THE APPLICATION OF SATELLITE RADAR INTERFEROMETRY TO THE EXAMINATION OF THE AREAS OF MINING EXPLOITATION

Edward Popiołek, Ryszard Hejmanowski, Artur Krawczyk
Department of Mining Area's Protection, University of Mining and Metallurgy, Faculty of Mine Surveying and Environmental Engineering, Adama Mickiewicza Ave 30, 30-059 KRAKÓW, artkraw@uci.agh.edu.pl, tel. 617 22 76

Zbigniew Perski
Department of Geological Mapping, Faculty of Earth Sciences, University of Silesia, UL. Będzińska 60, 41-200 SOSNOWIEC, perski@us.edu.pl, tel. 32 291 8381 extension 420, 206, fax 32 2915865

Satellite Radar Interferometry is a unique method making it possible to investigate land subsidence in precisely specified time and within exactly the same period of time, on the area of tens of thousands square kilometres simultaneously. So far in Poland, the above-mentioned method has been used on the underground coal mining excavation areas in the Upper Silesian Coal Region and on the underground copper excavation areas in the Legnicko-Głogowski Copper Region. The research has given information about the land subsidence, about its location, range and size. In other countries the method is mainly used to observe vertical terrain motions caused by underground water and oil exploitation. The paper presents the discussion on the application of the method in the research into the terrain deformation caused by drainage of rock mass.

1. Introduction

A constant development of remote sensing technology makes it possible to get more diverse information about phenomena, which used to be the focus of other scientific disciplines. One of such techniques is SAR (Synthetic Aperture Radar) Interferometry, InSAR in short. The image obtained thanks to this method (the interferogram) enables us to observe the height changes of the terrain surface. At first, interferograms were used to observe the movements of the Earth crust caused by the deformations of continental plates edges and earthquakes. The usefulness of the interferometric images in observation of the changes in the terrain of underground exploitation has been proved very early. The first research in Poland was undertaken in 1997 in the Industrial District of Upper Silesia (Perski 1998). This research confirmed a high veracity of the interferometric data and their exceptional usefulness in the environmental monitoring as well as in detecting the dynamics of land subsidence caused by underground mining exploitation. The next research was carried out on the copper ore exploitation field in the vicinity of Legnica (Krawczyk, Perski 2000). Presently the research is being carried out to establish the possibility of monitoring horizontal dislocations with multi-level drainage troughs.

2. Example 1, region of copper ore exploitation

2.1. The characteristics of the researched terrain

In the Legnicko-Głogowski Copper Region (LGOM,) there are seven mining fields where three mining establishments carry out exploitation. The total mining area of all the mines in LGOM occupies about 400 square km. Within the range of the immediate effects of mining exploitation there are two towns and several villages. To protect the town buildings and mine shafts, protecting pillars were set up. The copper ore exploitation, carried out since the early 60-ties has led to the appearance of subsidence troughs of the terrain caused by both the intensive underground exploitation and by the drainage of the rock mass. The size of the land
subidence in the LGOM over the areas of intensive exploitation carried out mainly according to pillar-chamber method with the breaking down of the roof reaches the average of 2000 to 2600 mm. The maximum land subsidence, 3380 mm was observed in the mining area "Polkowice II". The surveying as much as theoretical calculations indicate that the average rate of these type subsidences above the breaking down exploitation does not exceed 1,25 mm per twenty-four hours.

The subsidence caused by copper ore exploitation is also influenced by the height changes of the terrain surface brought on by the appearance of so-called multi-level drainage. The maximum land subsidence, measuring 710 mm, has been observed on the mining area 'Lubin I.' The maximum speed of the subsidence did not exceed 30 mm per year, which is 0,085 mm per 24 hours (Popiolek, 1997.) In practice, the estimated average subsidence caused by drainage is about 7 to 11 mm a year.

Until now the examination of the vertical shifts of the terrain have been done on the basis of the precise levelling (the main routes) in the net of height points covering the whole territory of the field. The height surveying is carried out on the basis of some height points on the area under the selected mining shafts. The mining areas of copper ore are also covered with the net of so-called 'measuring lines.'

2.2. The applied research methodology

The interferogram was processed from two SAR images acquired by ERS-1 satellite of the European Space Agency during repeat-pass observations. The obtaining of radar data by satellite ERS-1 consists of recording radar waves reflected back towards the SAR antenna. At the time when the SAR data are recorded, some information about the intensity of reflection of the backscattered radar wave as well as its phase are registered. The information about the intensity of the reflection in form of an image called radarogramme is useful in creating land-use maps. The information about the phase from two acquired scenes are used for interferogram processing. The interferogram archiving the differences between the phases of reflected waves on the same area but at different times is clearly presents information about phase changes. The interferometric image depicts the height changes of the terrain in the form of the interferometric fringes. The phase change visualised by a set of interferometric fringes which presenting e.g. a full phase cycle of 360° reflects about 2,8 cm of the height difference of the terrain which occurred in between the two data acqisotions. Due to the angle of the radar signal, the recorded subsidence of 2,8 cm measured along the direction of the signal towards the satellite corresponds to the subsidence of 2,58 cm of the vertical surface change.

