

**DETECTION AND OBSERVATION OF UNDERGROUND COAL MINING-INDUCED SURFACE DEFORMATION
WITH DIFFERENTIAL SAR INTERFEROMETRY**

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ABSTRACT: Underground hard coal mining in the German Ruhrgebiet causes significant surface movements. Due to requirements by law, the German coal mining company *Deutsche Steinkohle AG* (DSK) is obligated to assess environmental impacts and to forecast effects of current excavations [1]. Required data are part of the "Geographic Information System" (GIS) and are integrated into the "Geo-Database" (GDZB) set up by DSK. With regard to the increasing demand for extensive information and cost effectiveness, DSK started to evaluate new observation and data processing techniques. It is important to monitor possibly affected areas with a nearly realtime up-to-date surveillance because occurring effects may entail lasting changes and influences on the environment. Especially methods of analytical and digital photogrammetry as well as remote sensing techniques may have the potential to be suitable techniques for a contemporaneous and economic monitoring of large areas [2]. As a rule of thumb, about 90% of the coal mining-induced subsidence will occur within one year of the excavations and movements have to be expected for nearly three years. A combined evaluation of spaceborne differential interferometric SAR (dInSAR) techniques, high accurate terrestrial observations, GPS-measurements and if available digital elevation models (DEM) or digital terrain models (DTM) from aerial imagery, airborne radar or laser imagery are promising for a precise monitoring of surface deformation movements like mining-induced subsidence for large areas.

1. INTRODUCTION

This paper presents the analysis and first results of a current research and development (R&D) project set up by DSK in cooperation with the *Institute for Photogrammetry and GeoInformation* (IPI), University of Hannover. One topic of the evaluations is to determine the potentials and limitations of differential interferometric SAR data collected by ERS satellites to monitor large areas in urban and rural regions. The dInSAR processing was performed by the Swiss company *Gamma Remote Sensing* (GAMMA). ERS satellite radar data is mostly uninfluenced by changing weather conditions. The data with relatively high spatial and temporal resolution of 35 days is of interest for monitoring purposes. Linked with terrestrial measurements like line levelling, EDM- and GPS-measurements or GIS data of the GDZB like active mining areas and subsidence models an interdependent evaluation and amendment can iteratively be performed for each data record. Up to date information concerning an ongoing excavation like the migration of the so called "zone of affected ground" can be acquired and documented. Connected with the GIS the combined methods allow to support an economic, independent and actual integration of information available from different sources.

First evaluations using differential InSAR methods for the detection of mining induced surface deformation were performed by GAMMA and DSK within the European Space Agency (ESA) Data User Programme: "Differential Interferometric Applications in Urban Areas" [3]. The results were promising and local analyses were performed for three mine sites located in the cities of Gelsenkirchen, Dorsten (1995–1997) and Recklinghausen (2000) with different extraction-, geological and topographic conditions. The satellite data for Recklinghausen will also be used to perform a 3D-analysis based on ascending and descending orbit data.

For these three mining areas levelling lines have been measured during and after the active mining as terrestrial reference. After the parameters of the excavations were available within the GDZB so called "Subsidence Model Calculations" were performed. With this information it is possible to build up and compare a time-series of highly accurate punctual terrestrial data and the subsidence map derived from ERS satellite data. If these independent data takes will contain similar height-change values it will be possible for

the first time to perform a real-time subsidence-monitoring accompanying the current mining activities. For more information about the ERS dInSAR processing see [4, 5, 6, 7].

2. REFERENCE DATA

2.1 Photogrammetric Data

Since the 1980s aerial images are used for photogrammetric data capture of topographical surface changes. DSK has developed an archive of digital terrain models (DTM) annually or bi-annually measured by analytical photogrammetric plotters, images matching techniques and, in the latest years, DTM gathered by laser-scanner records. These DTM and the used ground control points (GCP) that are necessary for the triangulation of the aerial images serve as reference data for the present evaluations. Most of the GCP could be retrieved after several years and can therefore serve to combine and connect the available data of the GDZB and the new collected satellite data by using current GPS-measurements. The reference data is originally measured and mapped within the Gauß-Krüger coordinate system so it has to be taken into account that differences between the geodetic datums of terrestrial, airborne or satellite measurements still have to be expected. To bridge the gaps of time between the different measurements and evaluation periods the photogrammetrically measured DTM can be corrected and subsided using the "Subsidence Model Calculations" [8].

