THE VIEW FROM SPACE

M. GRANICZNY, Z. KOWALSKI AND M. PRZYLUCKA, POLISH GEOLOGICAL INSTITUTE, POLAND, WITH D. COLOMBO, T.R.E., ITALY, EXPLAIN HOW SATELLITES HELP THE POLISH MINING INDUSTRY IN DETECTING COAL MINING INDUCED SURFACE DEFORMATION.
With the complexity of today’s mining sites, together with the growing pressures operators face in delivering greater economic value from these assets, increasing production and reducing risk are central to long-term success.

It is against this backdrop that a host of new technologies have come to generate more accurate information from complex mining environments and previously intractable geologies.

An important addition to production monitoring and exploration techniques, which is generating considerable interest among operators today, is the ability to monitor the surface deformation occurring over the mining area from space. This is achieved through Interferometric Synthetic Aperture Radar (InSAR).

This article will look at the development of InSAR interferometry, its applications to mining areas and how it can reduce risk in such operations.

**Measurements from space**

InSAR is a remote sensing technique that uses satellite radar systems, which circumnavigate the globe, measuring ground displacement from space.

![Figure 1. A schematic representation of the measurable ground points using radar satellites.](image1)

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**InSar milestones**

There are a number of requirements for InSAR to work effectively and accurately.

Measurements are only possible when ground points have specific electromagnetic characteristics: ground targets should be present on the ground surface (scatterers) and visible in all satellite images acquired throughout the period of observation; and such ground targets should have a sufficiently stable phase signal in time (permanent).

These requirements led to a number of milestones in the development of InSAR, starting with a new multi-image approach (PSInSAR™), which was developed at the Politecnico di Milano in the late 1990s. This was followed in January 2010 with the SqueeSAR™ algorithm.

Both algorithms have contributed significantly to reservoir monitoring today. The PSInSAR algorithm, for example, made it possible to use multi-image data sets, enable atmospheric and orbital errors to be
removed and generate the histories of movement for each radar target. Perhaps most importantly of all, PSInSAR made it possible to identify permanent scatterers (PS) points on the ground that consistently return stable signals to the satellite sensor.

Such PS tend to be manmade structures, such as buildings, bridges and antennae, as well as stable natural reflectors, such as exposed rocks. By identifying PS, ground displacement velocities can be measured with even greater accuracy.

The latest algorithm, SqueeSAR, takes this process a step further. It can identify a new set of ground targets known as distributed scatterers (DS). It can also be used for monitoring ground displacement. DS consist of an extensive area where the back-scattered energy is less strong but remains statistically homogenous within that area and can correspond to rock outcrops, non-cultivated lands or desert areas.

The SqueeSAR algorithm enables the user to process this energy and detect ground displacement in DS areas where there are poor levels of PS but with the same accuracy. SqueeSAR provides a higher spatial density of measurement points, typically 700 points km\(^2\).

Figure 1 provides a schematic representation of the measurable ground points using radar satellites. For each ground point, the following information is supplied: the position on a reference map with a precision of one metre, the average annual velocity of the ground point, with an accuracy that can exceed 1 mm/year, and a time-series of ground point displacements.

Today, InSAR is more sophisticated than ever, handling multi-image data sets, identifying PS and DS ground points and providing pin-point accuracy on ground displacement values. Applications include the characterisation of areas vulnerable to landslides, the monitoring of faults and earthquakes and infrastructure stability. Recent InSAR survey examples include a subsidence study of the city of New Orleans following Hurricane Katrina, deformation analysis over Mexico City and the monitoring of the ground displacement resulting from the January 2010 Haiti earthquake, which T.R.E. carried out with Infoterra GmbH. In 2010, T.R.E. processed InSAR data over an area of 2.1 million km\(^2\).

Applications for the mining sector: precision, cost and accessibility

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So what applications are there for the mining sector? How can satellite radar data reduce risk in opencast or underground operations?

As previously mentioned, InSAR provides highly accurate data – in either a vertical or east-west direction – on ground displacement, with the high density of ground points ensuring many more measurement points are generated than traditional survey techniques, such as GPS, levelling or tiltmeters. Millimetre precision is usually achieved by analysing long data stacks of InSAR acquisitions.

While there are opportunities for InSAR exploitation over opencast mining areas, this article will focus on how risk can be reduced in taking into account the deformation that occurred in an underground coal mined area in Poland. Here, InSAR is proving to be a rich data source in helping operators and controllers better understand the behaviour of the subsurface. This is being achieved through the accuracy and quality of the data generated and the cost effectiveness and accessibility of the technology.

**The Silesian Coal Basin: a long history of mining exploitation and subsidence**

The Upper Silesian Coal Basin (USCB) is located in southwest Poland and northeast Czech Republic. The USCB forms the western part of the Silesia-Cracow upland and peripheral part of the Silesian Beskids. The total area of USCB is 7400 km².

