SUBSIDENCE AND UPLIFT AT WASSENBERG, GERMANY DUE TO COAL MINING USING PERSISTENT SCATTERER INTERFEROMETRY

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Abstract: The town of Wassenberg is situated in western Germany close to the border with the Netherlands. Black coal mining activity in this area (district of Erkelenz) started in 1914 and stopped in 1997. Until 1997, this caused subsidence of up to 3 meters in the period 1953-1997. When mining operations ceased, the drainage of the mine also stopped causing ground water to invade the empty space. Once it reached the lower bound of the overburden, this resulted in surface uplift. In particular, the strongest movement was detected during 2001 to 2004, with an estimate of 8 to 9 cm uplift. The geophysical structure of the region made the uplift to be discontinuous in space. In fact, Wassenberg is crossed by the Meinweg fault creating a natural limit to the mining subsidence and consecutive uplifting. The goal of this paper is to present results of the study and analysis of this land movement using Persistent Scatterer Interferometry, PSI. The employed time series started in 1992 and continued until 2007, covering both periods of subsidence and uplift. The data were acquired by the satellites ERS1/2 and Envisat.

1. INTRODUCTION

The mine district of Erkelenz, figure 1, in the state of the North Rhine Westphalia, is located in central western Germany in the border with the Dutch province of Limburg. The geology, very rich in coal, drove the economy of the region since its exploitation begun in 1914 until the closure of the last shafts in 1997. The influence of the mining was also reflected in the ground morphology, parts of the land subsided down to several meter since the coal extraction started. The hydrology was also affected, because the water was continuously drained from the mines.

The Sophia-Jacoba mine opened the first shaft in 1914, and the second in 1946 both in the Wassenber horst (see I and II in figure2). They closed in 1980. In the areas 1, 2, 3 and 4 in Northeast and Easte of Wasssenberg, the coal was extracted from 1978 till 1997.

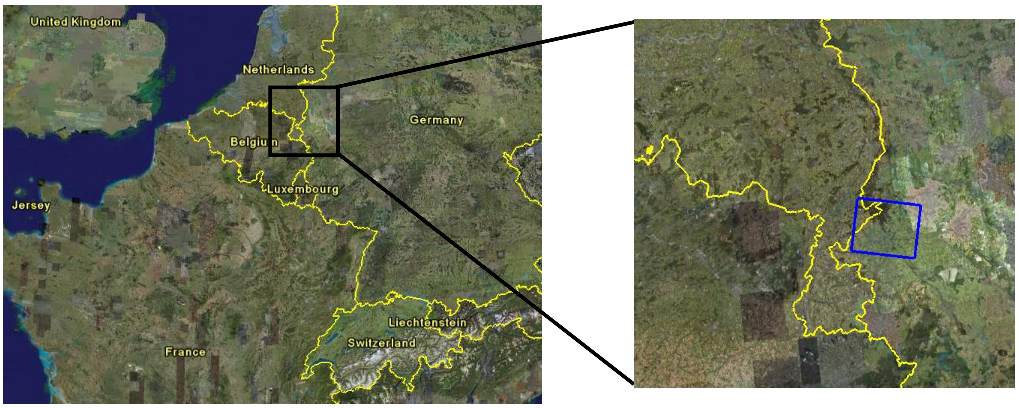

Figure 1: Location of the processed area, blue rectangle, (Google Earth).

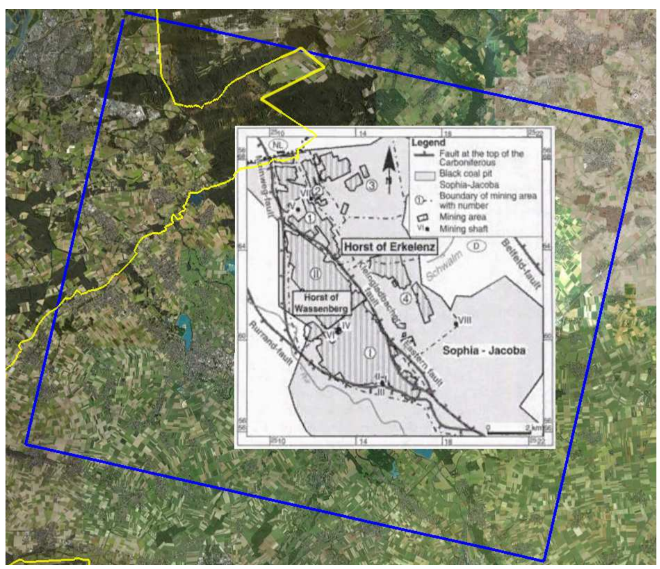

Figure 2: Location of the mines, after Heitfield et al. 2004, and the processed area, blue rectangle, (background from Google Earth)

Once the mines were abandoned the drainage of the water stopped with it. As a consequence, the water re-entering the mine resulted in ground uplift. The amount and rate of the uplifting depends on the geology of the terrain. Clay will swell in contact with water, but it seems that the major contribution is the increase of the pore pressure in the rock mass, [Bekendam et al. 1995]. In addition, Wassenberg is crossed by the Meinweg fault creating a natural limit to the mining and consecutive uplifting. Hetfield et. al (2004) reported a maximum uplift of 1-2 cm per year until 2000.

