INTERFEROMETRY OF SPATIAL RADAR IMAGES FOR POST-MINING SURVEILLANCE: EXPERIMENT FEEDBACK

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ABSTRACT: *For several years, satellite radar differential interferometry (DInSAR) has proven its efficiency for the detection of ground deformation with vertical precision measured by centimetres to millimetres. Currently, the technique can provide measurements on large areas of 100x100 km² with a 20m mesh or less. In this presentation, the validity of the DInSAR technique for post-mining risk assessment is evidenced from several interferometric studies. For that purpose, we propose a synthesis of already known interferometric products corresponding to various mining contexts (iron, coal, salt). It turns out that interferometric results are compatible with existing in situ measurements. In a complementary way of these last methods, DInSAR, in favourable cases, provides dense and historical ground movement information over large areas.*

KEYWORDS: *Interferometry, ground deformation, post-mining surveillance, remote sensing.*

RESUME : *Depuis plusieurs années, l'interférométrie différentielle d'images radar satellite (DInSAR) a prouvé son efficacité pour la détection de la déformation du sol avec une précision verticale sub-centimétrique. Actuellement, la technique fournit des mesures sur de larges zones de 100 par 100 km avec un pas d'au moins 20m. Dans cette présentation, la validité de la technique DInSAR est mise en évidence à partir de plusieurs cas d'études. Dans ce but, nous proposons ici une synthèse de produits interférométriques déjà obtenus dans des contextes miniers différents (fer, charbon, sel). Il s'avère que les mesures interférométriques sont compatibles avec les mesures pouvant être effectuées sur le terrain. Complémentairement à ces dernières méthodes, le DInSAR, dans les cas favorables, fournit une information dense et historique sur de larges zones.*

MOTS-CLEFS : *Interférométrie, déformation du sol, surveillance après-mine, télédétection.*

1. Introduction

For several years (Massonnet et al., 1993), satellite radar differential interferometry (DInSAR) has proven its efficiency for the detection of vertical ground deformation. The technique provides measurements on large areas of 100x100 km² with a 20m mesh. More recently, the advanced Permanent Scatterer (PS) technique leads to a dense network of points on a mesh of around 10m. This advanced method is based on DInSAR where the deformation parameter inversion only relies on the most pertinent pixels (Ferretti et al., 2000). These ones generally turn to be artificial or natural corners such as building/ground or rock/ground. Several limitations are known: data availability over the site, atmospheric artefacts, measurement along the sensor-antenna direction only and failure over rapid changing surface such as vegetated areas or most landslides. However, the radar database (ERS, RADARSAT, ENVISAT-ASAR, JERS) beginning in 1991, allows assessing historical measurements of the deformation under study. Such technique is also of great

interest in many cases where *in situ* measurements are missing, costly, or difficult to perform. Moreover, the current repetitive image acquisition on a same site should allow the monitoring from space of a given deformation.
BRGM has realised interferometric studies for more than 10 years, in particular for the assessment of urban and mining subsidence phenomena resulting from various anthropic or natural causes. In this presentation, the validity of the DInSAR technique for post-mining risk assessment is evidenced from several interferometric studies at BRGM and with collaborators. For that purpose, we propose a synthesis of interferometric products relative to the mining contexts (iron, coal, salt) in France. We focus on past or recent works at BRGM with collaborations, although, of course, many other examples can be found in the literature. This synthesis allows us to assess main advantages and pertinence of DInSAR for mining surveillance.

2. Experiments in Provence-Alpes-Côtes d'Azur

In this region, coal mining activity occurred near Gardanne at North of Marseilles since 17th century and stopped in 2004. Thirteen ERS images were processed, covering the period 1992-1995 and in a second project nineteen on the 1996-2000 period (Carnec and Delacourt, 2000). These studies supported by ESA, consisted in analysing each interferogram (produced from 2 images) with temporal baseline less than 6 months. Indeed, the context rather difficult (lots of vegetation) prevented from analysing interferogram with large temporal baseline. Several subsidence halos were detected. It was shown that the derived deformation maps correlate well with the underground activities (mined blocks) and lithologic formations (figure 1). In this example, DInSAR helped to the understanding of mining activity impact on geological environment.

