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Original article

Using radar interferometry and SBAS technique to detect surface subsidence relating to coal mining in Upper Silesia from 1993-2000 and 2003-2010

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ABSTRACT

In the presented research ERS1-2 and Envisat ASAR archive data were used for the periods 1993 – 2000 and 2003 – 2010. The radar images were acquired over Upper Silesia in southern Poland. DinSAR (Differential InSAR) and SBAS (Small Baseline Subset) methods were applied for the detection of the most subsided areas. The DinSAR images were layer stacked for an image using 26 interferometry pairs of ERS1-2 SAR and 16 pairs from Envisat ASAR images in an ascending-descending orbit combination. The stacking of these images showed the most subsided parts of these cities even under low coherent areas, but the results are less precise. In the Upper Silesian Coal Basin, intensive underground coal exploitation has resulted in several surface deformations under Bytom (~8-17 km²), Piekary Śląskie (~9-15 km²), Ruda Śląska (~32-42 km²) and Katowice (~20-23 km²) with 25-40 cm of subsidence (in general) in the studied time periods. The SBAS technique has also shown that coal mining caused subsidence in the cities of Bytom, Katowice, and Piekary Śląskie of 5-7 cm/yr. The presented SBAS method did not work for low coherent areas, e.g. dense forested areas. DInSAR data also pointed to several decreasingly less active mining areas, which relate to the mine closures in Bytom and Ruda Śląska, which is also verified by the time series analysis.

KEY WORDS: radar interferometry, ERS1-2, Envisat ASAR, SBAS, coal mining, subsidence

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1. Introduction

The coal mining industry in the Upper Silesian Coal Basin (abbrev. USCB) has operated for over 150 years. Recently the mining industry in the USCB has declined. The crisis is mainly connected with shortages of coal resources and decreasing coal demand as well as the necessity for coal mines. Most of the coal (old) mines operating under urbanized areas, or with unfavourable mining and geological conditions, were closed to reduce the operating costs of the mining industry (CABALA & CMIEL, 1999; CABALA ET AL., 2004). The typical operating system in USCB is longwall coalmining. Generally, the excavated coal layer is 2.5 m thick, 250 to 400 m long, and about 680 m deep. Recent subsidence reaches up to 70% of the excavated coal layer, which represents a 0.75–2.0 m displacement for every layer (KONOPKO, 2010; KLABIS & KOWALSKI, 2014). In highly urbanised areas such as Upper Silesia, the intensive underground coal mining influences widespread areas, resulting in several surface deformations, and road, railway and building damage (JUNG ET AL., 2007; CARNEC & DELACOURT, 2000; WOJCIECHOWSKI, 2006; PERSKI, 2000).

The scope of the research is to recognise and locate the areas with greatest subsidence related to intensive coal mining in the Bytom, Zabrze, Piekary Śląskie, Ruda Śląska and Katowice cities from 1993–2000 and 2003–2010, using ERS1-2 and Envisat ASAR radar archive images. In the presented research, subsidence (in cm-s) was found from two-pass interferometry layer stacked pairs and from SBAS (Small Baseline Subset).

The orbital Synthetic Aperture Radar (SAR) systems is a well developed method for monitoring ground displacement. In order to improve the resolution of radar images, synthetic aperture radar (SAR) was developed in the 1960s (JECHINTA & MARIAPPAN, 2010). The SAR is an active sensor (it uses its own energy source) and has day and night imaging capabilities since it uses microwave energy (Paradella et al., 2012; Tomás et al., 2014). This electromagnetic radiation penetrates the cloud cover: SAR sensors can therefore acquire data, regardless of the weather conditions. The SAR processing connects the Doppler frequency variations and demodulates by adjusting the frequency variation in the return echoes from each point on the ground and generates a high-resolution image (Chan & Koo, 2008; Raucoules et al., 2007).

Appling two SAR images (two-pass interferometry) InSAR provides a relatively dense spatial coverage of the deformation field. The combination of two radar images allows the detection and quantification of ground deformation between the two acquisitions (Differential InSAR - DInSAR) (Pratti et al., 1996; Hole et al., 2007). DInSAR has become an important remote sensing tool for estimating temporal and spatial surface deformation (Berardino et al., 2002; Colesanti et al., 2001). DInSAR has several important advantages such as high spatial coverage in urban areas compared with Differential Global Positioning Systems (DGPS) and instrumental methods, where the measure of ground deformation is concentrated only at a few discrete points, rather than over a wide continuous area and is neither time or cost effective for measurement periods shorter than a year. However, DInSAR could be used to set up a monthly, or annual, monitoring service at moderate cost (Colesanti et al., 2001; Tomás et al., 2014). The DInSAR method has been successfully applied for detecting mining subsidence e.g. Wegmüller et al., 2004; Herrera et al., 2012; Engelbrecht & Inggs, 2013; Bateson et al., 2015; Przyłucka et al., 2015). Moreover, in the study area there are several mines located under vegetated (mostly forested) areas, where other methods e.g. DGPS, SBAS, PSInSAR cannot be applied, but DInSAR can provide better results.

SBAS is a DInSAR algorithm and allows maps to be obtained with deformation time series corresponding to around 35 days using ERS-1/2 and ENVISAT data sets (Fernandez et al., 2009). For other methods, the SBAS technique was applied using 31 ERS-2 images from the 1995-2000 period and compared with the layer stacked image. The SBAS technique allows the generation of maps of average deformation and monitoring on the prone areas with precision to one centimetre or sub-centimetre. This method has been successfully applied for monitoring volcanic activity e.g. Lee et al., (2010) on Augustine Volcano (Alaska); seismic activity e.g. Shanker et al., (2011) in San Francisco Bay, and surface deformation caused by human activity e.g. Hu et al., (2014) in Beijing (China). The SBAS algorithm reduces the atmospheric artefacts and topographic errors in time-sequential interferograms. The algorithm uses only interferograms with small baselines that overlap in time to reduce spatial decorrelation. The method uses the most highly correlated areas to derive the deformation signal from multiple-examined interferograms, which reduces speckle and improves the phase estimate (Berardino et al., 2002; Fernandez et al., 2009; Trasatti et al., 2008). The technique relies on the use of unwrapped interferograms with the unwrapping operation on the minimum cost flow algorithm (Costantini & Rosen, 1999).