2.2 Terrestrial Measurements

Accompanying the excavations DSK performs extensive terrestrial measurements on levelling lines and ground control points. But according to the improvements the measurement methods changed within the years. Often only the changes in height and extension were recorded for each point but not the accurate position. Mostly the point positions were approximately marked on the maps by hand and had to be re-digitized from large-scale maps or re-measured by GPS-based traverse-lines. Only for the area of Recklinghausen the points of the levelling lines have been exactly determined with GPS-measurements.

2.3 Subsidence Model Calculation

The "Subsidence Model Calculation" is performed in two steps. Before the mining activities start extraction plans are used as model input to receive an overview of the expected environmental impact. After the real mining operation started parameters as the geometry, velocity and the amount of extracted matter are known and the influences can be more precisely estimated (BBVB) [9]. For the comparison with the dInSAR results the terrestrial measurements have to be adjusted to the ERS revisit times. All available information on geology, mining geometry, thickness of the coal seams and further information for each production panel was used to re-calculate the height differences between the moment of the terrestrial measurements to the time the satellite data were recorded.

2.4 Geo-Database (GDZB)

Since 12 years DSK has been using geo-information technologies at several departments for applications dealing with the acquisition, processing, analysis and presentation of all data needed for planning purposes and the daily work. Over the years a complex but well structured archive, the Geo-Database (GDZB), with all data concerning the coal mining activities and the monitoring of environmental impacts has been built up and was handled at the department DIG.

The reference data for the works on the dInSAR data were taken from the GDZB. The radar data, all DTM and subsidence models as well as the derived final results shall be included in the GDZB to be available for future access.

3. ANALYSIS

3.1 Survey Investigation: "Ruhrgebiet"

The use of dInSAR techniques to derive subsidence movements could be recognized after first interferograms covering the whole Ruhrgebiet were processed by *GAMMA* without any additional information [10]. Figure 1 presents a subset of an area of 25 km to 25 km wherein the fringes of movement structures can clearly be seen (figure 1, left image).

After the satellite scene was georeferenced to the Topographic Map 1:50.000 (TK50) the interferograms could be overlain with the active production panels at both dates the satellite data was recorded. For less vegetated and urban areas the detected fringes showing subsidence movements are centered to the production panels (figure 1, right image).

These first results were promising and more detailed evaluations for smaller areas were performed. For the years from 1995 to 1997 *GAMMA* processed ERS data for the mines of Gelsenkirchen and Dorsten. ERS SAR data for the year 2000 were also processed to survey the city of Recklinghausen. At DSK all available terrestrial and photogrammetrical reference data like DTM, line

levelling data, "Subsidence Model Calculation" and geometric mining conditions were taken from the GDZB or re-measured when needed. The height information for the levelling points was then adjusted to the satellite data using the parameters of the BBVB.

