
(in this case, part of the road) as a result of mining operation conducted by the correlation of subsidence troughs of the course of the above-mentioned construction.

4. Conclusions
We used the PSInSAR technique to detect LOS displacements that occured on the S3 Express Road section between the Glogow West Node and the Glogow South Node in the period from May 14, 2019 to April 26, 2020. For this purpose, 29 images from the Sentinel-1A satellite, free softwares - GMTSAR and StaMPS and a set of scripts enabling the conversion of results between them were used. We compared the obtained results with the OpenStreetMap shapefile containing information on the route of roads in the studied area in order to select only the displacements that this type of infrastructure underwent. We have demonstrated the impact of underground mining on the road infrastructure, in particular in the areas of formation of subsidence troughs (the highest rate of displacement overlap reaching -30 mm/yr) and the possibility of using InSAR techniques to monitor changes in the road surface, with the emphasis that they should always be verified by classical geodetic methods of determining displacements.
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