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Application of Synthetic Aperture Radar Interferometry to monitor surface deformations of the Trans-European Transport Network (TEN-T) – A case study of the motorways crossing areas of mining operations in the Upper Silesian Coal Basin, Poland

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Abstract

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Keywords

mining activities, Interferometric Synthetic Aperture Radar, InSAR, road deformation, high-way

RESEARCH ARTICLE

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Abstract

Underground hard coal mining causes surface deformations. When the mining operations are conducted beneath linear objects, such as motorways, there is a risk of deformations of the axis of the road and its horizontal and vertical alignment (additional bends and vertical curvatures, longitudinal inclinations, deformations of cross-sections). In the areas subjected to mining operations, mining plants conduct geodetic monitoring. Due to their labour intensity and costs, geodetic measurements are usually made only a few times a year. The article discusses the possibility of applying Interferometric Synthetic Aperture Radar (InSAR) to monitor the subsidence of the vertical alignment of motorways caused by mining operations and its advantages and disadvantages compared to the currently used methods of geodetic measurements. The tests were conducted in two sections of motorways within the Upper Silesian Coal Basin (Poland) in the areas of intensive hard coal mining operations. Radar imaging of the surface made by the European Space Agency's (ESA) satellite Sentinel-1 equipped with the Synthetic Aperture Radar (SAR) was used.

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1. Introduction

In Poland's Upper Silesian Coal Basin area, there are located two transport corridors that play an essential role for Polish and European economy within the Trans-European Network for Transport (TEN-T). They are north-south motorway A1 (corridor no. III) and west-east motorway A4 (corridor no. IV). Both motorways cross mining areas. On a European scale, the Upper Silesian Coal Basin is a specific area, considering the extent of hard coal deposits and the time of their exploitation [1–3]. Mining operations have been conducted continuously in the area since the Middle Ages. Initially, to extract metal ores and, since the 18th century, hard coal [4,5]. Long-term exploitation of underground deposits located at different depths results in severe, often overlapping, deformations manifesting on the surface in the form of subsidences, inclinations and horizontal, compressive and tensile, deformations [6]. Such deformations have a significant negative influence on the surface infrastructure. Changes in the technical parameters of roads, especially of motorways (due to heavy traffic and high speeds), such as longitudinal and transverse cants of the vertical alignment caused by mining exploitation, negatively influence the comfort of travelling and the safety of users. The changes in longitudinal and

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transverse declines may disturb the process of draining the motorway surface.

Mining plants monitor surface deformations caused by mining operations through cyclical geodetic measurements (levelling) of geodesic benchmarks [7–9]. The points may be dispersed throughout the area (to monitor important objects, e.g. public buildings), grouped as, e.g. observation lines (applied to monitor linear objects, such as roads), or as strain gauge rosettes. Due to the width of a roadway, observation lines are often located on both sides of the road for motorways [10,11]. For the safety of drivers and passengers and geodetic teams conducting the measurements, observation lines are often located outside the road crown, along the boundaries of a roadway. Access to such places is limited as the motorway is fenced. Thus, the measurements are made from the areas adjacent to the motorway. The geodetic equipment (a level, a total station) has to be set in-situ, and measurements have to be made at each point along the observation line with a level staff or a prism rod. The line of sight is required between the instrument and the measured point. At least two people must operate the equipment who need access to the geodesic benchmarks (sometimes in difficult terrain and weather conditions).

The requirements presented above make geodetic monitoring an expensive task [12,13]. Hence mining plants make such measurements once a quarter, sometimes twice a year. Only comparing the results of two consecutive measurements provides information on the scale of the surface deformation [14]. By comparing the results of consecutive measurements with the reference measurement (made before mining operations), we obtain information about surface subsidence changes over time [15–17].

A viable alternative to geodetic monitoring is SAR Interferometry [18,19]. It is applied to observe changes in the elevation caused by various human activities like agriculture, mining operations (both open pit and underground), or natural phenomena occurring in the earth crust: landslides, tectonics [19,20].

Synthetic aperture radars the satellites are equipped with operate in a few microwave bands:

- X (frequency 12.5–8.0 GHz and wavelength 2.4–3.8 cm), e.g. satellite TerraSAR-X of the German Aerospace Centre (Deutsches Zentrum für Luft-und Raumfahrt, DLR),
- C (frequency 8.0–4.0 GHz and wavelength 3.8–7.5 cm), e.g. satellite Sentinel-1 of the European Space Agency (ESA), and
- L (frequency 2.0–1.0 GHz and wavelength 15.0–30.0 cm), e.g. satellite ALOS-2 of the Japan Aerospace Exploration Agency (JAXA).