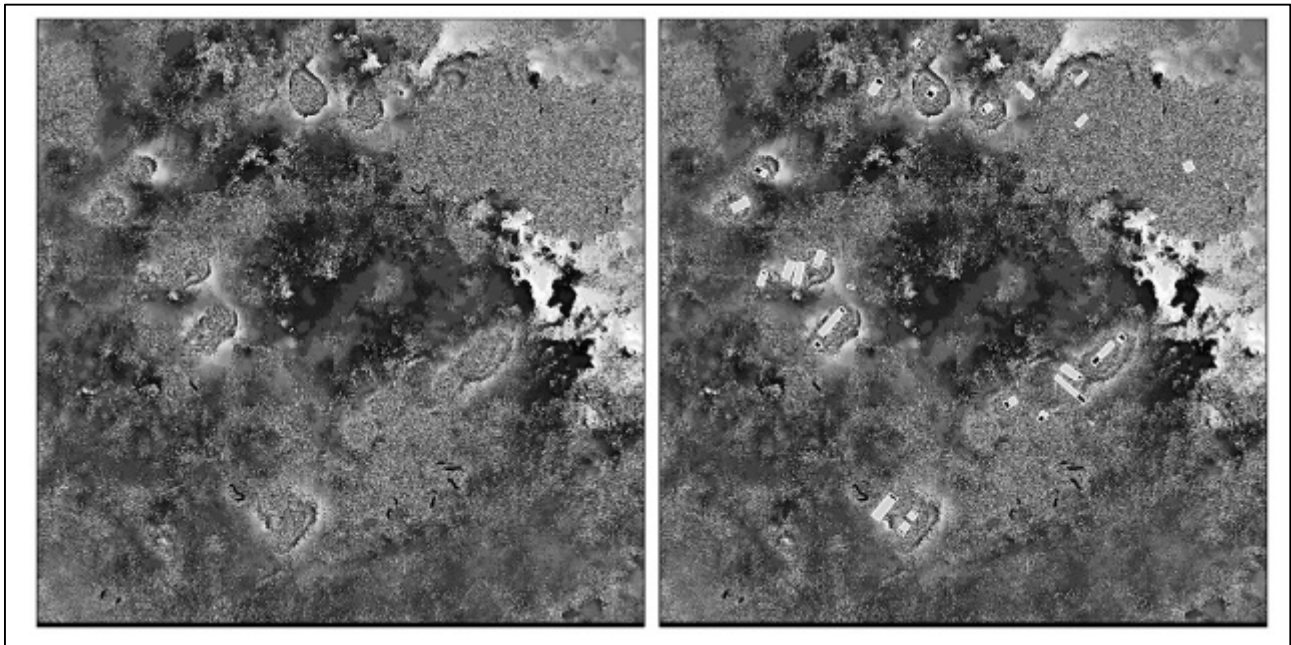


Figure 1: Interferogram: December 12th, 1996 to February 2nd, 1997. Left image without, right image with the overlay of the excavation information at both dates for active production panels. (Gray: December 12th, 1996, black: February 2nd, 1997). Region: 25 km x 25 km.

3.2 Detailed Investigation: "Gelsenkirchen-Erle / Parkstadion"

For this mine site several levelling lines and a DTM measured with analytical photogrammetric plotters were used as reference data for the evaluations. The levelling lines used are shown in figure 2 (upper left image). *GAMMA* processed the dInSAR data and performed the geocoding based on the TK50. Afterwards the subsidence calculated from the interferograms was compared with the adjusted height measurements for each point of the levelling lines.

The DSK subsidence model derived by the "Subsidence Model Calculation" shows parts westward of the "Parkstadion" and in northern Erle that, compared with the terrestrial measurements, include subsidence anomalies (figure 2, upper left image). To reveal the reasons for these anomalies would mean a large effort of subsidence calculations for each production panel because the region was densely mined out within the years 1992 to 1997 (figure 2, upper right). The most probably reason for the subsidence anomaly might be that a production panel mined out in 1993 did not completely collapse after mining ended. When new mining activities started again in the neighborhood in 1995 the old left-over wholes in the ground broke down and caused the additional subsidence observed. Because no reasonably stable subsidence parameters could be derived for a larger area the "Subsidence Model Calculation" were not performed for the adjustment of the levelling-data to the ERS revisits. For this reason the levelling-data was approximately adjusted by linear interpolation.

In figure 2 (lower left) it can be seen that from November 1996 to February 1997 the dInSAR data contains low coherence caused by the long baseline of 323 meter. This is the reason why the solving of the ambiguities (*phase-unwrapping*) [4, 5] could not be properly calculated and the fringes could not be separated as well as for the other interferograms.

Nevertheless the interferograms can precisely represent the location of the so called "zone of affected ground" that separates static areas and dynamic regions with beginning subsidence movements. At these places high tensions occur within the ground and mining-induced subsidence leads to the most heavy impacts on infrastructure. Furthermore the interferograms show an area in the south-east where the "zone of affected ground" does not migrate and seems to be static. This phenomenon depends on the special geotectonic conditions in the underground.

The images in figure 3 present the comparison of movements for the points of three levelling lines. One unit of the vertical axis presents one centimeter of subsidence. The dInSAR profiles are very similar to the measured subsidence just up to an amount of about 8 cm. So the *phase-unwrapping* technique is first of all able to detect subsidence movements within the wavelength (5,6 cm) of the ERS radar system. The subsidence profiles contain a small offset to the levelling profiles. This offset may depend on a reference point for the SAR processing that might not be taken from a static area.