The USCB foredeep consists of Carboniferous molasse developed on the Precambrian block of the Upper Silesian Massif. Cambrian, Devonian and Carboniferous rocks were recorded. Carboniferous rocks continuously overlie Devonian deposits. The profile includes the top of the pre-flysch carbonate association, marine clastic sediments that correspond to the flysch succession about 1000 m thick, as well as the coal-bearing molasse of a foredeep depression. Lower Carboniferous deposits of the carbonate association do not have an established lithostratigraphic division, whereas

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**Figure 5.** Mining damage in Karb district.

**Figure 6.** Subsidence basins in the evangelical parish area on the basis of 11 days interferograms from TerraSAR-X satellite.
Upper Visean and Late Mississippian (Lower Serpuhovian) marine clastic deposits have been classified into two lithostratigraphic units of a formation rank. The Upper Carboniferous coal-bearing sequence has been divided into lithostratigraphic units of different rank. However, these are not defined according to the principles of the stratigraphic code. Four lithostratigraphic series have been distinguished as follows: the Paralic Series, the Upper Silesian Sandstone Series, the Mudstone Series and Cracow Sandstone Series.

Coal mining activity in the USCB has been conducted since the 17th century. In 2012, almost 79.2 million t of hard coal was mined from the USCB. There are currently 30 active coal mines in the region. The average depth of coal extraction is about 700 m below the surface and the longwall mining method with caving or hydraulic stowage is used. In the USCB, hazardous ground deformations are caused primarily by mining operations. The subsidence in this region reaches velocities of a few cm/month and in some cases can reach even 5 mm/day.

**Bytom case study**

**Introduction**

Bytom is located in the northern part of the USCB. The topography is characterised by numerous hills and valleys, the altitudes ranging from 249 to 330 m. The city’s area is 69.3 km² and population is 175,000.

One characteristic feature of Bytom is its highly diversified land use (Figure 3). Forests, woodlands, agricultural lands and water reservoirs constitute over 57% of the city’s area, while the urban areas account for less than 29%. The remaining parts are transport routes, as well as mines and deposit extraction areas (Figure 2).

The first mining activities near Bytom took place in the 17th century. Until the middle of 20th century, the mining involved mainly zinc and lead ores. In the second half of the 19th century, large deposits of hard coal were discovered and their extraction began. Longwall mining with caving was the main method of hard coal extraction. Mining with hydraulic stowage proceeded in the city centre, within the protective pillar.

Bobrek-Centrum hard coal mine is the main company active in the Bytom area. This mine was established on 1 January 2005, after the Bytom-III and Centrum mines were merged. The mine belongs to Kompania Węglowa S.A. and employs 3500 people, making it the largest employer in Bytom.

**The detection of subsidence in Bytom based on radar interferometry and geodesic data**

Several satellite monitoring campaigns have been carried out over the area, using different satellites.

From the initial stage where ESA ERS data (collected from 1992 – 2000) were exploited by means of the first PSInSAR approach, Japanese ALOS PALSAR acquisitions and German Terrasar-X images have also been used recently to produce deformation maps. Advances...
in processing techniques brings the results closer to the user experience, increasing the resolution and the precision of the information provided.

In Figure 4, a map showing how much subsidence occurred between 5 July 2011 and 12 June 2012 is provided. This map has been obtained through the processing of Terrasar-X acquisition by means of the SqueeSAR algorithm. More than 135,000 stable targets have been identified, resulting in a density of nearly 2000 benchmark/km². The maximum subsidence in the period in question reached 145 mm/year.

The highest subsidence exceeding 100 mm/year has been observed in the Miechowice and Karb districts. Significantly lower subsidence, ranging from 50 – 100 mm/year, has been observed in the Downtown, in the quarter surrounded by Piekarska, Kwiatowa, Adama Mickiewicza and Powstancow Śląskich Streets.

A further analysis has been carried out on the area, in order to characterise movement where subsidence is heavier. Taking into account interferograms (obtained as differences of subsequent SAR images), it has been possible to isolate areas where subsidence is greater than 100 mm/year.

Using this speculative data, it is possible to detect that subsidence in the Karb district occurred between 5 July 2011 and 9 September 2011. The results of the extraction of seam 504 in the Bobrek-Centrum mine and the construction disaster in the Karb district were publicised in the mass media. As a result of the mining damage and the poor condition of the residential buildings, approximately 460 inhabitants of Techniczna and Pocztowa Streets in Bytom were evacuated. According to the director of the Bobrek-Centrum mine, 0.7 – 1.2 m of subsidence had been predicted, while it actually subsided by as much as 1.9 m.

As a result, approximately a dozen buildings in the Karb district have been demolished (Figure 5).

In 2012, Kompania Weglowa S.A. spent approximately Zloty 25 million (€6 million) to repair the mining damage in Bytom.

Using the same approach it has been possible to detect that:

- The subsidence in the Miechowice district began 14 November 2011 and was still in progress on 21 June 2012.
- The subsidence on the border of Miechowice and Karb districts began 23 October 2011 and was still in progress on 21 June 2012.
- The subsidence in the Rozbark district was still in progress on 5 July 2011 and ended on 28 December 2011.