Depending on their frequency, radar waves show different penetration through the cover, e.g. foliage or snow. The shorter the wavelength of radar radiation (e.g. X band), the more the signal gets dispersed on the surface of plants (tree leaves), and the less of the signal reaches the ground. Band L radar waves are mainly reflected by the surface independently on the foliage or snow cover.

Over the 30 years of applying SAR Interferometry, there have been developed different methods of processing obtained data. One of the first methods is Differential – InSAR (D-InSAR) In the method, data collected during two satellite passes over the same area [21,22]. The difference in phases of the signal reflected from the surface during the first and second passes gives us information about possible changes in the distance between the satellite and the ground. The difference results from changes in the area elevation and changing atmospheric conditions, differences in the trajectory of the satellite orbits in each pass, noise, and errors in data transmission and processing [23]. We can eliminate some of the undesirable factors or, at least, decrease their influence on the value of results obtained with the method. Nevertheless, atmospheric conditions' influence is the hardest to eliminate (virtually impossible to eliminate) in the D-InSAR method [23–25]. The error is caused by the difference in the speed of electromagnetic waves in the atmosphere at different water vapour contents. Although microwave radiation, unlike the visible spectrum, penetrates clouds, yet their variable thickness and the water vapour contents change the waves' speed. An ideal solution would be a pair of scenes taken by the satellite in identical weather conditions that are hard to do in practice [26].

Through processing the data obtained from two satellite passes of the same area, we receive an image, so-called interferogram, which, with a sequence of colours, presents information about differences in phases of the waves reflected from each point during given passes. If the value of surface subsidence is greater than the radar's wavelength, the interferogram contains additional sequences of fringes [27].

The differential method may be used for detecting and imaging surface deformations in the form of subsidence occurring between two passes of the satellite. The value of subsidence ought to then be comparable with the wavelength. For satellite

Sentinel-1, at the wavelength of 5.6 cm, it is assumed that the value of surface subsidence should be at least 1 cm between two passes, to visualise it in an interferogram.

Other methods which can reduce the negative influence of the atmosphere on the obtained results, and, at the same time, offer greater accuracy of measurements (of 1 mm over a few months) are Multitemporal InSAR methods, including the Small Baseline Subsets method (SBAS) [28]. More scenes are collected (at least 20 which, if the satellite passes every 12 days, requires collecting data for approximately eight months) and calculating interferograms are between given scenes. The algorithm selects pairs of scenes looking for compatibility between them. The method provides information on how the surface subsidence is accrued over time. By analysing data from many scenes, a proper algorithm can eliminate the influence of changes in the atmosphere. Hence the results obtained with the method are, to a great extent, free of the errors caused by changeable atmospheric conditions.

The article aims to show the possibility of applying SAR Interferometry (InSAR) for monitoring subsidence of the vertical alignment of motorways, caused by mining operations. The article also discusses its advantages and disadvantages compared with the geodetic method and compares the accuracy of the results obtained with both methods.

2. Materials and methods

Within the framework of the research, there were selected sections of motorways in Silesian (Poland), located in the vicinity of the places where, in the analysed period (between November 2015 and October 2017), there were observed effects of mining operations (the area of the Upper Silesian Coal Basin). The plants conducting the mining operations obtained the data from geodetic measurements of the surface deformations caused by mining operations. Then, we analysed the deformation index in the form of subsidence of the area by employing the SAR Interferometry method. The Small Baseline Subsets method (SBAS) was applied using radar images of the area (so-called scenes) made by the European Space Agency's (ESA) satellite, Sentinel-1, equipped with Synthetic Aperture Radar (SAR) [29,30]. A total number of 49 scenes were used in the analyses. The European Space Agency's constellation of SAR satellites consists of two units: Sentinel-1a and Sentinel-1b. Both of them fly over the same point every 12 days. Hence, employing images from both satellites makes it possible to shorten the time between the passes to six days. Satellites Sentinel-1 applied in the described tests use microwave band C of 5.6 cm wavelength [31]. The radar mounted on the satellite can work in various modes, switched automatically depending on the area it passes. The mode commonly used over the landmass provides the resolution (size of one pixel) of approximately 5×25 m. The scenes are available free of charge on the website of the European Space Agency.