It was then that the water level in the mine reached the overburden boosted the uplift to a maximum of 3-4 cm per year, from the end of 2001 to May 2003, [Hetfield et. al (2004)]. The consequences were considerable and damaged houses were reported.

The radar images employed in this contribution dated from April 1992 to December 2000. Therefore the accelerated motion due to the water level reached the overburden of the mine was not consider in the estimations. The work focuses on detecting any possible changes due to the cease of water drainage in December 1997. The covered area is about 20 x 20 km, and it is centered in the Wassenberg Hosrt.

2. PERSISTENT SCATTERER INTERFEROMETRY

Spaceborne Radar Interferometry has been proved to be an efficient tool for measuring land deformation. The basic concept rests on calculating phase differences between two images. Unfortunately, not all the pixels of an image contain valuable information of the process of interest, and when a long time series is employed most of them are polluted with noise. Persistent Scatterer Interferometry, PSI, makes use of the coherent pixels to estimate land deformation, atmosphere delay and topography. The bibliography on PSI is extensive. We will refer to Ferreti (2001) and Kampes (2005) for a deeper insight to the methodology.

One of the major difficulties of employing this technique is that the measured phase is wrapped, i.e. the values are between $-\pi$ and $+\pi$. Therefore, the integer number of full cycle is unknown and has to be estimated. In this context, several techniques has been proposed, in this contribution we employed the bootstrapping procedure, [Teunissen (2001)].

A local deformation phenomenon was expected in the Wassenberg area due to the influence of the mining activities. For those pixels two episodes of linear deformation were considered, before and after December 1997, time at which the remaining mines were closed and consequently the water drainage stopped. However, the rest of scatterers of the processed area were not probably affected by this situation. Therefore, an adaptive deformation model was used, [van Leijen et al. 2007]. It consists of testing two different models in order to obtain the best unwrapping solution. The models were linear and linear with a breakpoint event at which the slope will change. The latest was expected for the pixels affected by the cease of the coal extraction and water drainage.

The adaptive deformation method does not only improve the displacements estimations and unwrapping solutions but also increase the number of detected PS, because fewer points will be rejected when tested. In this case the number of PS obtained with the adaptive method increased in 6.1% when compared with the traditional single deformation model approach.

2.1. Analysis of the results

Figure 3 shows four times series of pixels in the East a), inside b) and c), and at the West d) of the Wassenberg Horst, see also figure 4. The three first time series clearly showed the moment at which the last mines were abandoned. The consequent uplift due to the water reentering in the mines was not sequential to the closure but it had about three months delay. The time series d) in the west of the Wassenberg Horst outside the area of influence of the coal extraction does not show this event.