2. Methodology

In the case of interferometric pairs, each of them was filtered by the Goldstein method, unwrapped, refined and re-flattened using coherence and DEM – Digital Elevation Model (SRTM-3 version 4 was used as height reference). Afterwards the phase was converted into displacement (in cms), which followed the geocoding where the grid size transformed into 25 * 25 m. For the layer stacked image, 26 interferometry pairs of ERS1-2 SAR and 16 pairs from Envisat ASAR images were used in ascending-descending orbit, combinations were prepared as Single Look Complex (SLC). The applied images were operated in C-band which has decreased capability over vegetated areas. Unfortunately, X- and L-band data were not freely available e.g. Alos-Palsar, TerraSAR-X, which is less sensitive for vegetation cover and has the ability to measure faster motion, at several dm/yr with better resolution to complement Envisat ASAR, ERS1-2 SAR images.

In the selection of DInSAR pairs the maximal perpendicular baseline, abbrev. B*perp* (m), was up to 180 metres, but the most usable pairs were < ~100 meters, because the study area is covered by different features such as forests, parks and large urban areas. In some cases, where the temporal baseline was more than one year and the B*perp* (m) less than 50-60 metres, the generated interferometry pairs were suitable to detect the larger extension of subsidence, and these pairs were also added to the layer stack. The interferograms with small perpendicular baselines are particularly suitable for deformation measurements, since they have a reduced sensitivity and are only slightly affected (at least) by the decorrelation noise (Raucoules et al., 2007; Caduff et al., 2014). The selected radar images were those without snow cover. Such atmospheric ditsurbance was removed in the

InSAR pairs using Refinement and Re-flattening. Refining the orbit serves to correct the possible baseline inaccuracies and remove orbital fringes. This step calculates the phase offset (e.g. to obtain the absolute phase values before phase conversion to elevation or displacement values) and removes possible phase ramps caused by such things as atmospheric effects (EXELIS, 2015). In addition, the stacking and summarising of these images also helped to avoid the remaining atmospheric disturbances. The stacked image was divided by the number of study years to assess the general subsidence in a year. With that idea it was possible to use images from other orbit tracks and add to one layer stack. Averaging InSAR images tends to reduce atmospheric noise, because water vapour patterns are generally not spatially correlated over the time intervals spanned by interferograms. Therefore, the corresponding phase term varies from one image to the other, whereas ground deformations are situated at the same place (RAUCOULES ET AL., 2007; LEE ET AL., 2010). Atmospheric influences can be as high as one fringe (e.g. a full phase cycle) on a few kilometres. The level of atmospheric phase distortion depends strongly on the meteorological conditions (CROSETTO, 2002; CADUFF ET AL., 2014; PARADELLA ET AL., 2012).

In the case of SBAS processing after interferometric, refinement and reflattening workflows, those images which were discarded were where large phase jumps, low coherence or strong orbit inaccuracy appeared. In addition, a Digital Elevation Model (DEM – in the study SRTM-3 version 4) was also included to estimate the topographic errors. The applied DInSAR and SBAS processes were prepared in ENVI Sarscape 5.0 and the final refinements were done in ArcGIS Desktop 10.0.

3. Evaluation of interferometric results

The representative interferometric data are shown in Figs. 1, 2, 3 and 4 and are where the pattern of interferometric fringes relates to surface deformations (subsidence) within the different periods between the radar image acquisitions (Table 1). The detected fringes are where they appear/disappear and their extension was increasing, or shifting, according to the exploitation of hard coal. In the centre of the fringe (the area of maximum surface downwarp) is the zone with the highest rate of surface change, exactly in the middle of the ctive (advancing) slope (PERSKI & JURA, 1999). In a short time interval shifting, or continuously extending fringes, can be caused by underground mining, where it influences the surface even after only 3 to 4 months. Such a short impact time can be explained by the relatively shallow exploitation (PERSKI, 2000; WOJCIECHOWSKI, 2006).

Table 1. Information about the used radar images for Figs. 1, -2, -3, -4. B*perp*: perpendicular baseline in metres, B*temp*: temporal base

Number of path	Master		Slave		B*perp* (m)	B*temp* (days)	Satellite
	Orbite	Date	Orbite	Date			
222	21118	05.05.1999	21619	09.06.1999	110.7	35	ERS-2
222	21619	09.06.1999	22120	14.07.1999	29.7	35	ERS-2
222	22120	14.07.1999	23122	22.09.1999	103.7	70	ERS-2
222	23122	22.09.1999	23623	27.10.1999	121.4	35	ERS-2
143	6209	08.05.2003	12722	05.08.2004	61.6	455	Envisat
415	16501	26.04.2005	23014	25.07.2006	42.6	455	Envisat
494	39125	24.08.2009	43634	05.07.2010	65.9	315	Envisat
143	11219	22.04.2004	11720	27.05.2004	95.7	35	Envisat
143	12221	01.07.2004	12722	05.08.2004	97.05	35	Envisat