3. Results and discussion

Figure 1 shows a result interferogram for the Upper Silesian Coal Basin (USCB) area obtained by processing scenes between 9 November 2015 and 23 October 2017. The boundaries of mining areas of given motorways A1 and A4 are marked. The multicolour areas shown in the figure reflect the surface deformations detected by the satellite in the period mentioned above.

Among the motorway sections preselected for tests, the fragment of motorway A1 near Bytom (Poland) (marked in the figure as XX) deserves special attention. A blow-up of the section of the motorway is presented in Fig. 2. In Figs. 1 and 2, the black lines contour the areas belonging to two Mining Plants (marked I and II), where hard coal mining operations were conducted, and the course of motorway A1 in the area.

The graphs of time and surface subsidence (along the motorway axis) are presented in Fig. 3. The abscissa presents the length of the subsidence profile along the motorway's axis and measured in metres [m]. The ordinate shows surface deformations (subsidence) measured along the satellite's Line of Sight (LOS) [32]. Given profiles visible in the graph show increasing deformations (subsidence) over time. They were acquired from given pairs of radar scenes made between 9 November 2015, and 23 October 2017. The graph obtained basing on satellite images may be compared with the graphs of surface subsidence obtained with geodetic measurements made in the same period along the observation lines along the motorway. Mining Plant I makes cyclical geodetic measurements along the observation lines. The line along the southern edge of the roadway (L-2) and the line located along the northern edge of A1 (L-3) are particularly interesting. For each of the observation lines, four measurements were made:

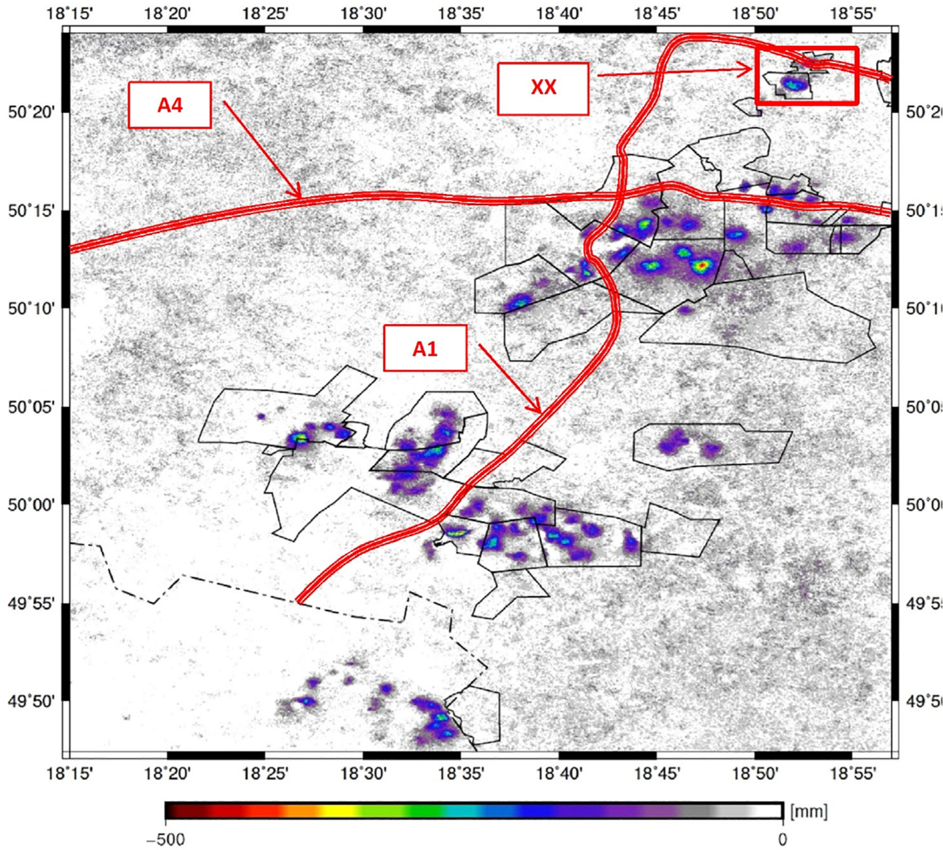

Fig. 1. Interferogram of the USCB surface deformations, 9 November 2015 – 23 October 2017.

– measurement 1, November 2016,
– measurement 2, January 2017,
– measurement 3, May 2017, and
– measurement 4, September 2017.