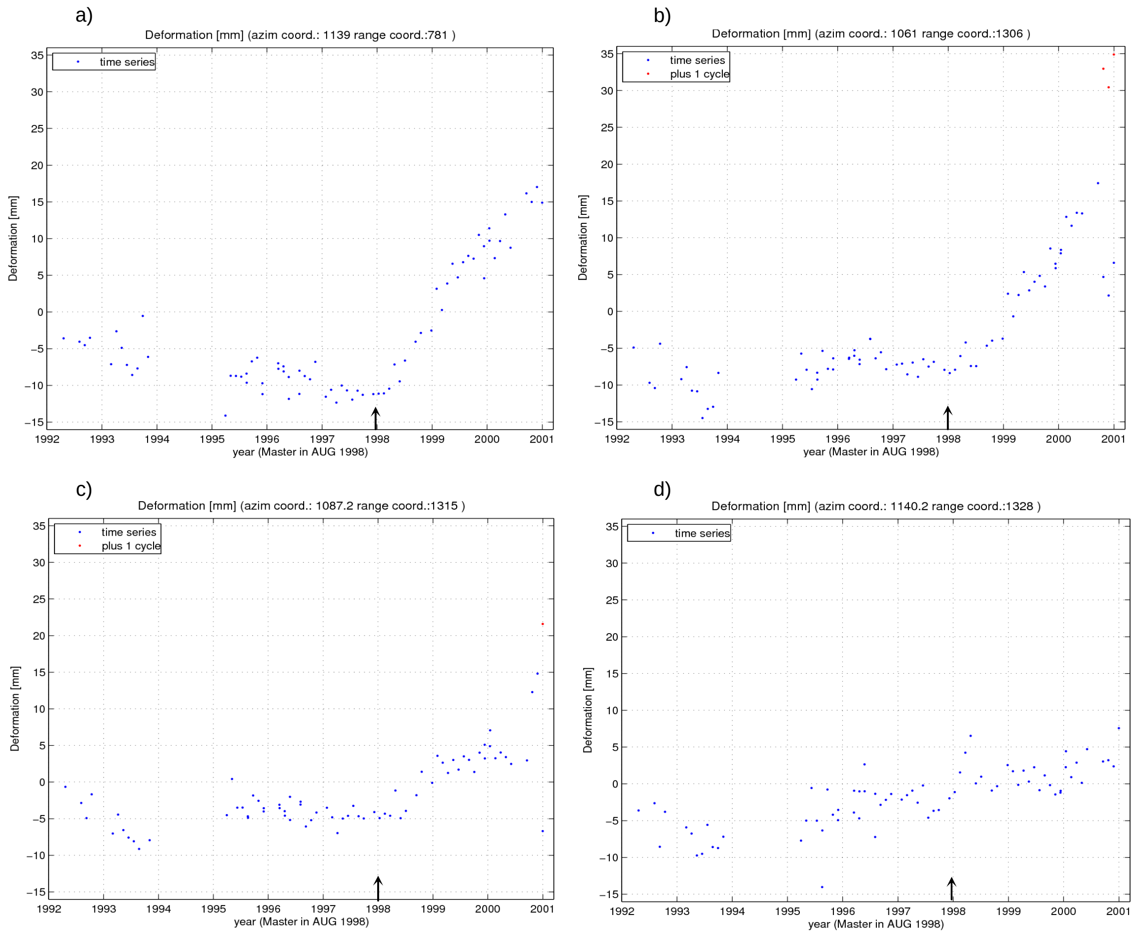

Figure 3: Time series of the deformation [mm] of 4 PS pixels in the East a), inside b) and c), and at the West d) of the Wassenberg Horst, see also figure 4. The time at which the last mines were closed, December 1997, is indicated with a black arrow. The motion showed by time series b) and c) seem to be accelerated during the year 2000 coinciding with the moment at which the water reached the overburden of the mines below the Wassenberg Horst. However, the latest measurements of these time series appear affected by unwrapping errors; adding to them a full phase cycle (showed in red) gives a very acceptable match with this new deforming phase.