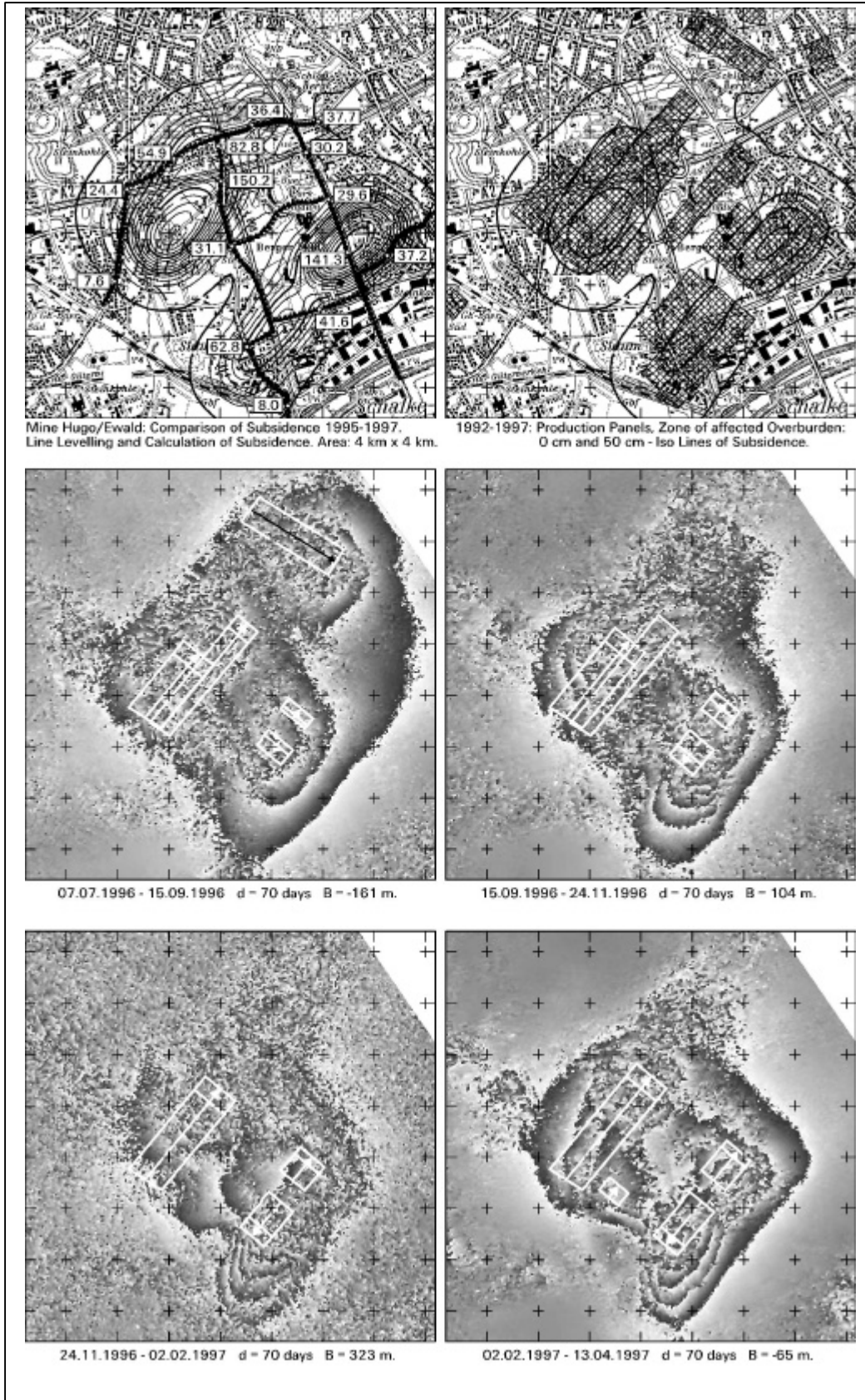


Figure 2: "Subsidence Model Calculation" with 10 cm iso-lines of subsidence compared to selected leveling-points (u.l.). Production panels from 1992 to 1997 overlain with 50 cm iso-lines of subsidence (u.r.). Interferograms from July 7th 1996 to April 4th 1997, ERS revisit: 70 days. Geocoded and superimposed with the TK50 and the current active production panels (mid and lower row). Area: 4 km to 4 km.