**Example of subsidence basin in Miechowice district (parish of the evangelical church in Bytom)**

Many areas affected by the mining operations are located in the Miechowice district in Bytom. One such place is the region of Matki Ewy Street and Ks. Frenzla Street. The infrastructure of the parish of the evangelical church, especially the church, nursing home Ostoja Pokoju and the children’s home are located in this region (Figure 8).

The mining in the area started in the late 1930s. In the period between 1996 and 2012, the mining in the region proceeded within the seams of the 500 group at the depths of 720 to 840 m. Longwall mining with caving was used as the primary method. The detailed data regarding the exploitation face, the duration of mining, the seam thickness, the depth of mining and the mining method are reported in Table 1.

The observations of the condition of the evangelical church parish buildings, located directly above the exploitation faces indicate that significant subsidence and mining damage took place.

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**Table 1: Mining workings in the neighbourhood of Matki Ewy Street in the period 1996 – 2012**

<table>
<thead>
<tr>
<th>Level</th>
<th>Panel number</th>
<th>Thickness of coal seam (m)</th>
<th>Depth of exploitation (m)</th>
<th>Time span</th>
<th>Type of exploitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>510</td>
<td>18</td>
<td>2.0</td>
<td>766 – 807</td>
<td>1 July 1996 – 31 May 1998</td>
<td>Longwall with caving</td>
</tr>
<tr>
<td>509</td>
<td>97</td>
<td>2.0</td>
<td>740 – 840</td>
<td>30 June 1999 – 30 June 2000</td>
<td>Longwall with caving</td>
</tr>
<tr>
<td>507</td>
<td>72</td>
<td>2.0 – 3.9</td>
<td>720 – 770</td>
<td>1 October 2006 – 1 September 2007</td>
<td>Longwall with caving</td>
</tr>
<tr>
<td>507</td>
<td>72a</td>
<td>1.55 – 2.0</td>
<td>723 – 765</td>
<td>1 January 2009 – 1 December 2009</td>
<td>Longwall with caving</td>
</tr>
<tr>
<td>509</td>
<td>97a</td>
<td>1.5 – 2.0</td>
<td>734 – 782</td>
<td>1 August 2010 – 1 February 2011</td>
<td>Longwall with caving</td>
</tr>
<tr>
<td>510</td>
<td>18a</td>
<td>2.0</td>
<td>780</td>
<td>1 October 2011 – present</td>
<td>Longwall with caving</td>
</tr>
</tbody>
</table>
The mining of seam 510 and wall 18a started on 1 October 2011 and continues until this day. The seam being extracted is located at the depth of 780 m and is 2 m thick.

Analysing radar responses highlights that displacement began 14 November 2011. It can therefore be concluded that the impact of the mining of seam 510 manifested itself on the surface about 44 days after the mining began. Based on the polygons generated through radar interferometry, it is possible to determine the direction of the extraction from wall 18a, proceeding northbound.

The Central Mining Institute (CMI) has been measuring displacements in the vicinity of Matki Ewy Street, especially the evangelical church parish buildings, since 1965. The primary task is to level the benchmarks on the walls of the buildings, as well as the ground benchmarks. Based on these measurements it can be concluded that the area of the parish subsided by almost 1.7 m in the period between 1 October 2011 and 30 August 2012 (Figure 7).

The Building Research Institute (ITB) took geodesic measurements of the area around the evangelical church parish buildings. These measurements show that between 20 March 2012 and 30 July 2012, the parish area subsided by 0.94 m.2

The results of mining and the damage to the parish buildings are shown in Figure 8. The Bobrek-Centrum mine has changed its traffic plan and mining methods in order to diminish the mining damage. It has planned to disperse the mining and to proceed with mining operations along four or five walls at the same time. Additionally, in the regions particularly subjected to subsidence, the mining will proceed with a small daily progress of mining operations and with hydraulic stowage.

Summary
Based on the analysis of old German topographical maps in the scale of 1: 25000 (Meßtischblatt, 1883) and the latest terrain model from the airborne laser scanning (ALS), it can be concluded that the surface topography in the Bytom area has been significantly transformed. It is estimated that during the last 100 years of the hard coal (as well as zinc and lead ore) mining, the land surface in some areas subsided by as much as 35 m. Such subsidence means that, in extreme cases, construction disasters may occur.

The InSAR method is an excellent addition to the classic geodesic measurements (precision levelling, tachymetry and GPS).

The use of the SqueeSAR algorithm allowed for an ascertainmement of the subsidence basins. Additionally, the TerraSAR-X satellite with an 11 day recording interval allows for a high-probability determination of the direction of the longwall mining and the progress of mining operations.

References

Further reading
KOWALSKI, A., “Surface deformations in the Upper Silesian Coal Basin”, presentation given at the DORIS Workshop and Stakeholders Meeting (Bedzin, Poland; 16 - 18 April 2013).

Acknowledgements
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