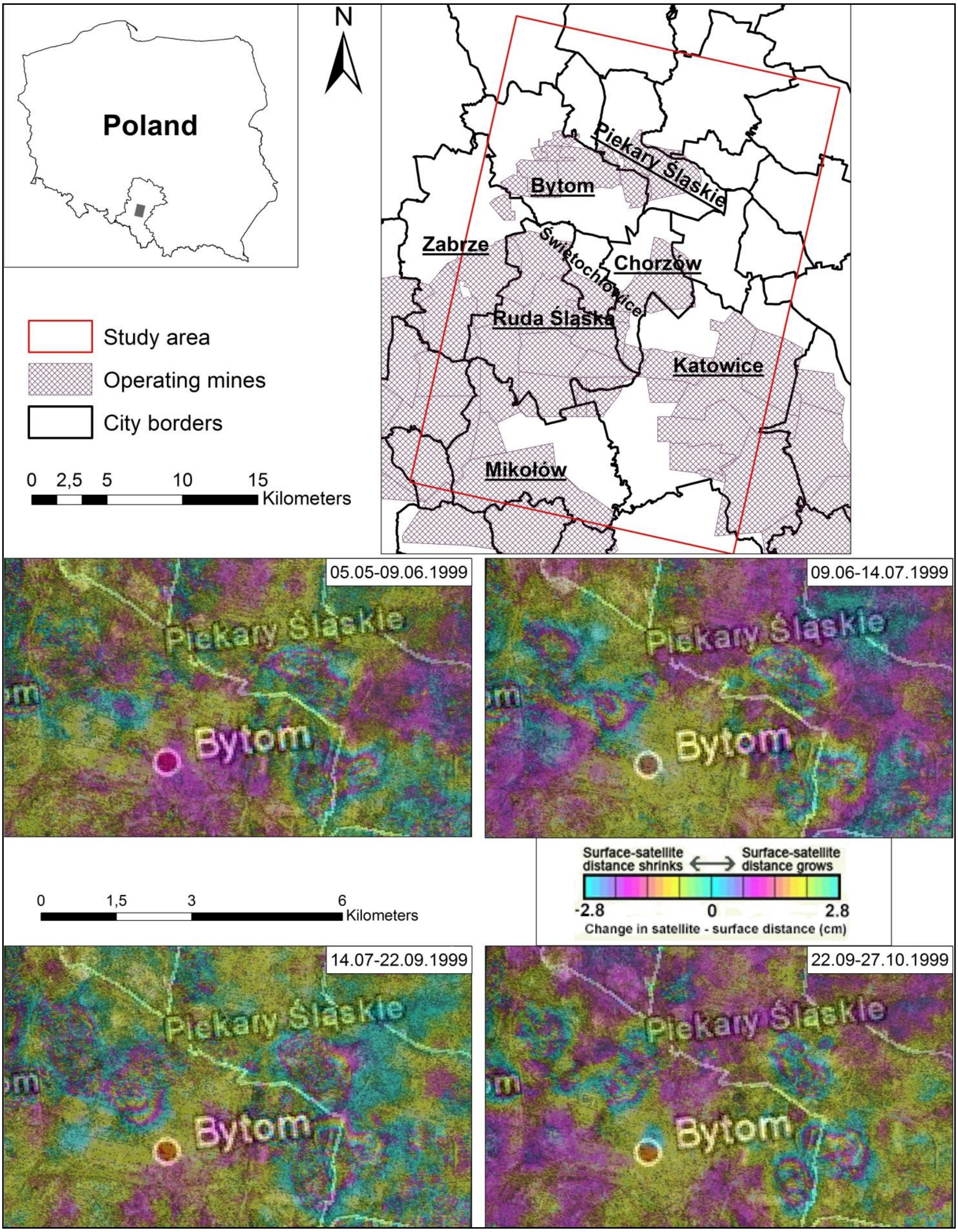

Fig. 1. The interferograms show well developed subsidence (fringes) under Bytom city in the monthly time ranges. Used images ERS-2 SAR, background map: GoogleEarth