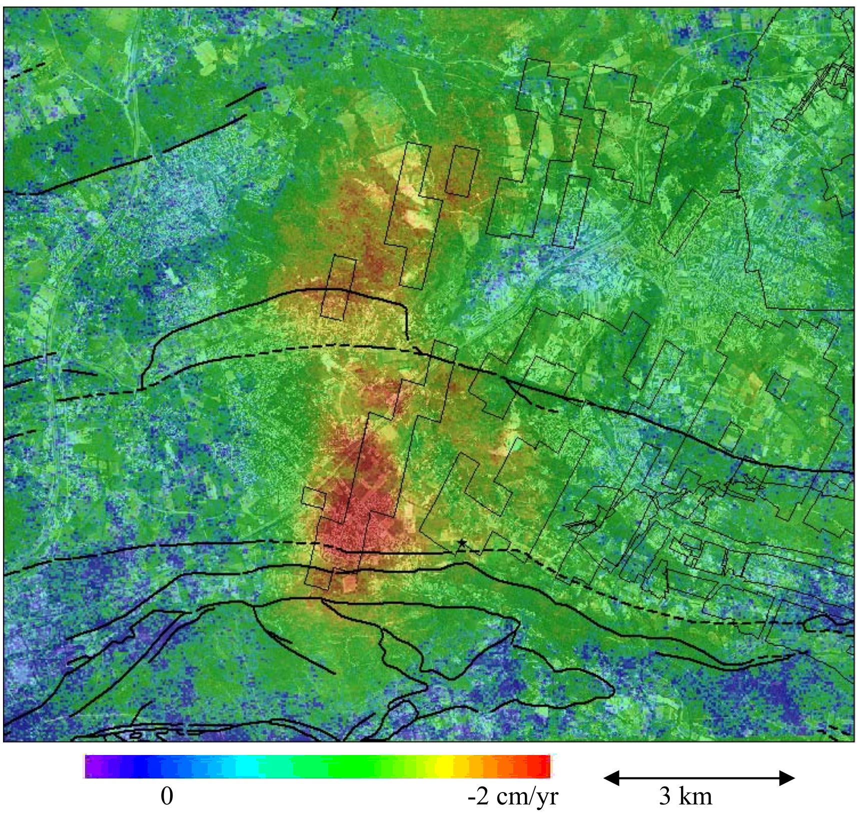

Figure 1 : Subsidence (velocities) map on the area of Gardanne derived from INSAR on the period 1996-2000 overlaid with mining map, superficial formations and an aerial orthophoto (source IGN). The eastern pannels were the last exploited (after 1995).

3. Experiments in Nord/Pas de Calais

In the region of Nord/Pas de Calais in North of France, coal exploitation occurred between 1750 and 1990. Since then, underground water pumping ended and surface deformation was expected due to the increase of the underground water level. Supported by CNES and the French Research Ministry (RTE, RGCU), an interferometric study on this area has been performed in the framework of the RESUM project (http://resum.brgm.fr), that deals with the surveillance of urban and mining subsidence by radar interferometry. Using ten ERS images ranging from 1992 to 2000, individual interferograms reveal subsidence phenomena over 4 cities: Lens, Billy-Montigny, Courrières, and Ostricourt (Raucoules et al., 2004; Raucoules et al., 2005). Measured subsidence rates are ranging from -3 to -4.5cm/year between 1992 and 2000 (Figure 2). A further observation of interferograms showed that deformation occurred until 1995-1996 and after 1996, the terrain stabilised. Levelling measurements in Courrières were also available. They showed a stable period until 1996 followed by uplift until 2001. DInSAR maps proved that the levelling point used as reference of the network was in a moving area, explaining the disappearance between both techniques. Changing the levelling reference point then led to compatible measurements. Thus, DInSAR can efficiently help field missions by providing the deformation spatial area.

