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IDENTIFICATION AND MEASUREMENT OF MINING SUBSIDENCE WITH SAR INTERFEROMETRY: POTENTIALS AND LIMITATIONS

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Abstract

This work presents some conclusions regarding the operational use of SAR Interferometry over one of the biggest in Europe coal-mining field of Upper Silesia in Poland. The Upper Silesian Coal Basin (USCB) covers an area of about 7250 km^2. Mining activity of Carboniferous hard coal deposits has been carried out here for over 200 years. As a result, the region becomes highly urbanized, industrialized and thus environmentally degraded. At present there are 39 active coalmines in the Polish part of the basin. However, because of restructurization of Polish industry, the significant number of the coalmines is going to be liquidated.

Since 1998 the 50 ERS SAR scenes over Upper Silesia have been analyzed and processed. As the result of this study the interferogams of variable baselines (between 0 to 431 m) have been successfully generated using 2-pass, 3-pass and 4-pass approaches. Detailed analysis of these data demonstrates that SAR interferograms contain two types of information: quantitative information concerning the rate of subsidence during a period between repetitive ERS SAR acquisitions and qualitative information regarding the shape and extent of subsided area.

1. Introduction

The region of Upper Silesia is stretching almost in the centre of Europe in the southern part of Poland and has borders with the Czech Republic and Slovakia. Geologically, the main geological structure of the region represents the Upper Silesian Coal Basin (USCB). It covers an area of about 7,250 km^2 and it is the primary coal basin in Poland, and also one of the largest in Europe.

In recent years coal mine subsidence is associated with underground large-scale highly mechanized technology named “long wall mining” operations with allows the almost total removal of a coal seam. In that system a seam of coal can be extracted in a form of parallel strips at a length of 1 to 2 km and width of 200 to 500m. With modern equipment around 10.000 t of coal can be exploited from one face per day. The pace of an average long wall mining extraction front is 3 to 10 m per day.

Mine subsidence phenomena, commonly related to underground coal mining are known, as a sag subsidence, which is in theory a gentle, gradual settling of the earth’s surface. In the context of underground mining, is the lowering of the Earth’s surface due to collapse of bedrock into underground mined-out areas and subsequent sinking of surface unconsolidated materials - sand, gravel, silt, and clay.

The surface deformations are expensive to measure using traditional methods and thus the common strategy of the coal mining industry, is to measure as less as possible. Typically the measurements are done only at limited, most important locations with as low as possible frequency. In result many of the deformation phenomena are not well recognized.

2. The geology and mine deformations in Upper Silesia

The coal bearing formations of the USCB include several Upper Carboniferous litostratigraphic series, totalling 8,500 m in the greatest thickness. These series are featured by a gradual reduction of their thickness toward the east and southwest. The lower part includes sediments characterized by numerous periodic marine transgressions (paralic sediments) separated by a sedimentary gap from the overlying “limnic” part of the sequence, consisting of continental sediments. On the great area of the USCB boundary is located at the base of the important the thickest 510 seam (max. 25 m thick).

Mining activity of Carboniferous hard coal deposits has been conducted here for over 200 years. During this last two centuries the coal mining industry exploited about 7 billion tons of raw material. In '90s the region is producing up to 100 million tonnes of hard coal per year. As a result, Upper Silesia has become highly urbanized and simultaneously environmentally degraded. At present there are 39 active coalmines in the Polish part of the basin operating at the depth ranging from 200 to 900 m below the terrain surface. Among them, the significant part of he coalmines is going to be liquidated because of restructurization of Polish industry. In Upper Silesia, the mining activity has caused an area of almost 600 km2 to sag (by trough) subsidence with local appearances of pit subsidence (sink-holing). Both types of subsidence are accompanied by surface deformations and discontinuities such as fractures, crevices, faults, step folds and slides. The subsidence has caused particular changes in topography of Upper Silesia, as well as in hydrography, and is still affecting buildings, roads, railways and pipelines. Between 1970 and 1999 many exploitation fields has been located under densely urbanized cities like e.g. Katowice (the capital of the province) and historical town Bytom. Since that time, mining deformation has become an important problem for construction, settlement, communication and investment policy (Kwiatek, 1997).