The profile of the levelling lines 3-20-19 show at first glance a lower accuracy what depends upon the lower coherence and therefore higher phase-noise in these regions. Such low coherence areas can be detected and masked out from the further processing. Very good results can be seen on the levelling line 6. Line 5 shows that the limit of the *phase-unwrapping* to detect surface deformation movements is reached at 6 to 8 centimeters. For higher deformation rates the phase gradients became too large to be correctly solved. On the other hand it also has to be taken into account that the reference data may contain inaccuracies that have to be determined. Regarding the levelling profiles, line 5 for example, shows gaps caused by destroyed points (no. 30 to no. 32) or false height measurements like point no. 45.

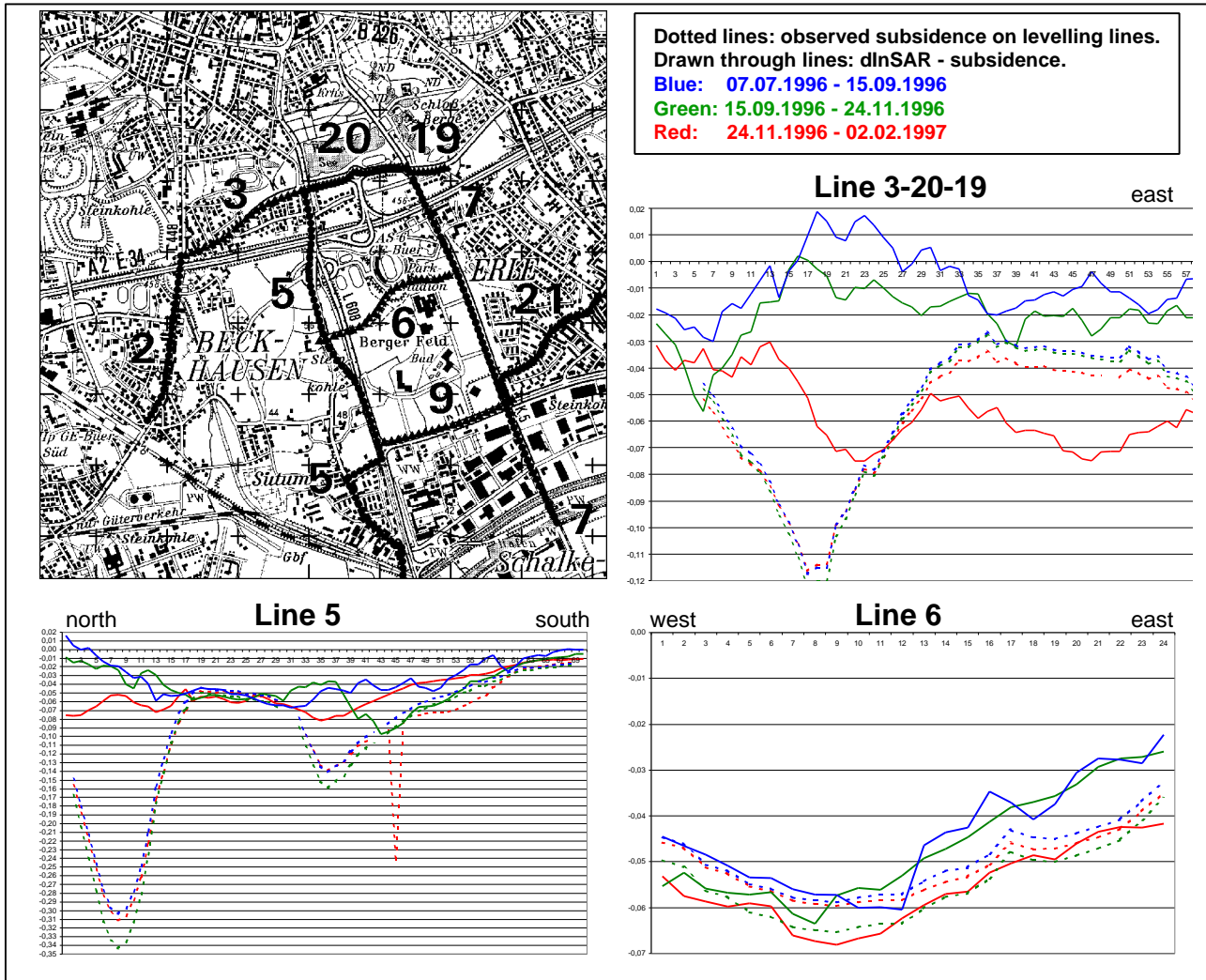


Figure 3: Gelsenkirchen-Erle / Parkstadion: Location of levelling lines (u.l.) and comparison of observed and dInSAR-derived subsidence. Horizontal line unit: 1 cm of subsidence. Image area: 4 km x 4 km.