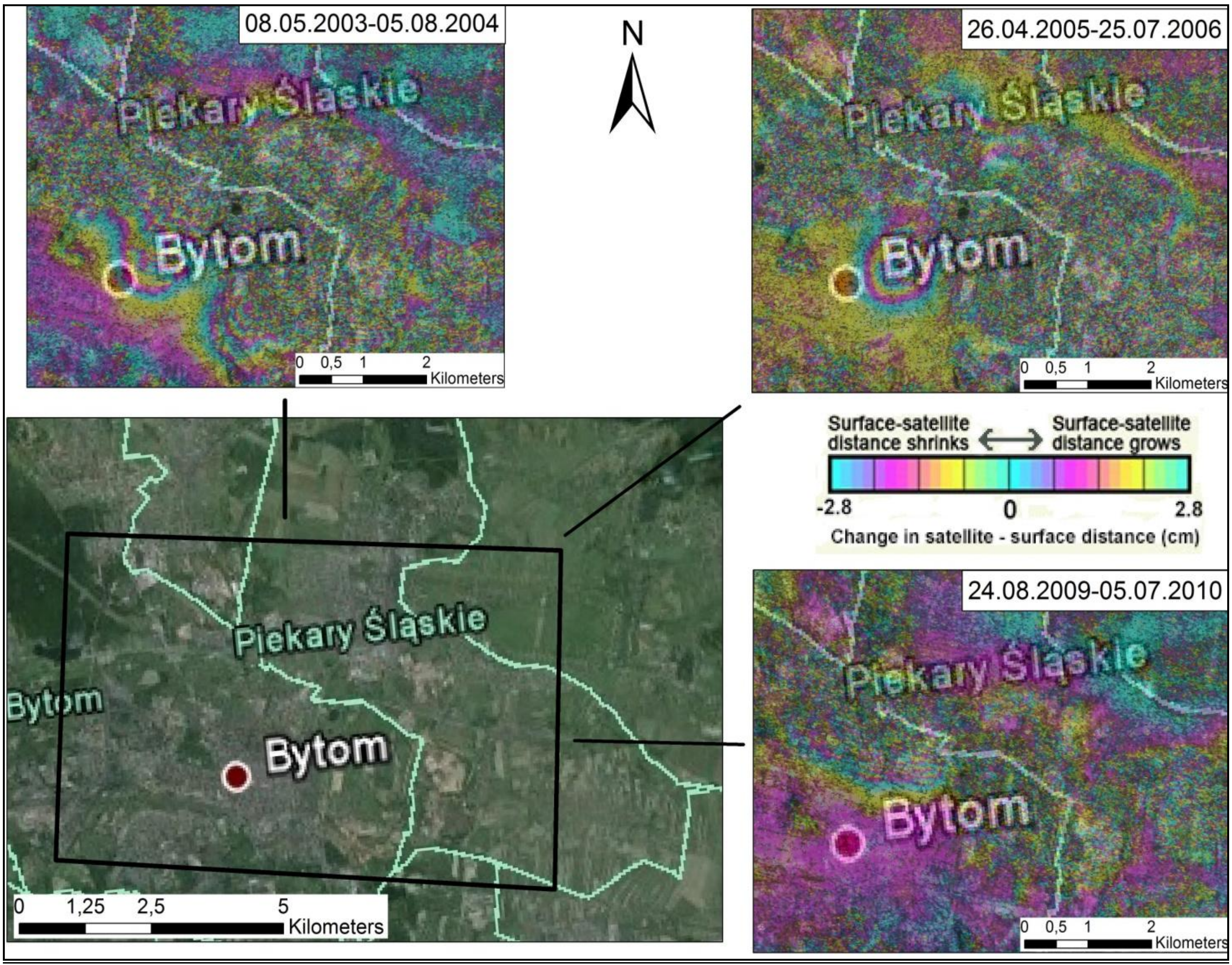

Fig. 2. Well developed subsidence under Bytom city, despite large Btemp ~in a year time range. Used images Envisat ASAR, background map: GoogleEarth

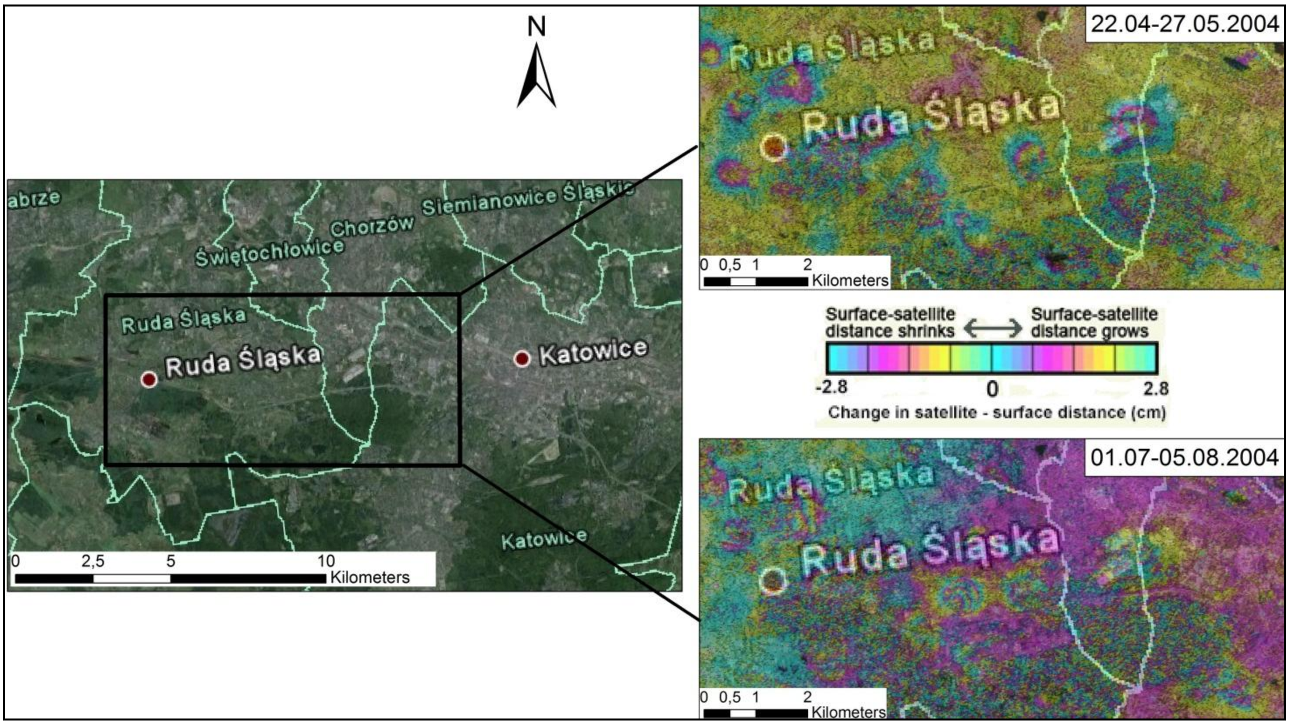

Fig. 3. Extended subsidence in a few months' time range in Ruda Śląska, used images Envisat ASAR