The subsidence in Upper Silesia reaches velocities commonly of a few centimeters per month but there are many areas with subsidence of 1 cm daily, or more. Such a rate of downwarping usually appears 3 to 6 months after exploitation and then during the next two years the subsidence gradually ceases. If an area has been previously subsided due to mining in coal seams above current exploitation the subsidence is usually faster and ceases in a shorter period. In a most common case of the longwall technique for coal exploitation the area of the highest rate of subsidence follows the exploitation front during the spatial expansion of settled area. The extents of the final subsidence basin named subsidence trough are determined by the size the exploitation field and its depth depend on the thickness of coal layer.

3. ERS SAR Interferometry for Upper Silesia

Since 1998 the 48 ERS SAR scenes over Upper Silesia have been analysed and processed within AO-127 ESA Project. To cover whole area of mining activity full SAR scenes acquired from adjacent tracks 494, 222, 451 have been selected (Fig. 1). As the result the interferograms of variable baselines (between 0 to 430 m) have been successfully generated. The best results were obtained for tracks 494 and 222. Depending on seasonal conditions, land use type and temporal baseline the interferograms presents various qualities and finally only a few were suitable for quantitative analysis. For interferometric processing the differential 3 and 4 pass interferometry have been applied (Massonnet and Feigl, 1998). To reduce topographic effect on the differential interferograms the tandem data acquired in 1995 and 1999 have been used.

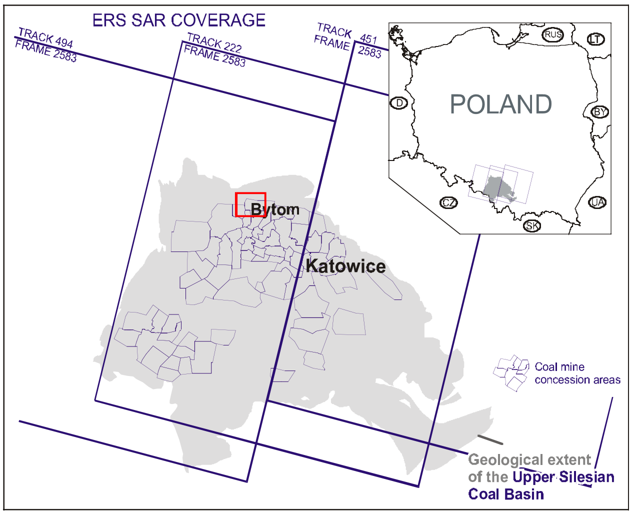

Fig. 1 Location map of presented examples and ERS SAR data coverage of Upper Silesia

The interferograms present various coherences depending on seasonal and weather conditions. Only a small numbers of interferograms were suitable for quantitative analysis. Comparative studies shows that it is a typical situation for Central Europe and for other areas of moderate climatic zone (Usai and Hansen, 1997). Low coherence strongly reducing interpretation of the fringe pattern and usually preclude the subsidence measurements. To omit this problem and derive the quantitative subsidence data the interferograms must be constructed from SAR data of as small as possible temporal baseline. In this case the fringe pattern presents only a subsidence increment during a period of repeated SAR observations. For typical long-wall coal exploitation under ground the highest subsidence increment occurs on a dynamic slope of expanding subsidence basin. Consequently, SAR interferograms of small temporal baseline present valuable information only about subsidence velocity pattern but with spatial quality impossible to reach using traditional terrestrial methods (Perski and Jura, 1999).

4. Case study – Municipality of Bytom

Municipality of Bytom is located in the north-western part of USCB (Fig. 1). The town have been settled in medieval and now it reached 200 000 inhabitants. Bytom was rapidly developed in XIX-th century when extensive coal mining was started and thus the most of urban and communication infrastructure has been established in that time. In medieval the silver ore mining from Triassic dolomites at the depth of 60-200 m was started and later, in XIX-th century lead and zinc ores have been also included. Hard coal mining started in XIX century and operates at the depth of 100-800 m.

