Monitoring of mining-induced surface deformation in the Ruhrgebiet (Germany) with SAR interferometry

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ABSTRACT

Subsurface coal mining causes significant surface deformations. In this contribution the potential and limitations of ERS repeat-pass differential SAR interferometry for mining induced surface deformation monitoring is evaluated based on the example of the German Ruhrgebiet. ERS data in ascending and descending mode, including Tandem pairs suited to estimate the topography related phase, are used for the analysis. Especially for urban areas the technique performs well as confirmed through validation with mining information. The main limiting factor identified is temporal decorrelation of the signal which does not allow estimation of surface deformation velocities in forested and in many cases agricultural areas.

INTRODUCTION

Underground coal mining in the German Ruhrgebiet, currently at depths of about 950m, causes significant surface movements [1,2]. Due to legal requirements, the German coal mining company Deutsche Steinkohle AG (DSK) is obligated to assess environmental impacts and to forecast effects of current excavations. Important data required are Digital Elevation Models (DEM), deformation maps, and information on land-cover. With regard to the increasing demand for information and cost effectiveness, DSK started to evaluate new survey techniques including remote sensing.

In this contribution the evaluation of the potential and limitations of ERS repeat-pass differential SAR interferometry for surface displacement monitoring in the Ruhrgebiet is presented.

DATA SELECTION AND METHODOLOGY

Nine ERS-1/2 SAR acquisitions in descending mode and eight in ascending mode were selected for this investigation. For each mode the selection included two Tandem pairs suited to estimate the topography related phase. Winter acquisitions were preferred for the higher coherence over agricultural areas. In spite of the very high population density in the Ruhrgebiet most of the subsiding area is non-urban.

All ascending and all descending scenes were registered separately to common geometries. Interferometric processing included common-band filtering. At the time of the processing no appropriate homogeneous digital elevation model was available for the entire 100 km x 100 km area of the ERS scenes. Therefore, the topography related phases were estimated from one of the Tandem pairs and subtracted from the longer time interferograms. The phase noise of the differential interferograms was reduced using an adaptively bandpass filter. Further discussion on the differential interferometric processing steps is found in [3,4].

Considering the high deformation velocities expected for the active mining areas we selected pairs with short acquisition time intervals (35 or 70 days) and short spatial baseline (possibly less than 200 m). For the analysis of areas with slower movements (e.g. over old excavation fields) interferograms with around one year time intervals and very short spatial baselines (less than 50 m) were preferred. In this case, interferogram stacking [5], a technique to reduce the atmospheric error on the subsidence velocity estimation, was applied.

In a first step, only the differential interferograms were considered in order to study when and where information is available from SAR interferometry. For this purpose, the differential interferograms were geocoded to the German Gauss-Krüger coordinate system with 25 m pixel spacing. In a second step, some of the differential interferograms were unwrapped and converted to displacement velocities in cm/year. The results were again geocoded for the validation with subsidence information retrieved from levelling campaigns and calculated by a subsidence model based on actual mining data.

QUALITATIVE EVALUATION OF RESULTS

The differential interferograms were compared to mining plans of the area in order to verify the correspondence between the information content of the interferograms and the mining activity at the coalfields. The available mining information consisted of the location of the mining at the SAR acquisition dates, the mining direction, and the number of days of active mining prior to the first acquisition. A clear correspondence between all the signals observed with SAR interferometry and active coalfields was identified. The surface displacement took place where coal extraction was ongoing. Complicated shapes of surface displacements can be observed in the case of simultaneous activity in neighboring fields. Outside of the urban areas the surface displacements can often not be observed with SAR interferometry due to low coherence.