Once again it should be mentioned that the analysis presents first and preliminary results. It can be assumed that the detection-range might be enlarged, for example if approximate values from the "Subsidence Model Calculation" will be available to improve the phase ambiguity resolution.

3.3 Detailed Investigation: "Recklinghausen"

The dInSAR analysis for Recklinghausen is currently still ongoing so that only first results can be presented. As reference data serves an analytically measured DTM from aerial images and line levelling data collected every three weeks accompanying the mining activities in 2000. About 90 points of the lines were re-measured by GPS in November 2000 and May 2001 close to ERS revisits. In the city of Recklinghausen three permanent GOCA-GPS [11] receivers recorded three dimensional movements to a reference station located in static parts on a building at the mine site. So this data may serve as reference data for a planned future analysis of 3D-movements from ERS ascending and descending data. First comparisons of levelling and dInSAR subsidence data are presented

in figure 4. This comparison is based on the assumption that only vertical displacements occurred but further analysis will include the combination of ERS SAR data acquired in ascending and descending mode.

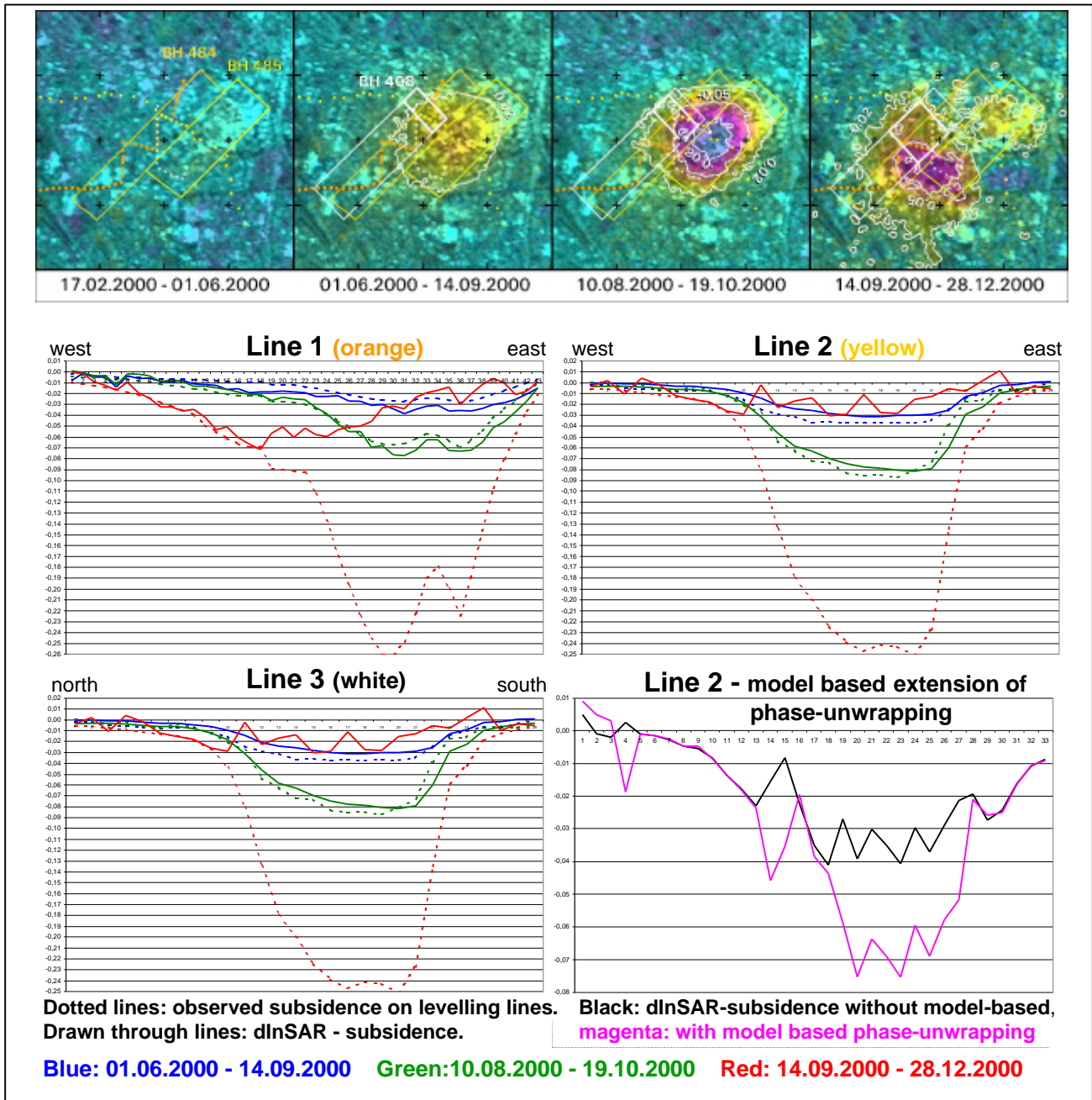


Figure 4: Recklinghausen: Upper row: movements derived by ERS-dInSAR - one color-cycle corresponds to 12,8 cm vertical subsidence, superimposed with 2 cm, 5 cm and 8 cm contour-lines. Image area: 2 km x 2 km. Production panels: BH 484 (Jan. 98–Dec. 98) - orange, BH 485 (Apr. 99 – Nov. 99) – yellow and BH 408 (Jul. 00–Jul. 01) – white; points of levelling lines 1 (orange), 2 (yellow) and 3 (white). Comparison of subsidence movements for levelling and dInSAR data (mid row, lower left). Lower right: comparison of subsidence derived by *phase-unwrapping* techniques without (black) and with model-based approach (magenta).

For a better overview the images present the movements derived by dInSAR techniques (one color-cycle = 12 cm vertical subsidence). They are superimposed with the former production panels: BH 484 (January 1998 to December 1998, orange) and BH 484 (April 1999 to December 1999, yellow). The slight green-yellow colors to be seen in the left image still show little amounts of remnant subsidence caused by BH 485. In July 2000 mining activities started again with BH 408 (July 2000 to July 2001, white). The fat solid white rectangle