Geologically, 20 to 60 m thick layer of Quaternary sediments covers the Bytom area. Upper Triassic limestones and dolomites, which appear below Quaternary, are formed into a gentle syncline. Its thickness varies between 20 and 220. m. Triassic formation covering carboniferous rocks which area are recognized up to 1000 m depth thanks to mine workings. The Upper Carboniferous formations of sandstones and mudstones of Namurian A,B, C and Westfalian are folded and below the city centre dipping up to 45o to the North.

4.1 Mining activity and terrain deformations

The coal mining under the city is carried out by 4 coalmines and up to 1987 also by the Zn-Pb ore mine, which operates on the same area, but on shallower level. The summarized thickness of mined out coal banks is 15 to 25 m in the western edges reaching 40 m in the eastern part of the area. Under the City centre, which was protected against damages, the total thickness of mined coal banks is 7 m. The oldest, medieval ore mining under the city have unrecognised locations. The most extensive exploitation of the ores has been here carried out during World War II (Chudek and Sapicki, 1984) and the resulted, abandoned cavities create a hazard of reactivation of subsidence with recent coal exploitation on deeper levels.

Such large extensive and intensive mining activity results huge terrain surface changes. The total subsidence reached 12- 15 m locally in the northern part outside of urbanized areas the subsidence reached 30 m (based on unpublished reports; courtesy of Bytom Mining Company). The densely urbanized centre has been subsided up to 2.5 m. Within the area affected also by ore mining sinkhole hazard is very common. Between 1956 and 1994 the 53 major sinkholes (2 to 5 m in diameter) have been recorded. The subsidence and associated horizontal, stress causing damages to buildings, infrastructure and hydrological problems (overflooding). Up to 1950 (before extensive exploitation under the town) 36% of the buildings have been damaged (Chudek and Sapicki, 1984).

4.2 InSAR measurements

Selected interferograms, which presents acceptable for analysis coherence have been analysed. Densely urbanized centre of Bytom permits to generate coherent interferograms with long temporal baseline. The details of data processing are presented in Table 1.

Table 1. The interferograms from Bytom area

No.	Data acquisitions	Satellites	Track	Temporal baseline	Perpendicular baseline
1	1995-07-04 – 1995-09-13	ERS-1, ERS-2	222	71 days	8 m
2	1998-01-19 – 1998-02-23	ERS-2	494	35 days	30 m
3	1997-08-13 – 1997-12-31	ERS-2	222	140 days	160 m
4	1998-01-19 – 1998-08-17	ERS-2	494	210 days	210 m
5	1999-08-24 – 2000-04-03	ERS-2	494	315 days	47 m

Interferograms have been generated using two-pass method in case of perpendicular baselines smaller than 100m. In other cases the DEM correction has been applied using interferometricaly generated DEM from “tandem mission” data.

Interferograms with short temporal baseline (interferograms 1 and 2; Tab.1) presents the fringe pattern of mining subsidence related only to a “differential effect” – i.e. the temporary velocity of subsidence instead of the subsidence trough elevations obtained with terrestrial leveling (Perski and Jura, 1999). The highest temporary velocity of subsidence is occurring on the dynamic slope of expanding subsidence trough following long-wall exploitation. The examples from Bytom show that the subsidence velocity may reach more than 3.4 mm/day (Fig.2). Moreover, the velocity is often higher than the range of measurement with C-band SAR (Perski, 2003). In case of low rate subsidence and high coherence of urban areas interferograms the short time interferograms like 35-days present unique information about subsidence velocity pattern which extraordinary spatial quality. Interferogram from data acquired in 1995 (Fig. 2) present the subsidence velocity pattern due to coal mining under Bytom city centre.