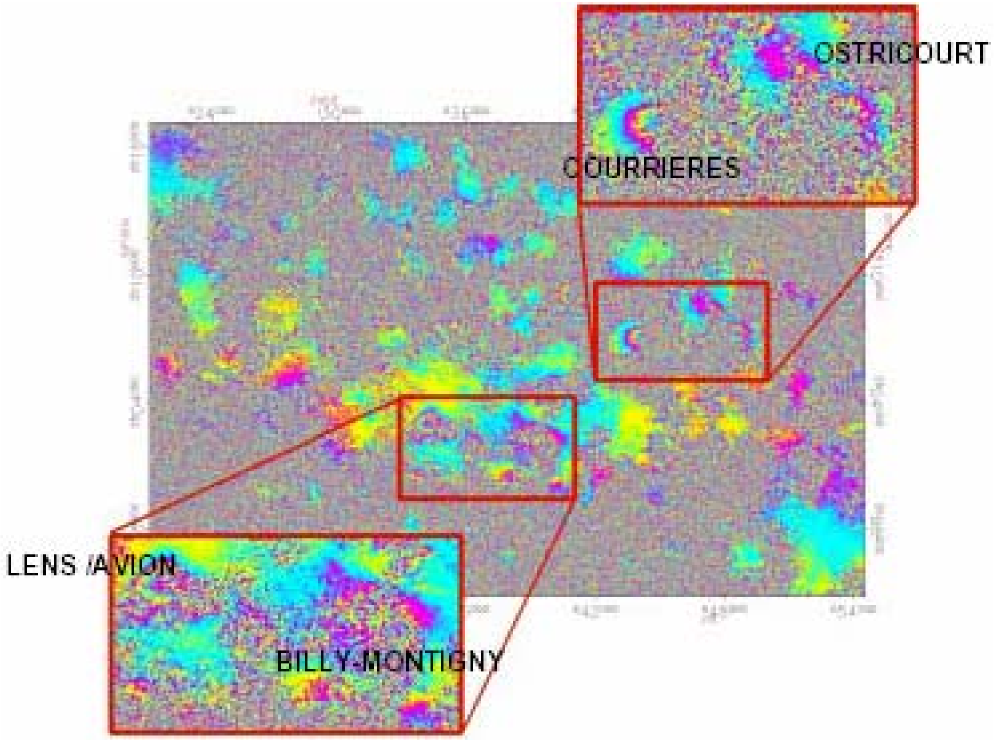

Figure 2. A deformation map obtained by DInSAR in Nord/Pas de Calais between 1992 and 2000. One fringe corresponds to a deformation of about 3cm. Noisy areas contain no information and correspond to non-urbanized areas such as vegetation. Adapted from (Raucoules et al., 2004; Raucoules et al., 2005).

4. Experiments in Bourgogne

In Montceau-Les-Mines, terrain uplift was detected by radar interferometry between 1995 and 1998 (Carnec et al., 2001). This phenomenon was most likely linked to the increase of water level after the end of exploitation. *In situ* piezometric measurements also confirm the observation (figure 3).