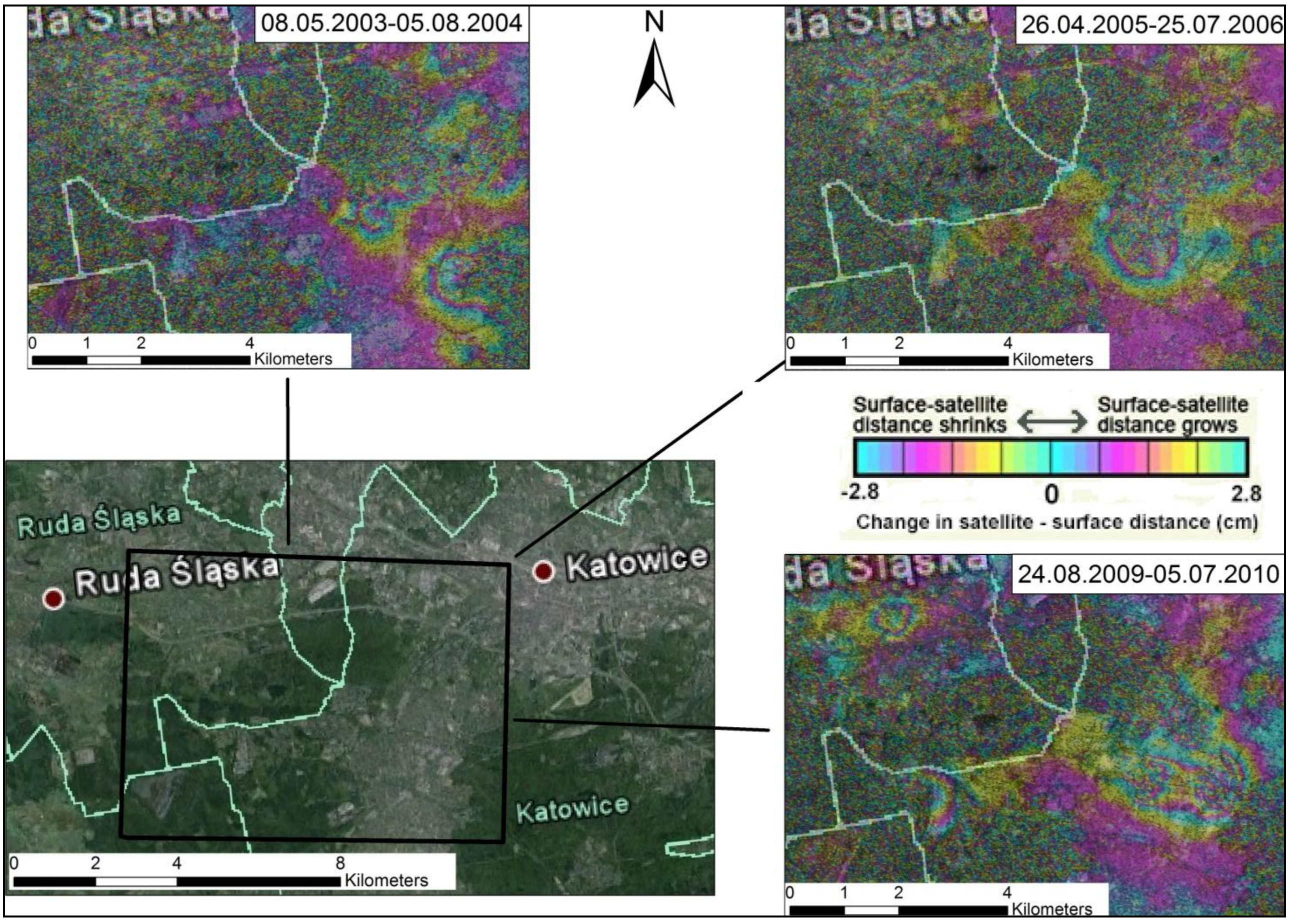

Fig. 4. Large subsidence detected with larger Btemp ~in a year time range in Ruda Śląska, used images: Envisat ASAR

The results of SBAS represented the subsidence caused by coal mining (coloured by purple, dark blue in Fig. 5) in Bytom, Katowice, and Piekary Śląskie cities with 5-7 cm/yr. For low coherent areas, e.g. dense forested areas, the SBAS method presented here did not work. The banded pattern which appeared (uplifting, subsiding) is related to the tectonic vertical movements in the region and to intensive coal mining. This pattern matches the known faults e.g. Kłodnicki fault and lithological contacts within productive Carboniferous sediments (Upper Silesian Sandstone Series and Mudstone Series) (Graniczny et al., 2006, 2008, 2011; Ventisette et al., 2013). Unfortunately, the PSInSAR analysis did not work in areas strongly affected by coal mining, due to very high levels of subsidence. The PSInSAR limitations appear mainly when the displacement rate is too high (called "fast" deformation phenomena) and it mainly provides long temporal time series deformation of the surface (Crosetto et al., 2009; Peltier et al., 2010). With this technique it is problematic to measure deformation rates above 4-5 cm/yr, whereas its sensitivity is suited to small deformations, which in terms of deformation velocity are in the region of 1 mm/year (Crosetto et al., 2009). The SBAS method also showed the fast uplifting areas in Zabrze and Bytom approx. 0.5-0.9 cm/yr (Fig. 5). On stable and minor uplift areas the active mining had finished, thus it resulted in changes in different hydrogeological conditions. After mine closures, the groundwater levels rise resulting in a small uplift, especially around any fault zone (Przyłucka et al., 2015). In addition the uprising region in the Carboniferous sandstones contain high percentages of argillaceous binder and common swelling minerals, which have low strength and high strain features, thus these rocks are sensitive to the influences of water (Ventisette et al., 2013; Graniczny et al., 2011). The time series analysis from SBAS is shown in Fig. 6. The B, C, E representative points were directly chosen from that areas where mining operations were closing or had closed in analysed time range. It represented by the concave shape of curves compared to the trend line (black), the intensity of subsidence has decreased, in counter to the A, D, F representative points, where the trend line matches the shape of the curves. It represents intensive, continuous underground coal mining during the time range.