QUANTITATIVE EVALUATION OF RESULTS

The retrieval of quantitative surface displacement information with differential SAR interferometry requires phase unwrapping. From the complex interferogram the interferometric phase is only known Modulo 2π and, in order to be able to convert the interferometric phase to surface displacement, the correct multiple of 2π has to be added. Phase unwrapping is a problematic step due to discontinuities and inconsistencies (residues as a result of high phase noise). Phase unwrapping of selected interferograms was performed over some of the active coalfields. In this analysis we were particularly prudent in order to avoid phase unwrapping errors. As a consequence, some areas of the differential interferograms could not be unwrapped. Another important fact is that the interferometric observation corresponds to the displacement along the SAR look vector. After phase unwrapping the surface displacement along the look direction of the satellite (approximately 23° incidence angle for ERS) can be quantified.

For mining areas with high deformation velocities, interferometric pairs with short acquisition time intervals of only one or a few 35 day repeat cycles are preferred. Four displacement velocity maps of a small area with active mining showing the observed deformation for different time periods, are shown in Figures 1a to 1d. The deformation velocity is indicated along the look direction of the satellites since vertical displacement of the mining induced subsidence cannot be assumed. The maximum displacement per 35 days was on the order of 6 cm. This sequence of observations clearly reflects the progress in the sub-surface coal excavation. During the first time period (Sept. - Nov. 1995, Figure 1a) relatively fast deformation is observed with the maximum velocities near the image center. Almost no deformation was observed for the time directly following the first period, reflecting that the excavation has stopped (Figure 1b). In fall 1996 we observe again fast deformations, but this time with the center about 1 km further to the East (Figure 1c). This activity stopped again as indicated by the much slower deformation velocities observed in early 1997 (Feb. - Apr. 1997, Figure 1d).

Detailed studies and a quantitative validation with excavation plans, deformation modeling, and comparison with levelling data are ongoing. The high dynamics of the mining induced deformation are complicating the direct comparison of results obtained with different methods. In particular the validation of deformation information with a relatively high temporal resolution, as feasible with SAR interferometry, is difficult due to the typically lower temporal resolutions of the other methods. From the examples looked at it becomes clear that phase unwrapping is one important limitation in the case of noisy data with sparse coherent areas. Nevertheless, the examples also demonstrate the feasibility of the interferometric technique for the Ruhrgebiet.

In Figures 1a to 1d the surface displacement in the look direction of the satellite is indicated. However, for displacement studies in the region it is of interest to know the complete 3-dimensional displacement field. In the case of mining induced surface deformation the assumption of vertical subsidence, as used in the case ground-water extraction related subsidence, is not correct. Even the combination of ascending and descending interferograms, which allows to retrieve the displacement along two directions is not sufficient to derive the full 3-dimensional displacement vectors. Subsidence models may be able to provide the missing geometrical information, though.

CONCLUSIONS

The use of ERS repeat-pass differential SAR interferometry for mining induced surface deformation monitoring in the German Ruhrgebiet was demonstrated. Especially for urban areas the technique performs well as confirmed through a qualitative validation of the interferometric result with mining plans. Data selection was found to be important for the influence of the acquisition interval, baseline, and the seasonal differences in the vegetation cover, on the coherence. The main limiting factor identified is temporal decorrelation of the signal which does not allow estimation of surface deformation velocities in forested and in many cases agricultural areas.