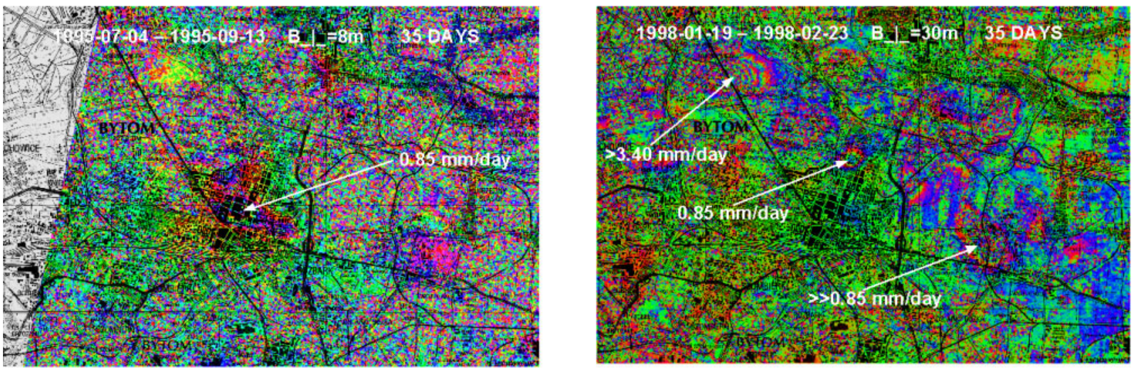

Fig.2. 35-days ERS SAR interferograms from Bytom area. SAR SLCI data courtesy of ESA

The new information associated with SAR interferometry is the interpretation of the shape and extent of subsided areas. Such information could be derived also from relatively low quality interferograms where quantitative information is unavailable. The detailed extent of subsided areas is very difficult and expensive to measure using traditional levelling methods. The combination of terrestrial measurements of the selected points and mapping of the extent of subsided area seems to be the most efficient measurement method.

The traditional InSAR techniques have been extended in last years to pixel-based approaches like e.g. Permanent Scatters method (Feretti et al., 1999). The comparison of two interferomgams from 1995 and 1998 on Fig. 2 present how dynamically is changing the subsidence pattern in a case of underground mining. However, also with PS technique the main problems related to decorrelations still remain A potential advantage in this matter seems to be possible using alternate polarization (Perski, 2003) and multifrequency SAR data.

Interferograms of long temporal baselines (No. 3, 4, 5 Tab.1) presents much more reduced coherence. From many analysed pairs only three was suitable for analysis (Fig. 3).