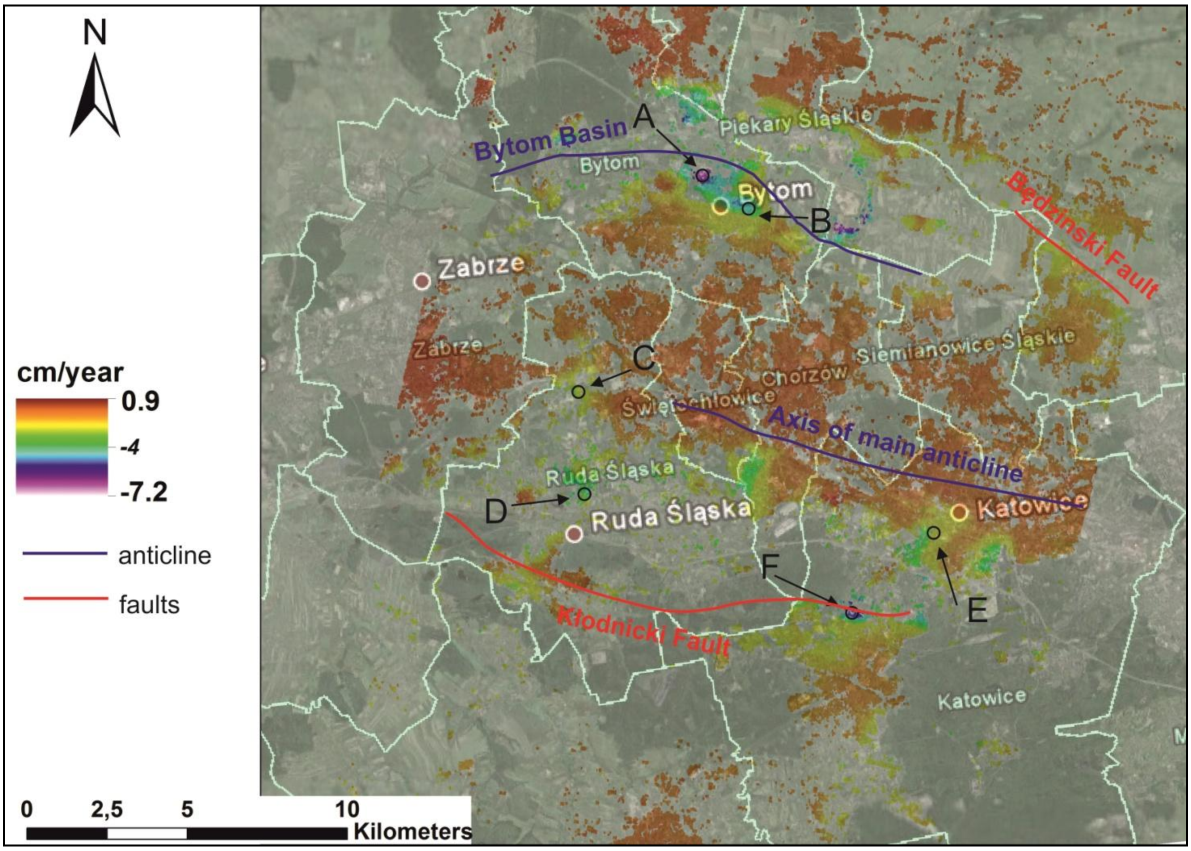

Fig. 5. The results of SBAS (Small BAseline Subset) technique used 31 ERS-2 images from the 1995-2000 period. The signed representative points on map are related to the time series analysis on Fig. 6. The anticlines and faults based on Graniczny et al., 2011

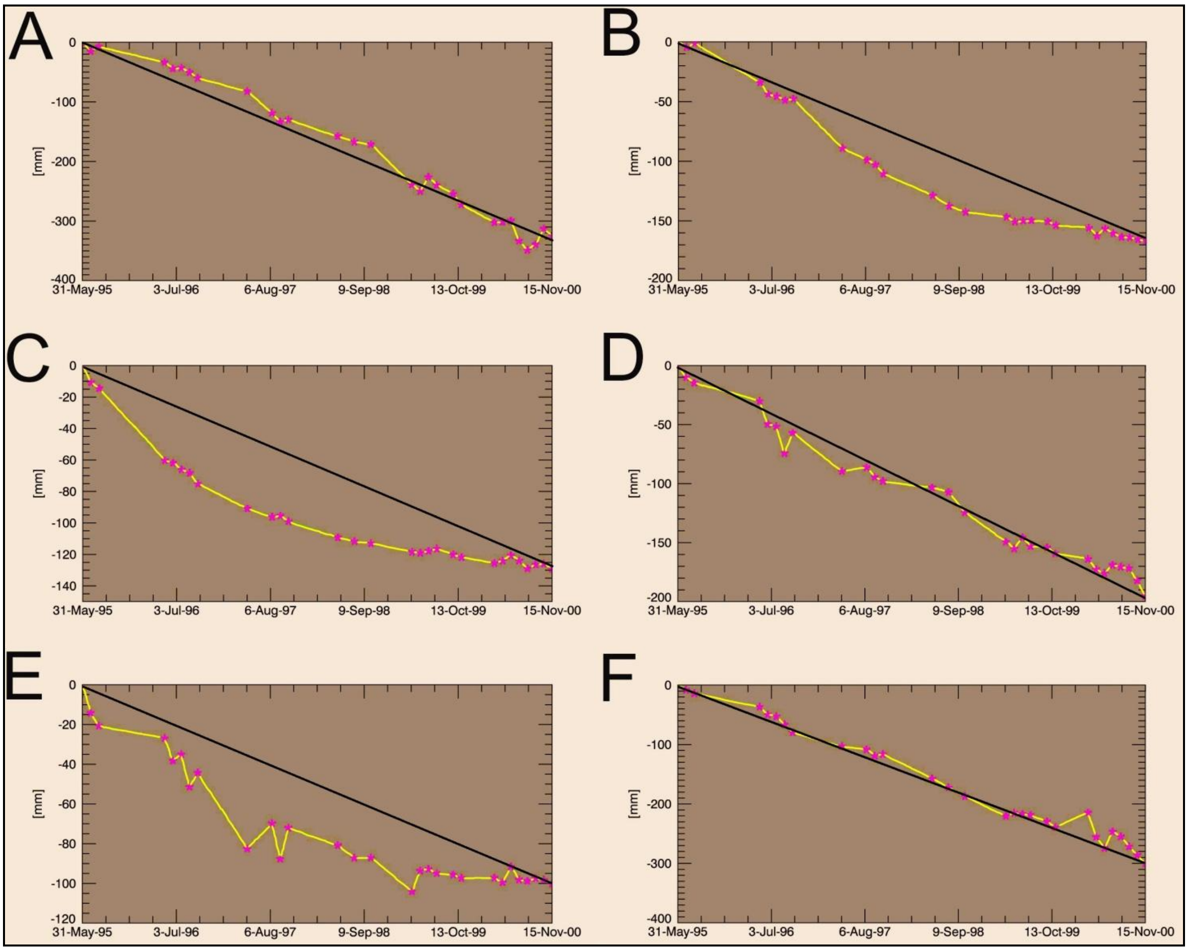

Fig. 6. The selected representative points for time series analysis from Bytom (A, B); Ruda Śląska (C, D) and Katowice (E, F) cities