shows the excavation between the ERS revisits. Within the second and third image it can be seen that the developing subsidence trough follows the mining activities but the center lies southward of the current working field in BH 408, amid the excavated BH 484 and BH 408. This effect depends on the already fractured rock strata in the south caused by BH 484 and BH 485 and the more stable underground northward of BH 408. For these periods with beginning movements up to 10 cm in maximum

for the ERS observation intervals the comparison of the levelling profiles and the dInSAR profiles shows the high similarity with a maximum difference of 2 cm. For the time period of the last image (u.r.) subsidence movements up to 30 cm have been observed with levelling and, as for Gelsenkirchen, again the dInSAR processing worked correctly only for movements up to 8 cm. A first model based attempt to enlarge the detection range of the *phase-unwrapping* with additional height information gained from the levelling lines was processed by *GAMMA*. The profiles in figure 4 (lower right image) show that the model based approach leads to a better representation of the subsidence trough than before but the maximum amount to be detected is still 8 to 10 cm. Further work to enlarge the detection range of subsidence movements with ERS dInSAR techniques with additional information are still going on.

An alternative to avoid this phase-unwrapping problem in the case of high phase gradients as observed for active excavation sites is to use a SAR sensor with a longer wavelength. First interferograms derived from L-band SAR onboard the Japanese JERS satellite for a region in the northern Ruhrgebiet confirms this and leads to the expectation that dInSAR processing with JERS-, or in the future, ALOS-data will be well suited for the detection of the absolute amount of movements caused by underground coal mining even for agricultural land and forested areas [12].

3.4 Integration into the Geo-Database (GDZB)

In chapter 2 it was described that reference data and "Subsidence Model Calculations" were taken from the Geo-Database GDZB. In similar ways new information sources like GPS- and dInSAR derived data sets, as subsidence maps or the position of the "zone of affected ground" shall become part of the GDZB. Thus, this data can be more easily provided to all potential users within the whole company. Figure 5 gives a small overview of how the data can be utilized for different tasks by different internal users.