The results of surface subsidence measurements obtained with geodetic measurements were compared with the reference measurement made in August–September 2016. Figures 4 and 5 present the

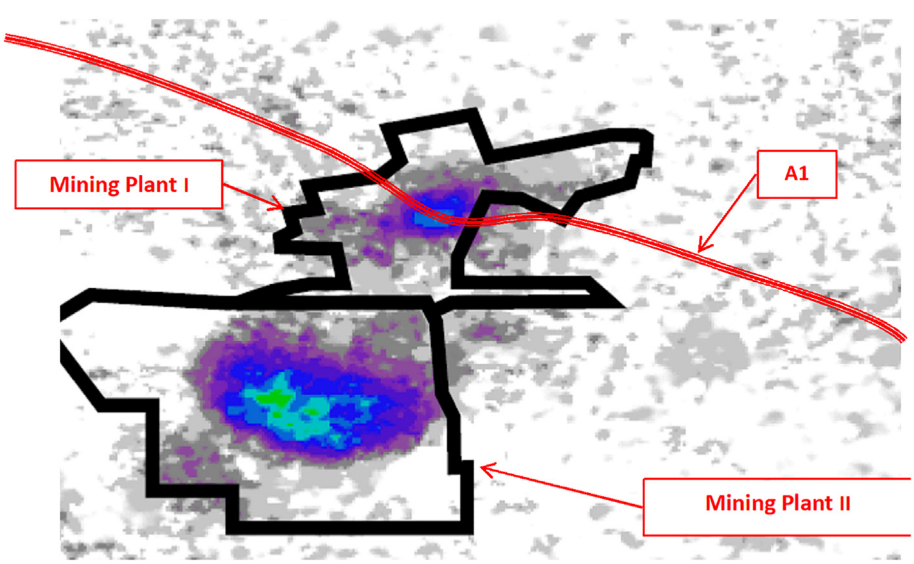

Fig. 2. Interferogram showing surface deformations near Bytom (Poland).

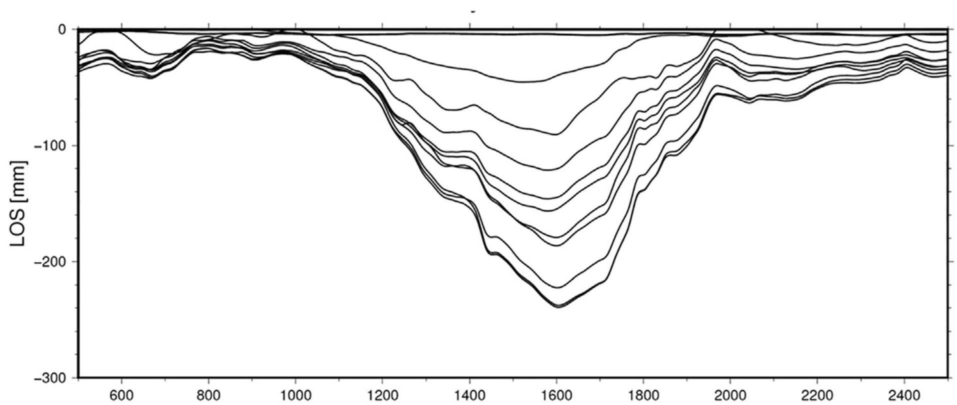

Fig. 3. Graph of surface subsidence along the axis of the motorway near Bytom (Poland).

differences in elevations of points along the observation lines for the four measurements for L-2 and L-3.

Comparing the graph of surface subsidence, obtained with SAR Interferometry method (Fig. 3) and the graphs of surface subsidence obtained with geodetic measurements along the observation lines located south (Fig. 4) and north (Fig. 5) of the motorway, a specific correlation was observed (Fig. 6).

It ought to be remembered there are significant differences resulting from applying different methods providing the results, as well as conditions and limitations of using them. The results obtained with geodetic measurements are undoubtedly precise and accurate. However, they are labour-consuming and require geodetic personnel on-site, which is costly. Hence, mining plants make such measurements every six months, sometimes every three months. Rarely are such measurements made more frequently. They can provide precise results, but only in the preselected points, stabilised adequately on the surface. The changes (surface deformations) which occur in other places can be only approximated based on the results of measurements in their vicinity. With the values of surface subsidence on both sides of the roadway, it is possible to conclude how the area in the crown behaves. However, it is not identical with the roadway's actual deformations and changes appearing on the roadway surface. The distance between the observation lines in the analysed motorway's section is approximately 70–80 m (depending on the embankment's height and the width of the roadway). While the results obtained with the SAR Interferometry method are collected from a specific area, it is divided into so-called 'pixels', i.e. the tiniest points characterising the resolution of the images provided by a satellite. For satellite Sentinel-1 of the European Space Agency (ESA) one ‘pixel’, in the mode most commonly used by the satellite, is between 2.7×22.5 m and 3.5×22.6 m, depending on the incidence angle. The shorter side is oriented towards the radar beam, i.e. more or less east-west,