The extension of the surface deformation related to the mine closures is also confirmed by the cumulated displacements (Figs. 7 and 8). Although, these images were less affected by tectonics and less precise than SBAS, the results achieved point to the most subsided areas and correlate well with Fig. 5. The most subsided areas were found in Bytom, Piekary Śląskie, Ruda Śląska, and Katowice. Large parts of these cities subsided during the period 1993-2000 as well as in 2003-2010, approx. 25-40 cms. The cities with the highest areas of subsidence were Bytom (~17 km^2), Piekary Śląskie (~15 km^2), Ruda Śląska (~42 km^2) and Katowice (~20 km^2) during 1993 to 2000. However, during the 2003-2010 period these areas were in Bytom (~8 km^2), Piekary Śląskie (~9 km^2) and Ruda Śląska (~32 km^2) where, in general, decreases relate to mine closures, and there was a slight increase in area in Katowice ~23 km^2. The surface deformations which occurred in the USCB are amongst the largest deformations found in coal basins around the world. Remarkable deformations appeared in the 1970s and 1980s during the intensive exploitation of a large part of the coal basin. The largest subsidence took place in the cities of Bytom, Katowice, Zabrze and Sosnowiec (Cabala & Cmiel, 1999; Cabala et al., 2004). It is worth noting, that during the 1949-2010 period of 1949-2010 in the city centere recorded subsidence appeared with approximately 7 meters (Skrzypczyk-Kogut, 2011). The results of Przyłucka et al. (2015) using TerraSAR-X over a one year period in the area of Bytom, showed faster displacements, which could have been potentially related to the centre of the mining bowl area that could not be detected due to interferometric decorrelation. Basing on a representative available geodetic data (2009-2014) provided for Karb, Miechowice districts and city center in yearly reports of Bytom city were confirmed DInSAR and SBAS results (Fig. 8). Unfortunately, earlier representative geodetic data was not available; however, these values showed several surface deformations. This intensive subsidence, appeared mainly in the Karb and Miechowice districts, however, in Karb mining was abandoned in 2012, which resulted in a lower subsidence intensity (Table 2). The City Centre measuring points generally showed fewer surface deformations. In addition, the geodetic measurements are generally agree well with the cumulated displacement maps, in contrary to the differences in the time of analysis.

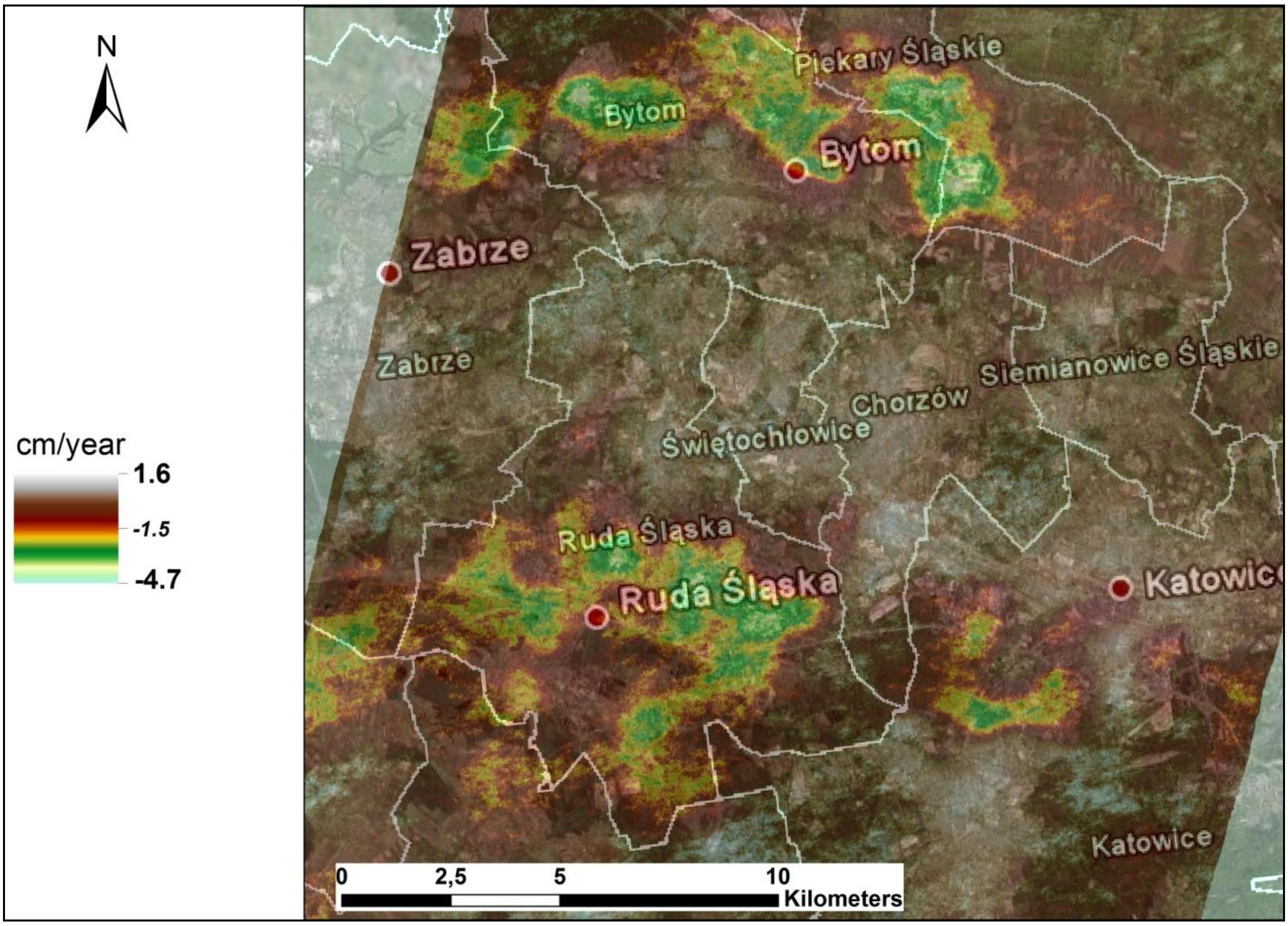

Fig.7. Stacked ERS1-2 images where the detected subsidence is related to coal mining zones during the period 21.05.1993–15.11.2000. The values are representative; the map mostly serves only to introduce the most subsided areas