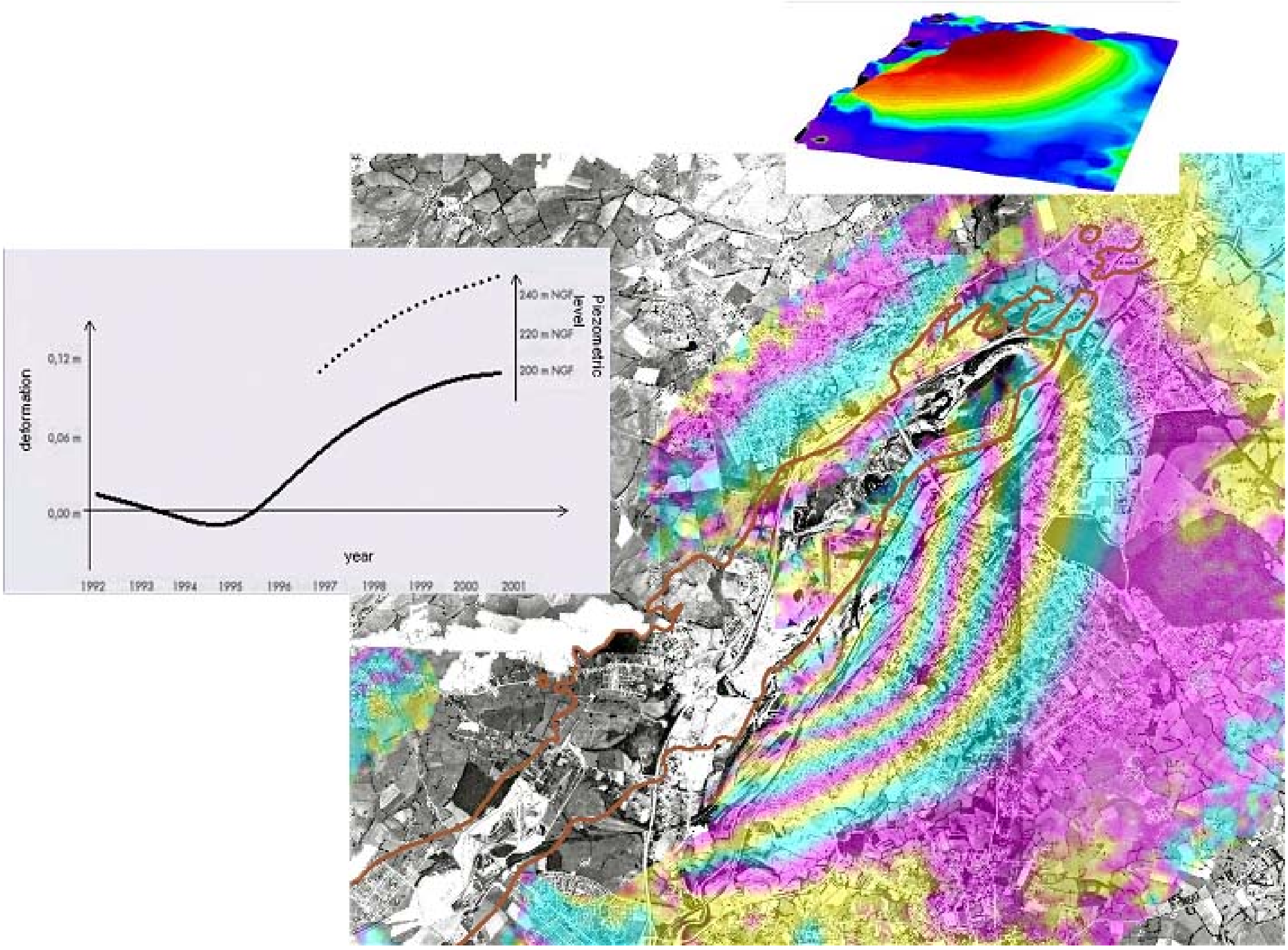

Figure 3. Example of deformation maps obtained by DInSAR in Montceau-Les-Mines. The curves show that DInSAR measurements are compatible with the piezometric level variations. Adapted from (Carnec et al., 2001).

5. Experiments in Languedoc-Roussilon

In the framework of the RESUM project, a study was carried out in order to survey an underground salt mine in South of France near the city of Vauvert (Raucoules et al., 2003). The processing is based on solution mining aiming at dissolving the salt and pumping the brine. 16 ERS data were used covering the period 1993-1999. The stack of three interferograms showed a 8 km large deformation bowl with around 15cm of maximal total subsidence at its center (more than 2cm/yr of displacement rate). Levelling was performed between 1995 and 1998 along black lines on figure 4. Levelling along white lines was used as reference points. One can observe that the reference points are in the moving area. DInSAR showed here how the technique could help *in situ* mission preparation. A new levelling profile (in blue) was then proposed. Deformation rates have been compared between levelling and DInSAR results. A good agreement was achieved between measurements with a RMS error of 2mm/yr, which is compatible with both technique precision.