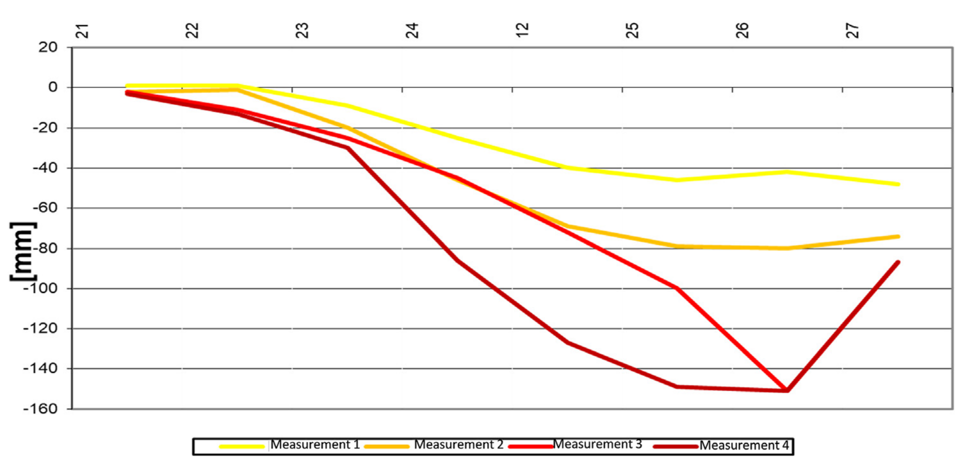

Fig. 4. Graph of surface subsidence along observation line L-2 (south).

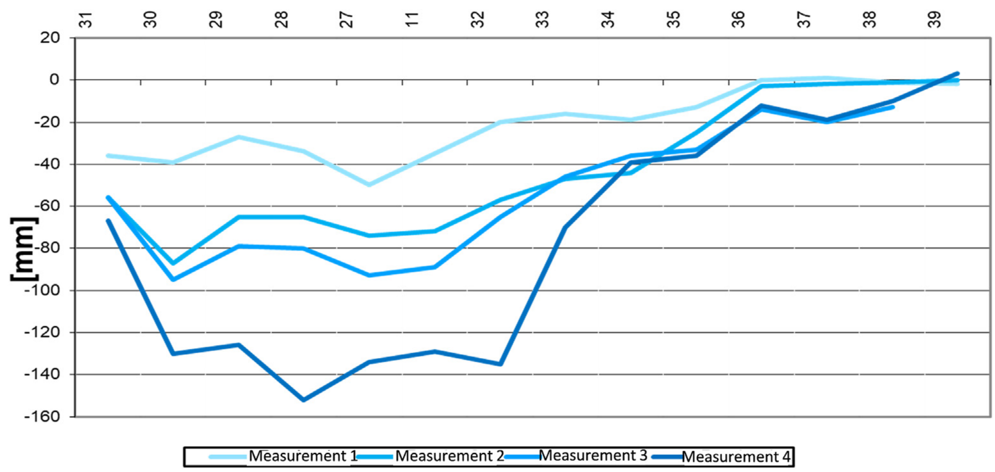

Fig. 5. Graph of surface subsidence along observation line L-3 (north).

while the longer one is oriented towards the direction of the satellite's motion, i.e. north-south. The gaps between 'pixels' are respectively 2.3 m east-west and 14.1 m north-south. It means that each pixel of satellite imaging contains average results of the area of approximately 3 × 22 m.

When we compare dimensions of a single 'pixel' with the width of one roadway, of approximately 11 m (for two lanes), or the width of the whole motorway crown, of approximately 30 m, it may be concluded that measurements of subsidence will be different for motorways oriented along meridians, and for motorways oriented along parallels. Motorway A1, generally goes north-south, however in the analysed section (area of Bytom, Poland), it goes parallelly. Figure 7 presents an example of a pixel arrangement in the analysed section of motorway A1.