Table 2. Geodetic information related to subsidence in different districts of Bytom (values in cms). Data source: Yearly reports on the state of Bytom city 2010-2014. (Skrzypczyk-Kogut, 2011, 2012; Domagała, 2013, 2014)

Measuring periods	City centre	Karb	Miechowice
Oct/Nov.2009-Oct/Nov.2010	1-16	1-180	3-90
Oct. 2010-Oct. 2011	2-15	3-90	1-50
Oct. 2011-Oct. 2012	2-12	1-22	0,5-147
Oct. 2012-Oct. 2013	2-15	1-20	2-170
Oct. 2013-Oct. 2014	4-8	1-6	7-172

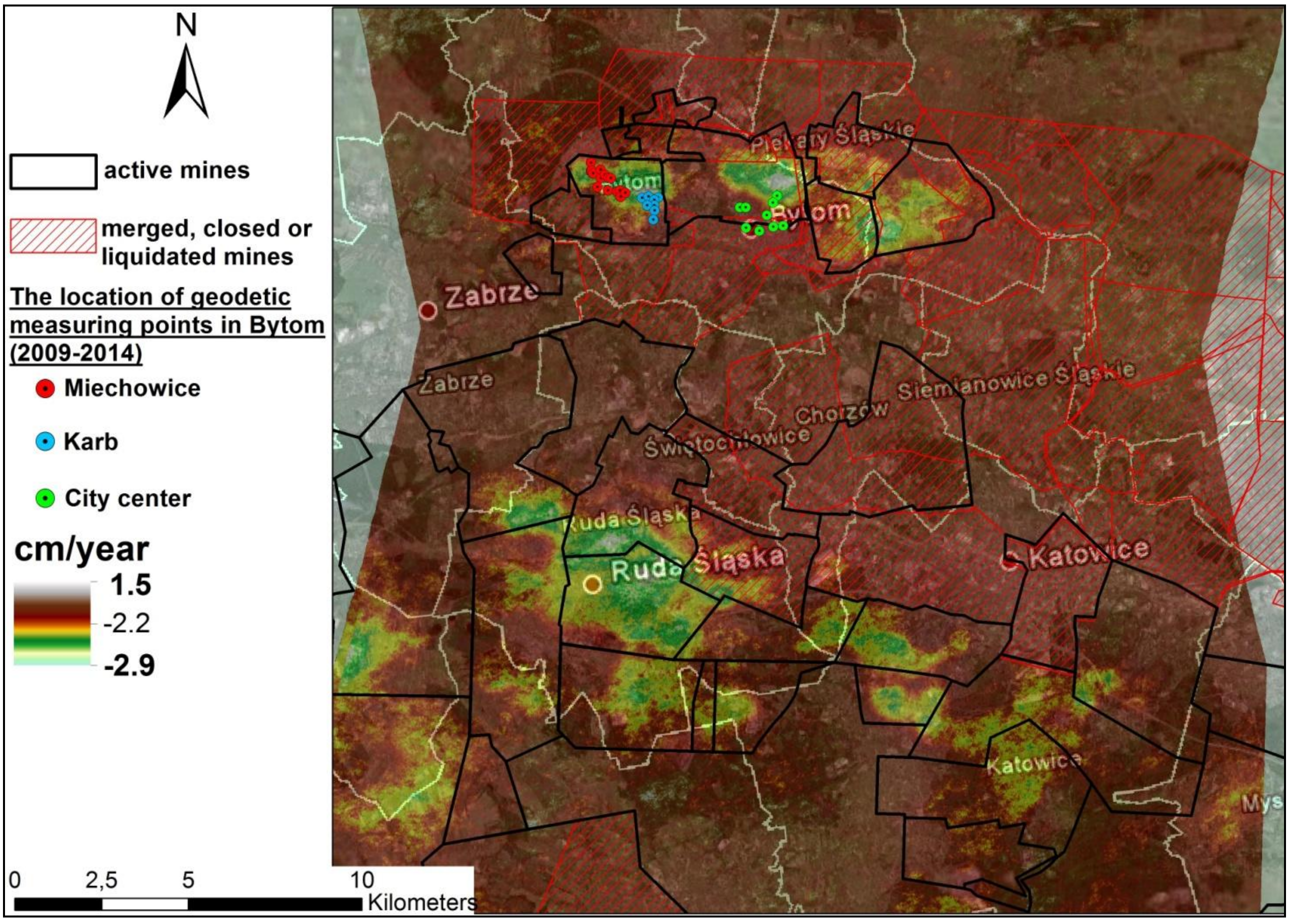

Fig.8. Mining caused subsidence from 08.05.2003– 5.08.2010 on Envisat ASAR layer stack, created with ascending-descending images from different paths. The values are representative; the map mostly serves only to introduce the most subsided areas together with the extension of active and inactive coal mines. The source of coal mining areas: http://dm.pgi.gov.pl/dm/DownloadManager_v1.aspx?lang=en, the data shows the status of mines in 2015

4. Conclusions

1) Thanks to the precise data from SBAS and the DInSAR layer the stacked images were suitable for detecting surface deformations during the periods presented 1993–2000; 2003–2010 with ~25-40 cm subsidence (in general).

2) The presented SBAS technique can be applied to high coherent areas e.g. highly urbanised areas and the detected subsidence caused by underground coal mining correlates with the layer stacked ERS1-2 image.

3) The influence of tectonics, intensive coal mining and mine closures were also shown by the SBAS technique as uplifting and subsiding.

4) The DInSAR layer stacked images indicate the most subsided areas, even under low coherent areas, but the results achieved are less precise. The received data also pointed to the decrease in several active mining areas, relating to the mine closures in Bytom and Ruda Śląska, which were also confirmed by the time series analysis.

5) The available representative geodetic data matched the cumulated deformation map despite the different time intervals; however, ERS1-2 and Envisat ASAR images have less precision.

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