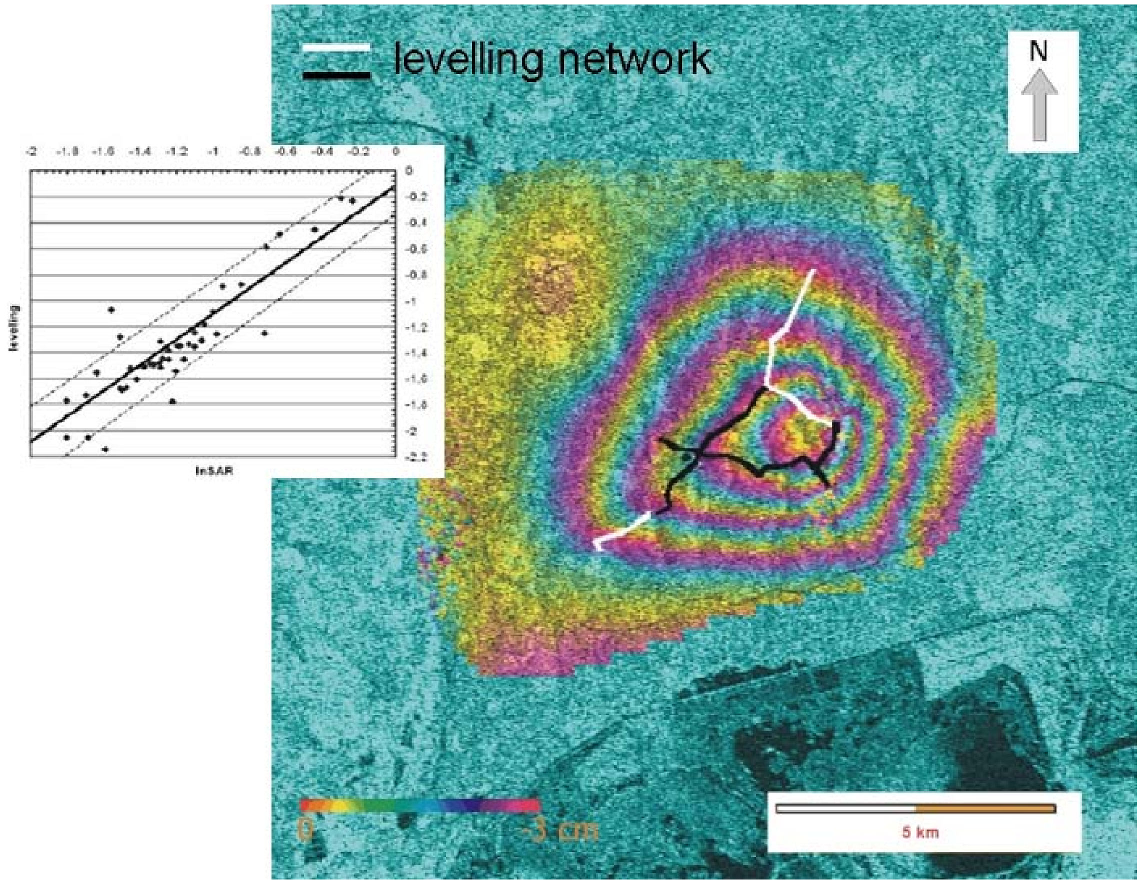

Figure 4. Example of deformation maps obtained by DInSAR near Vauvert in France. The curves accompanying map show that DInSAR measurements are compatible and complementary with the existing levelling network. Adapted from (Raucoules et al., 2003).

6. Experiments in Lorraine

In the East of France, in Lorraine, we were interested in several mining sites: an iron basin near Roncourt and a large coal basin including the cities of Merlebach, Morbach and Forbach. These studies were also conducted for the RESUM project.

In Roncourt, subsidence bowls and sudden collapses are likely to occur due to intensive iron ore exploitation since about 1870 using the chamber and pillar method. The PS technique was applied by the Italian company TRE (Tele-Rilevamento Europa), using 57 ERS images, acquired between 1995 and 2000 (Colesanti et al., 2004). Apart from the mean deformation rate map, the most remarkable result of this study was the detection of precursor signs 10 months before a major collapse that occurred in 1999, whereas no ground measurements were available yet to our knowledge (Figure 5). This result showed how DInSAR could be used for monitoring. After this date, field measurements using optical levelling were then registered. As the phase is measured modulo 2π, the displacement field is measured modulo 3cm with ERS. As consequence, if the amplitude of the deformation is more than 1.5cm during the time period separated two image acquisition dates, ambiguity errors can occur when one wants to ‘unwrap’ the information. This phenomenon has typically occurred in Roncourt (Carnec et al., 2004). On figure 5, it appears that the DInSAR technique was not able to resolve the inherent 2π ambiguity without *a priori* information. However, with the optical levelling measurements, this ambiguity was easily corrected. It shows how both techniques cooperate.