Such an arrangement results in quite satisfying resolution along the motorway. The 'bottle neck' of the applied analysis is, in the analysed case, the transverse direction, as one pixel is twice as big as the width of the roadway. It means that the information about the elevation of a given point is an average result of the roadway, the median strip or the hard shoulder and the embankment. The roadway gives a relatively stable value of reflection (or rather dispersion) of the radar beam. In turn, the value of reflection for the median strip, hard shoulders and embankments, covered in foliage, differ, depending on the season, plant growth stage and maintenance works (mowing grass).

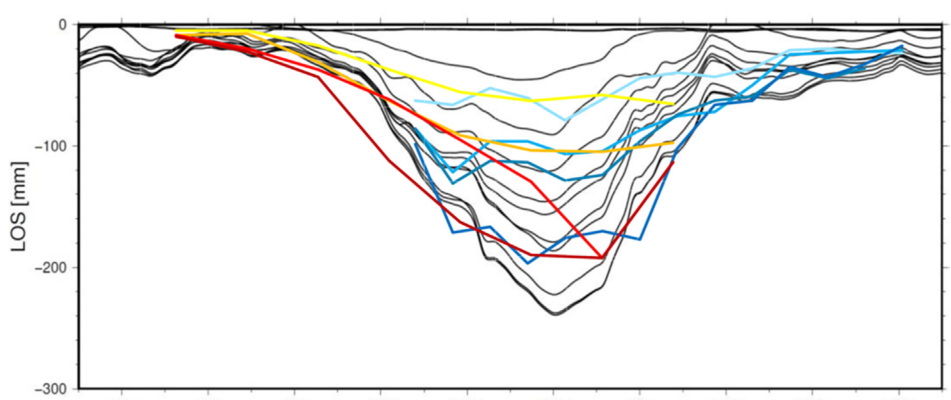

Fig. 6. Graphs of surface subsidence obtained with SAR Interferometry method (black lines) with the results of geodetic measurements along the observation lines: south (warm colours) and north (cool colours).

Fig. 7. Sample arrangement of pixels in the analysed section of motorway A1 Bytom (Poland).

A significant aspect of surface deformation measurements with SAR Interferometry is that there are available extensive databases of radar scenes collected by space agencies supervising the satellites. Thanks to them, any moment, we can check changes in the elevation in the area we are interested in, in a given time frame. It is impossible with geodetic monitoring.

4. Conclusions

In the areas affected by mining operations, mining plants conduct geodetic monitoring, enabling measurements of surface subsidence with up to 1 mm accuracy. However, geodetic monitoring is labour intensive and costly, which limits the number of measurements to just one quarterly. The article, basing on the measurements of sections of motorways affected by mining operations, shows that SAR Interferometry can also be applied to monitor subsidence in mining areas.

The D-InSAR method enables detection of surface subsidence, formed over a few days or weeks, with up to 1 cm accuracy. Slower increases in deformation over time may be detected with the Small Baseline Subsets method (SBAS). However, it requires a database of at least 20 scenes of a given area, collected for at least eight months. The method provides measurements of accruing surface subsidence over time with the accuracy of up to 1 mm/year, comparable with geodetic monitoring, conducted by mining plants.

SAR Interferometry enables determination of surface subsidence over a greater area than geodetic measurements, which are conducted only in the predetermined points. We also can 'rewind the time' and analyse again the areas that have not been taken into account before.

SAR Interferometry can be applied to monitor surface deformation in the Trans-European Transport Network (TEN-T), e.g. the motorways going through active mining areas. The method can improve people's safety driving motorways, as possible changes in the roadway's geometric parameters may be monitored even every six days, unlike with geodetic monitoring – quarterly.

A disadvantage of InSAR methods is presenting surface deformation results, as a 2-dimensional set of values. Each point of the obtained image represents the average value of a specific area of given dimensions. For the most commonly applied mode of satellite Sentinel-1, one pixel is 2.7×22.5 m. The gaps between pixels are 2.3×14.1 m. Such resolution cannot bring expected results monitoring objects like motorways in real-time when the object is as wide as one pixel. The results of subsidence measurements from the whole area in one pixel are averaged. The shortcoming can be eliminated by using, e.g. the data from commercial satellites, working at a different microwave band, such as TerraSAR-X, which offers the resolution of 3×3 m (one pixel). In such a case, the motorway is at least three pixels wide regardless of the motorway course.

Conflicts of interest

The authors declare no conflict of interest.

Ethical statement

The authors state that the research was conducted according to ethical standards.

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