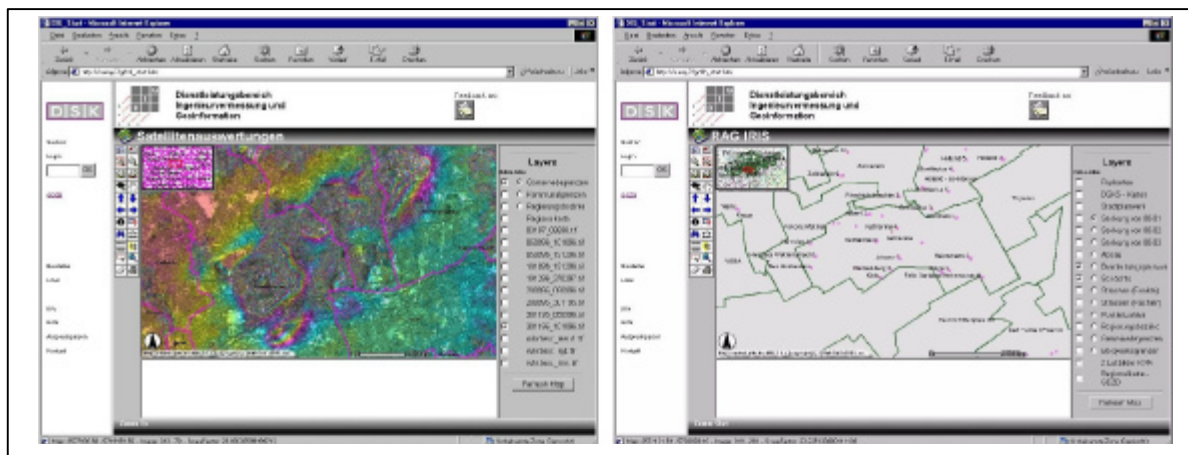


Figure 5: Integration into DSK-GDZB. Left image: overview of dInSAR subsidence and administrative information; right image: geographic operation information - active mine sites, shafts, air-shafts, old mining areas.

4. SUMMARY OF THE FIRST RESULTS AND OUTLOOK

This paper presents first results of an ongoing research and development project (R&D). Further analysis and validation will be performed within the project term.

As yet the comparison of terrestrial measurements and spaceborne dInSAR evaluations already clearly show the high potential to resolve little amounts of subsidence movements up to nearly one decimeter for an acquisition period of two ERS-data sets. For movements larger than 10 cm within an acquisition period the *phase-unwrapping*, even supported by a first model-based approach, can not definitely solve the ambiguities. The model-based *phase-unwrapping* approach will further on be modified and tested.

At the moment the maximal amount of subsidence caused by underground coal mining activities cannot be derived. Nevertheless, the dynamical change of topology and the shape of the migrating subsidence trough can be observed. Especially the position of the so called "zone of affected ground", the border of static and dynamic areas, can be detected with a high spatial accuracy covering large areas. With the high repetition rate of 35 days ERS-dInSAR methods can be used to back and estimate parameters for the "Subsidence Model Calculations" (BBVB) and in combination with terrestrial and GPS-measurements to correctly derive the absolute amount of subsidence.

The next analyses to be performed in the R&D-project shall examine the potential of a combined evaluation of terrestrial, photogrammetric, as well as airborne and spaceborne InSAR techniques to derive and validate 2D- and 3D-movements caused by underground mining activities, especially to delimit mining-induced subsidence against movements affected by other influences. Although only some small areas have been processed yet it can be stated that the data processed with dInSAR methods owe the potential to be a perpetual testimony for the whole area of interest. These data sets and knowledge about the accuracy could be very useful against objections of third parties who may use such data sets as well.

The currently operating radar satellite-systems use short wavelengths of about 5 cm so that only areas with high coherence like urban areas, settlements or rural regions with small amounts of changes (from autumn to spring) can be observed. The coal mining activities in the German Ruhrgebiet expand northwards into regions with primarily agricultural use where radar systems with longer wavelengths will lead to better results for the detection of movements. Such a system was the Japanese satellite JERS (1992-1998). For the year 2002 the launch of ENVISAT is expected. This satellite uses almost the same wavelength as the ERS satellites. Another system will then be the ALOS PALSAR, the successor of JERS, to be launched in 2003. Because of the promising results DSK will participate as co-investigator of GAMMA in an early-on evaluation of the potential of ALOS / JERS and ENVISAT data.

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