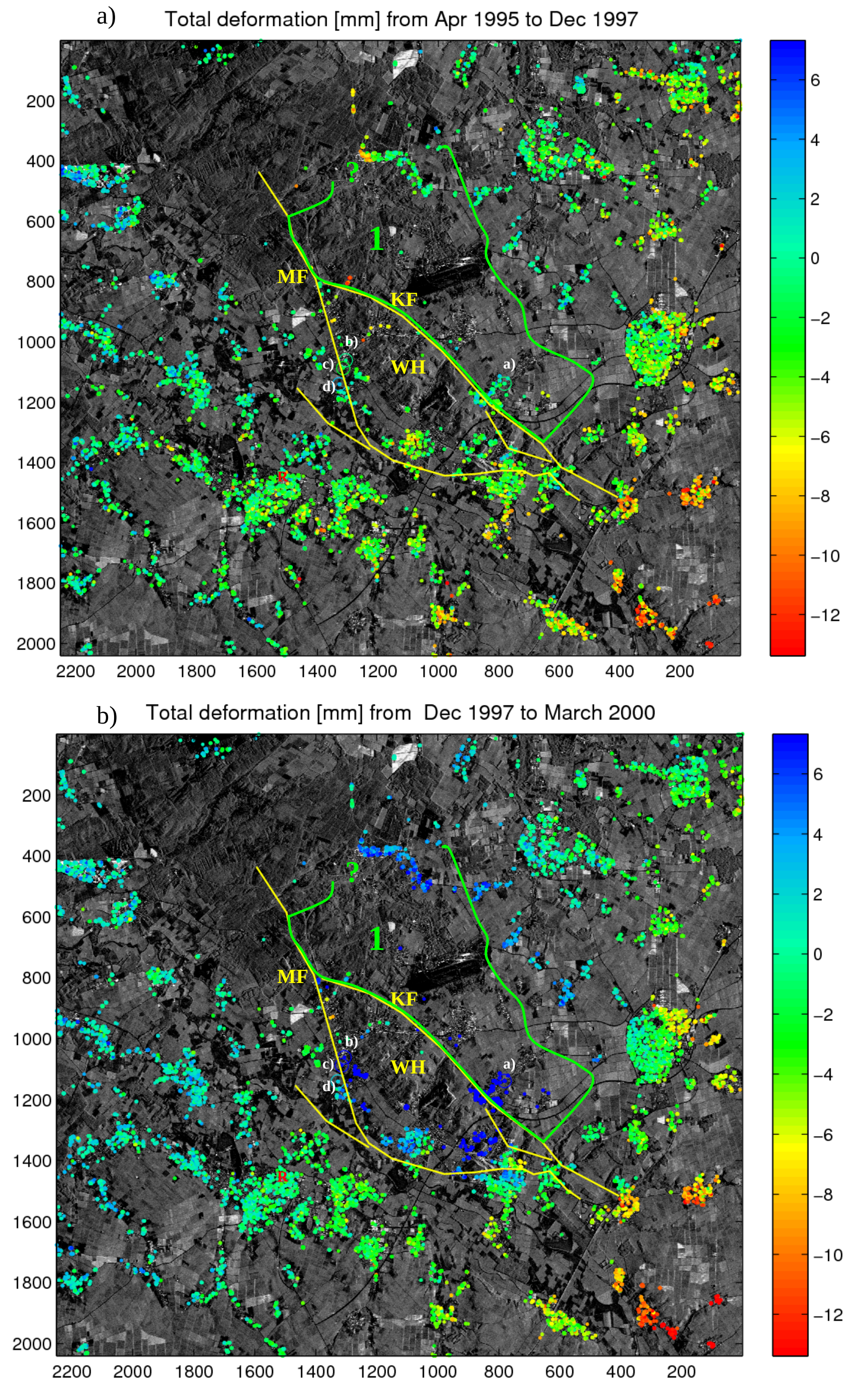

Figure 4: Total deformation before and after the last mines (1, 2, 3 and 4 in figure 2) were closed in December 1997. The green line shows the limit of these mines. The yellow lines represent the main faults, (MF Meinweg Fault, KF Kleingladbacher Fault), the Wassenberg Horst, WH, in the middle. The reference PS is shown in a red R, at the lower center. The time series of figure 3 are located in a), b), c) and d).

In the year 2000, the water inside the mine under the Wassenberg Horst reached the overburden. The estimations did not consider it since the number of measurements after this happened was very few, which can produce wrong estimations of the number of phase cycles, i.e. unwrapping errors. This seems to happen in figures 3 b) and c). A full phase cycle (28 mm) was added to the measurements affected by this error, showed in red in figure 3 that matches with the accelerated velocities.

The first part of the time series appeared to follow a particular regime, which we cannot interpret, even more due to the lack of acquisitions during the year 1994. In any case, an unwrapping error does not seem to explain it.

Figure 4 shows the estimated total deformation before and after the mine activity in the region completely stopped in December 1997. The PSI estimations are relative, i.e. respect to a reference PS pixel, which is marked with a capital red R in figure 4. Two time segments were chosen for creating the velocity maps, the first starts in April 1995, in order to exclude the first part of the time series. The second one ends in March 2000, so as to avoid any possible unwrapping errors, see figure 3. The area where the last mines were located, marked with 1 in figure 3, is delimited by a green line, and is drawn following figure 2. The Meinweg and Kleingladbacher faults (MF and KF respectively) are shown in yellow. The results reflect the changes in the mining areas. After December 1997, there is a clear uplift, affecting not only the zone 1 but also the surroundings including most of the Wassenberg horst, (WH). Unfortunately the number of PS detected in the area was not very high.

Both, time series and total accumulative deformation showed the discontinuity in the deformation field produced by the Meinweg Fault, with differences in displacements of more than 6 mm in 2.5 years. Even more, the time series showed acceleration in the motion during the year 2000 of the points in the Wassenberg Horst which is not visible in any the scatterers located in the west of the Meinweg Fault. During the year 2000, and taken into account the possible unwrapping errors, the time series b) and c) from figure 3 show a displacement of ~20 mm in 8 months.
The general deformation pattern is in agreement with Heitfield et al. 2004, although with some differences. We detect a wider uplifting area with a slower rate. However, the truly scattering object is usually unknown which makes difficult to compare with leveling data.