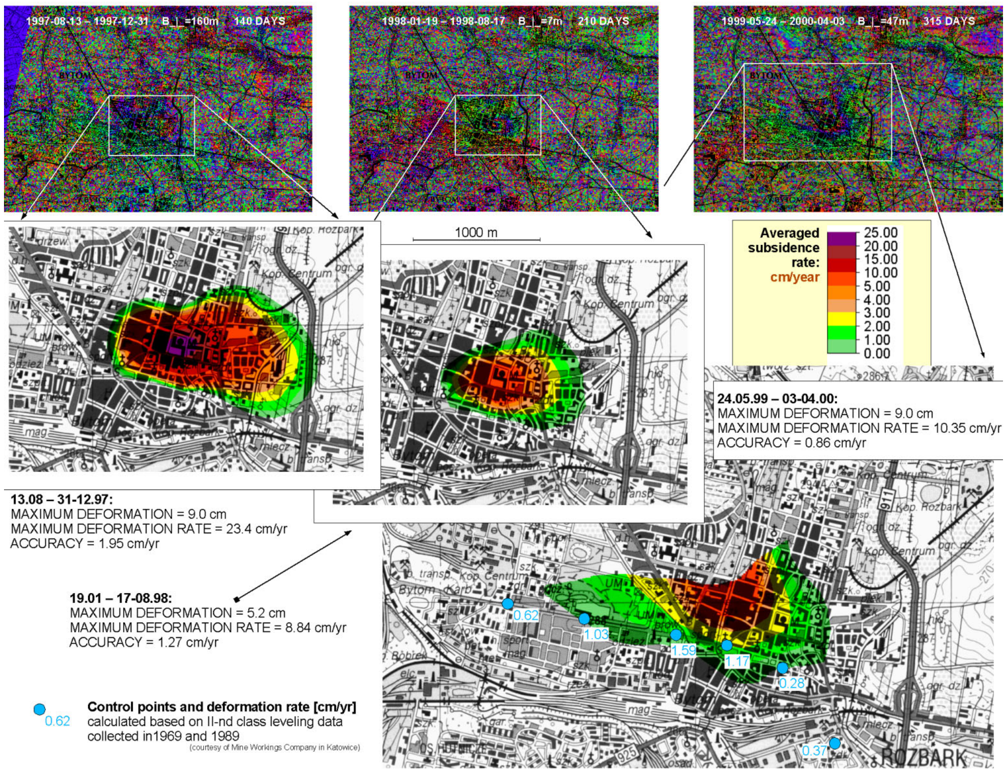

Fig.3. Long-term ERS SAR interferograms from Bytom area and its interpretation. SAR SLCI data courtesy of ESA

With such high subsidence velocity it was impossible to detect subsidence related directly to the mining but long-term effects. Short-term interferogram from January 1998 (Fig. 2) presents no subsidence in the Bytom centre. Long-term interferograms from years 1997, 1998, 1999 (Fig. 3) discover the slow movement of 10-20 cm/year related to more complex subsidence phenomena like post-mining relaxation and reactivation of old abandoned cavities. Their similar shape and value proves that observed fringes on different independent interferograms are not related to atmospheric or other errors. The comparison with terrestrial levelling provided by Katowice Mine Surveying Company in 1968 and 1989 II-nd class measurements shows similar subsidence annual rates. What is more the spatial differences of measured subsidence velocities along profile are very similar to the spatial variances obtained on Long-term interferograms. This phenomenon suggests permanent character of the slow subsidence in the city centre. However, for final conclusions more terrestrial data need to be analysed.

5. Archived InSAR limitations

5.1 Limitations due decorrelation

Successful coherent interferogram generation depends on seasonal and weather conditions during and before SAR data acquisition. Usually wet weather and dense vegetation cover significantly degrading coherence. SAR data selection must thus be performed very carefully considering detailed meteorological data. Typically, the SAR image pairs with temporal baseline longer than 70 days are incoherent. This limitation considerably decreases the number of data available for processing. In Central Europe of moderate climatic zone there are many areas, which are permanently inaccessible for InSAR observations (forests) or there are inaccessible temporary (arable lands). Only man-made structures remain coherent over long time scales (Usai and Hanssen, 1997). Applying very careful data selection according to meteorological data is possible to maximize coherence (Villasenor and Zebker, 1992). Detailed analysis of the low coherence areas on coherent interferograms from Upper Silesia shows that the volume scattering is the most important factor causing decoherence (Perski, 2003) in vegetated areas. This type of decorrelation takes place when the backscattering comes from targets with different elevation within resolution cell (Fortuny et al., 1994). Volumetric scattering occurring for vegetation targets and decorrelation is a caused by wavelength-order position changes of branches, leaves etc. The improvements seem to be possible applying SAR acquisition of HH polarization to omit influence of vertical structures.

5.1 Limitations due to ERS SAR sensor characteristics

During detailed analysis of interferograms from Bytom and also other mining areas the lost of the interferometric fringe signal due to extremely fast movement have been noted. If the increment of the slope angle of the subsidence trough during a period between SAR acquisitions of an interferogram is higher than some centimetres the fringe pattern will present wrong value to too high phase gradient in respect to spatial resolution. It happens because the areas affected by subsidence are relatively small (commonly 1 per 2 km) in respect to the typical 20m spatial resolution of SAR interferograms (typical multilook factor 5 in azimuth direction). In many cases the interferometric fringe of mine subsidence consists of dozen of pixels.

Taking into consideration C band wavelength and multilooking factor 5 the critical value, the land subsidence could be defined as:

$$w_{cr} = \frac{f_r}{d}$$

Where f_r is a vertical displacement corresponds to one fringe; d is a distance between adjacent pixels centres of multilooked interferogram.

For ERS-1 and ERS 2: f_r =3 cm and d=20 m, and thus w_{cr} = 1,5 mm/m

The value of w_{cr} may be also understand as the practical limit of InSAR measurements of changes in terrain inclination due to subsidence.

Acknowledgments

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