2.3. The interferogram analysis

In the course of the research, mining exploitation data in the years 1960 - 1994 in the LGOM area as well as topographic maps of the scale 1:10000 were obtained.

On the basis of the data about the subsidence in the LGOM area, it was estimated that to obtain the first interferometric observations of the subsidence a two-month time base is required. In the course of the research, over the caving exploitation, subsidence troughs of an average subsidence of about 75 mm per 60 days should be observed (the maximum land subsidence should not exceed 150 mm per 60 days.) At the same time, the size of the drainage trough should reach the average of 1,5 mm per 60 days.

For the sake of analysis in the paper, two radarogrammes ERS SAR were selected according to the following criteria:

- dry weather conditions i.e. no snowfall and rainfall,
- interferometric baseline i.e. the distance between satellite positions during repeated observations did not exceeds 100m,
time-base 60 days.

According to the above-mentioned criteria two images SAR SLC were selected. A small size of the examined area led to the thorough research of only the south-east quarter of the full image.

*The profile of selected data:*

<table>
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<tr>
<th>Satellite: ERS - 1, data type: SAR SLC quarter</th>
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<tbody>
<tr>
<td>Satellite</td>
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ERS SAR data were processed using Earth View software (Antalntis, 1997). The small baseline (100m) and relatively flat terrain allowed us to neglect the influence of topography of the area on the interferometric image. However, in some part of the image, there is visible a so-called atmospheric effect i.e. a regional phase change. Nevertheless it does not influence the obtained results significantly (Fig 1.)

*Fig. 1 The number and the configuration of dynamic subsidence troughs*

Already the preliminary stage of the processing proved a high quality of the data, the coherence close to one.

In the first stage of processing, the whole quarter of the ordered SAR scene was processed without corrections. Obtained interferogram made it possible to locate where exactly the land subsidence occurred on the selected area. It was affirmed that the interferometric fringes caused by land subsidence appear only in the northern part what precisely correlates
with the range of the mining fields of the LGOM area. Finally, the area of 1580x1530 pixels was selected for detailed processing and analysis.

The next stage of the processing was comparing the radarogrammes with topographic maps and the interferogram with mining maps to correctly locate and interpret the obtained images. At this stage of the project, the coregistration of the interferometric image into the local co-ordinate system of mining data turned out to be a significant problem. This difficulty resulted mainly from the size of the pixel, 20 x 20 m, which presents much less accuracy than maps in the scale 1: 5,000 and 1: 10,000.

2.4. The comparative analysis of the interferogram and mining exploitation development

26 dynamic subsidence troughs have been located as a result of interferogram analysis. After the coregistration of the interferogram into the co-ordinate system a correlation analysis of the appearance of subsidence troughs with the excavation fields was made. As a consequence of the analysis it was determined that the centres of 24 subsidence troughs are located on the boundaries of the exploitations carried out in the 4th quarter of 1993 and the 1st quarter of 1994. Whereas the two minor subsidence troughs were located in the vicinity of old excavation fields. Four dynamic subsidence troughs were observed on the "OG Sieroszowice I" mining area. None of those troughs exceeded 70 mm per 60 days. Generally, the area of about 342.8 hectares subsided in the examined period.

In the area "OG Polkowice II,” 6 subsidence troughs number: 6, 13, 14, 20, 21, 22 and 12 were observed. On this mining area, the deepest dynamical subsidence trough is the subsidence trough no 21. It reached the subsidence of about 110 mm within 60 days. Figure 2 shows the discussed subsidence trough as well as the shape and the configuration of the excavation fields.

![Fig. 2 Subsidence trough no 21](image)

Subsidence trough no 21 as well as all the remaining subsidence troughs directly resulted from copper ore exploitation carried out at the turn of 1993.

However, one relatively shallow subsidence trough no 12 is not connected with the above-mentioned exploitation. This subsidence trough was created above the area of excavation done in the years 1976 - 1982 (Fig 3.) The fact that in 1994 in the immediate vicinity of the old
mining fields, the panelling of the seam was carried out to prepare a new excavation area used in the years 1995 - 1998, casts some light on the origin of subsidence trough no 12.