The activity in the open cast mines, which are locate outside the processed area see Figure 5, is visible in the lower right part of the figure 4. They are large lignite mines and require important amount of water, which is extracted from underground aquifers. Figure 5 shows the hydraulic head (water pressure) pattern of the area to be driven by the lignite mines, gray areas, [Bense et al. (2003)], including the processed area is shown as a blue rectangle. It is noticeable that the gradients of the water pressure are higher in the lower right corner of the processed area, which is also visible in the deformation estimated by PSI.

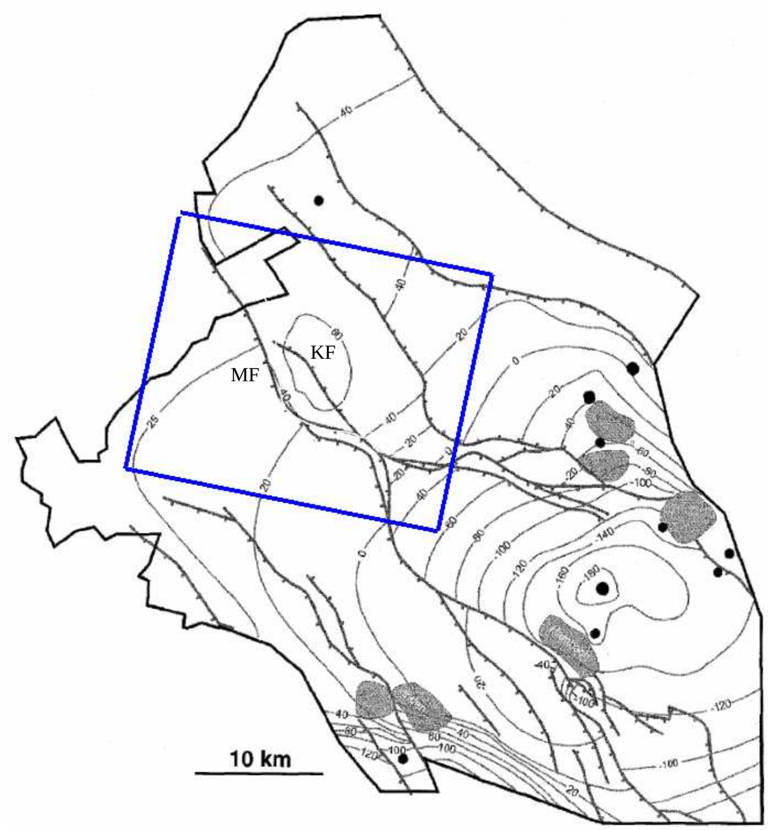

Figure 5: Hydraulic head pattern in the mine area. The pattern is consequence of the important water extraction happening in the lignite mines, (in gray) (after [Wallbraun 1992] redrawn by [Bense et al 2003]). The area processed using PSI is shown as a blue rectangle. The Meinweg Fault (MF) and Kleingladbacher Fault (KF) are remarked for convenience.

Another important characteristic of the hydraulic head pattern revealed by figure 4 is that the Meinweg fault is acting as hydrological barrier but the Kleingladbacher fault seems permeable. This is also reflected by the PS estimations, see figure 4. Comparing the Wassenberg horst (WH) from figure 4 a) to b), one realizes that both sides of the Kleingladbacher fault (KF) are affected by the uplift due to cease of the mining. On the other hand the deformation field across the Meinweg fault (WF) is not continuous.

3. CONCLUSIONS

The results of the PSI methodology show the area around Wassenberg to be affected by coal extraction activity. A clear uplift is visible few months after the abandon of the mines in December 1997, which is discontinuous in the Meinweg Fault. From hydraulic head data we concluded that the reason for this discontinuity was that the Meinweg Fault acts as a hydrological barrier, therefore the uplifting due to the water only affect to one of the sides of the fault. The estimated deforming rates show an uplift of the Southern Wassenberg of more than 6 mm from December 1997 to March 2000.

The time at which the water inside the mine reached the overburden, around March 2000 appears to be detected by our observations. However, we cannot draw definitive conclusions due to possible unwrapping errors and the lack of observations after or during the year 2000. In any case, during the year 2000, we measure about 20 mm displacement in 8 months when the unwrapping errors are accounted for.

The overall estimations agree with Heitfield et al. 2004, although with some differences. We detect a wider uplifting area with a slower rate. An exact comparison could not be carried out, since the truly nature of the scattering object is unknown, and the leveling measurements were not available to us.

The velocities map given by PSI showed also the influence of the lignite mines because of the important amount of water extracted by this industry. It matches the hydraulic head pattern, which is driven by the open cast mines.

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