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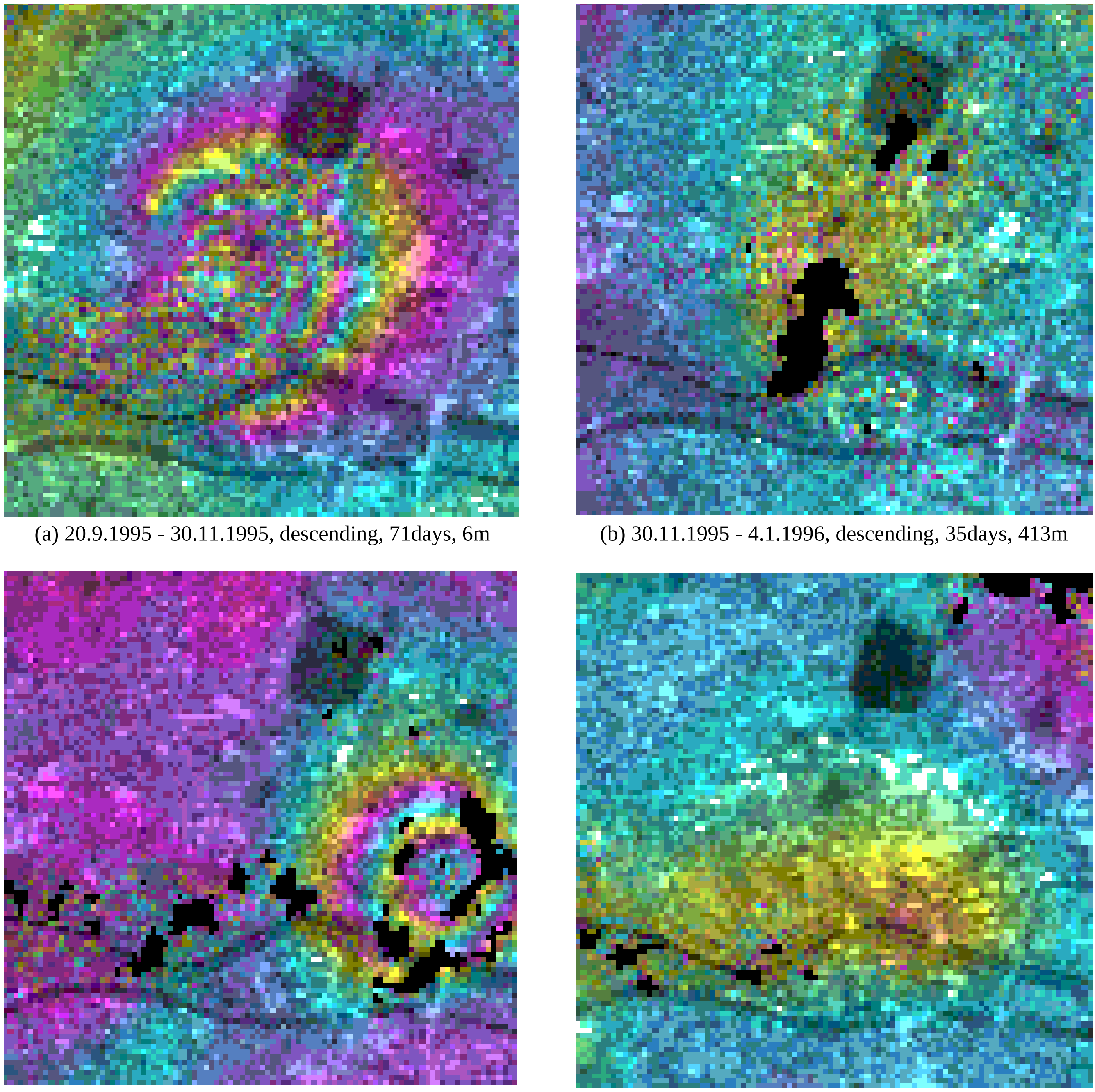

(a) 20.9.1995 - 30.11.1995, descending, 71days, 6m

(b) 30.11.1995 - 4.1.1996, descending, 35days, 413m

(c) 5.9.1996 - 10.10.1996, descending, 35days, 30m

(d) 2.2.1997 - 13.4.1997, ascending, 70days, 65m

Figure 1. Deformation maps for an active coal mining site in the Ruhrgebiet, Germany. The images are in the Gauss-Krüger coordinate system and have a width and height of 2.5 km, each. The colors indicate the surface deformation along the SAR look vector for the indicated time periods. One color cycle corresponds to a displacement of 2.83 cm. For the image brightness a backscattering intensity image was used. Below each image the time period, the orbit mode, the acquisition interval, and the perpendicular baseline component are indicated.