This piece of information allows us to formulate a hypothesis about the connection between the appearance of the discussed land subsidence with the preparation of a seam for exploitation and with the partial reactivation of the old mining fields.

In the mining area "OG Rudna I," 9 subsidence troughs were observed. Due to the exploitation in the protecting pillar of the town of Polkowice by the mine "Rudna," the rate of the subsidence increment within the area of the pillar was compared with the subsidence on the remaining areas around. According to the interferometric measurements, two dynamical slopes of the subsidence troughs no 10 and 11 were created due to the exploitation in the pillar. The average subsidence of these subsidence troughs amounted to about 25 mm per 60 days. All remaining subsidence troughs in the area "O/ZG Rudna I", the appearance of which directly results from the exploitation in the years 1993 - 1994, reached an average subsidence of over 50 mm per 60 days. Figure 4 below shows subsidence trough no 10.
Besides, in the discussing area between the shafts R-VII and R-IX, the largest as regard area, a single subsidence trough no 8 were observed. It measures approximately 199 hectares.

In the Mining Area "Lubin", the appearance of 6 dynamical slopes of the subsidence troughs numbers 16, 23, 24, 25 and 26 was observed. Only subsidence trough no 26 appeared in the boundary between the Mining Areas "Lubin I" and "Malomice I". Other interferogram subsidence troughs were formed within the limit of Mining Area "Lubin I". The subsidence trough number 23 is the deepest one. It reached the depth of about 110 mm within 60 days. In the Mining Area "Rudna II" and "Radwanice Wschód," no subsidence troughs were observed in the 1st quarter of 1994.

2.5. The conclusions of the research

1. The discussed measurement method of land subsidence can be classified as a non-geodetic measurement technique of permanent terrain deformations caused by the underground mining exploitation.
2. The fitting of the interferograms into the existing topographic and mining maps of the scale of 1:10,000 and bigger is very difficult to perform. More useful for this purpose are the maps of the scale of 1:25,000 and smaller ones.
3. Presently to interpret the whole area of the LGOM it is enough to obtain the 1/4 of the frame of ERS SAR image.
4. 24 dynamic slopes of subsidence troughs were observed, the origin of which is directly connected with the exploitation of the last quarter of 1993 and the first quarter of 1994.
5. All the observed subsidence troughs are suitable for further interpretation. Due to various kinds of land cultivation, especially because of woods, the subsidence troughs present different levels of difficulty of their interpretation.
6. The observed subsidence troughs over the exploitation area, where fall of roof system was used, during 2 months, reached a maximal value of approximately 110 mm per 60 days (1,83 mm/twenty – four hours) and didn't exceed an anticipated maximal value 2,5 mm/twenty – four hours.

3. Example 2, Upper Silesia

3.1. The range of the research

Owing to the wide range of SAR pictures, the regional analysis of the terrain deformation of the whole area of Upper Silesia (6000 sq km) was feasible. Since 1997 37 SAR images from 1992 to 2000 have been processed and analysed (Perski 2000). On the basis of the one of interferograms, the information about the configuration and the range of the areas that underwent subsidence in the period between Oct 4th 1992 and Nov 8th 1992 has been compiled. The analysis has been done using the Ilwis 2.2 system, as well as identification and the interpretation of the interferometric fringes caused by subsidence (Fig 5.) According to the analysis of the obtained image of the dynamics 143,15 sq km, what makes 8% of all the mining areas experienced some surface movements in October 1992, in Upper Silesia.
3.2 The interferometric image of mining subsidence of the city centre in Katowice and Muchowiec airport

The underground coal exploitation in steam 501 was carried out by KWK Katowice in the city centre in the years 1992 - 1996. The thickness of the exploited layer of the seam was 2.5 m. The exploitation was done at the depth of 300 m with three exploitation walls with hydraulic rock filling. The developing, dynamic slope of the subsidence trough was visible on the 35-days interferograms from 1992, 1993 and 1995 as elliptic concentration of interferometric fringes moving northwest. It was affirmed, that the area of the greatest increase of subsidence (about 2.57 cm per 35 days) in the centre of the ellipsis is located above the middle of the resultant exploitation mining front and is shifted back from it about 80 m i.e. an equivalent of a quarter forward movement of exploitation walls. Whereas the presented interferogram of 70-day time base show redoubled increase of subsidence as well as a bit bigger area of visible terrain motions. On the analysed interferograms, the influence of the mining excavation was observed on the surface after the 4-month period. This delay resulted from the small depth of exploitations. The old gobs i.e. abandoned mining fields, dating back even to the end of the 19th century, quickened subsidence. Apart from the exploitation in the centre of Katowice, the interferogram from 1992 shows as well the subsidence increase caused by the final exploitation stage in the southern part of the city (Fig 6.) In this case, the influence of the exploitation was comparable with a 6-month forward movement of the walls. A still longer delay, in this case, resulted from a different structure of the cap-rock of the ore.
3.3. The interferometric representation of the process of compaction of storage areas and waste heaps

In Upper Silesia, the storage area of the post-exploitation waste was examined. As shown in the figures below (Fig. 7), an explicit interferometric image of the subsidence caused by compaction was obtained (Perski, 2001)

3.4. The summary of the research in Upper Silesia

1. The compaction of the storage material on the waste heaps can be observed.
2. The InSAR technology, makes it feasible to analyse the deformations in the vast areas.
3. The level of the urban development of the researched area does not hinder the research (and for long time bases it is an advantage.)

4. Thanks to InSAR technology, it is possible to examine vertical, dynamic shifts resulting from current exploitations, from the activating influence of the old mining and from some other causes.

**4. InSAR application in the area of opencast mining**

In the area of opencast mining, interferometry can be applied in the examination of the following dynamic phenomena:
- exploitation progress,
- landslips, landslides, mass motions of the excavation slopes, uplifting and deformation of the excavation floor resulting from heavy exploitation,
- the mass motions of the cap-rock heaps,
- the depression and deformation brought on by drainage.

**InSAR potential application**

1. Monitoring exploitation progress is inaccurate and very difficult to carry out in practice. Opencast mining is conducted along a narrow and long front, what in case of the system of 20 m resolution cannot be detected. Interferometry can be applied only when the direction of the process of exploitation is parallel to the direction of the satellite movement and the angle of the exploitation cap-rock is perpendicular to the direction of the radar beam.

2. The monitoring of landslips, landslides and mass motions of the excavation slopes. The research can be carried out with the use of pairs of radarogrammes of a short time base of about 70 days. The interferometric research conducted world-wide has considerable potential in this particular field.

3. The monitoring of the uplifting and deformation of the excavation floor resulting from heavy exploitation. It is a very significant discipline as far as technology is concerned. However, it has not been yet examined thoroughly enough. The above-mentioned phenomena are frequent in Bełchatów opencast mining and are tectonical in their character. The interferometric examination of these phenomena is possible with longer than 35-day time base.

4. The monitoring of mass motions of cap-rock heaps can be carried out using SAR data within the time base longer than 35 days.

5. The monitoring of the depression and deformation brought on by drainage requires data of at least a year time base. A sharp decrease in the coherence of the interferograms makes it difficult to obtain useful data. The analysis of such data for LGOM has proved that the subsidence caused by drainage can be monitored but its interpretation is restricted to the urbanised areas.

**5. Conclusions**

- General atmospheric conditions influence significantly the quality of interferograms. All types of precipitation hinder the interferogramic examination.
- Due to the wavelength, woods are an obstacle in the penetration of radar waves, also the spring vegetation hinders the quality of the interferogram.
- The last factor, mentioned earlier in the paper, is the inaccuracy of the horizontal measurement. It makes the coregistration of the interferogramic images into the local co-ordinate system rather difficult.

In general, the full potential of the discussed technology has not yet been used. Yet the effects so far achieved prove a tremendous potential of Interferometry in the protection of mining areas.
References:


**Krawczyk A., Perski Z. 2000:** Application of satellite radar interferometry on the areas of underground exploitation of copper ore in LGOM – Poland, 11th International Congress of the International Society for Mine Surveying, vol.2, 209-218, Krakow

**Ostrowski J., Hejmanowski R., Kwinta A. 1997:** Dynamika ujawniania się bezpośrednich wpływów dokonanej eksploatacji górniczej na powierzchnię terenu O/ZG Rudna AGH Kraków 1997 praca niepublikowana

**Perski Z., 1998:** The test of applicability of land subsidence monitoring by InSAR ERS-1 and ERS-2 in the coal mine damaged region (Upper Silesia), International Archives of Photogrametry and Remote Sensing, vol. XXII, part 7, 555-558.

**Perski Z. 2000:** The Interpretation of ERS-1 and ERS-2 InSAR Data for the Mining Subsidence Monitoring in Upper Silesian Coal Basin, Poland, International Archives of Photogrammetry and Remote Sensing, vol. XXXIII

**Perski Z. 2001:** Zastosowanie satelitarnej interferometrii radarowej w Badaniach środowiska Górnośląskiego Zagłębia Węglowego, Fotointerpretacja w Geografii [w druku]

**Popiołek E. 1997:** Analiza rozwoju wielkopowierzchniowej niecki obniżeniowej terenu na obszarze LGOM wywołanej odwodnieniem warstw trzeciorzędowych i czwartorzędowych AGH, Kraków 1997