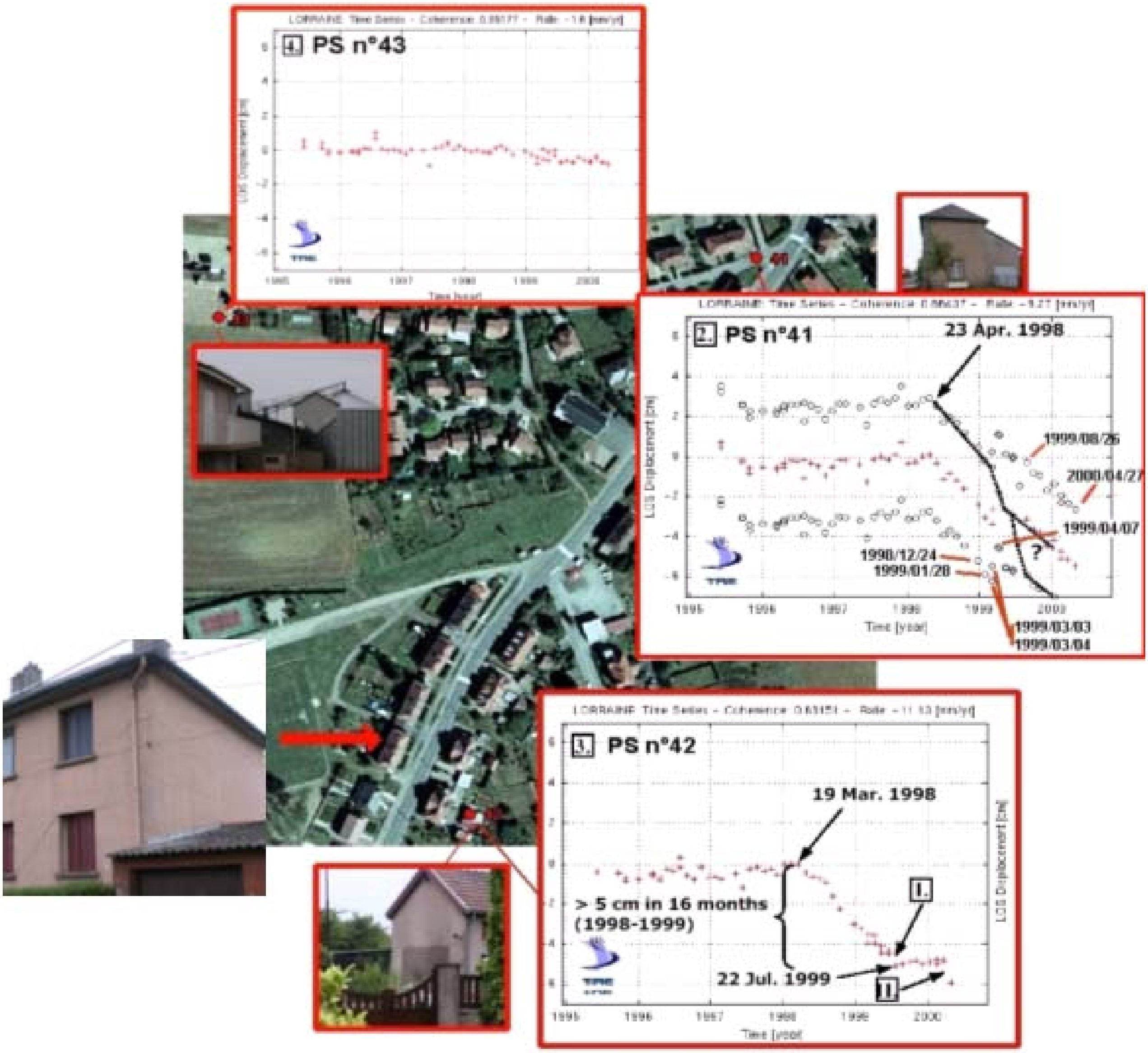

Figure 5. Cumulative displacement for three PS in Roncourt, localised on IGN orthophoto, between 1996 and 2000. The curves showed precursor signs of a major collapse in February 1999, since March/April 1998. For the PS 41, three temporal series are represented: the measured one and two others with an error of respectively one and two phase cycles (ambiguity errors). Black lines indicate potential real movement after manual correction of the ambiguity. Adapted from (Colesanti et al., 2004 ; Carnec et al., 2004).

In the coal basin of Lorraine including Merlebach, Morsbach and Forbach, conventional DInSAR has been applied using 18 ERS images acquired between 1993 and 1999 (Carnec and Raucoules, 2000). Individual interferograms revealed subsidence bowls with maximal amplitudes ranging up to 15cm/an at Merlebach, that are likely to be linked to the past coal exploitation (figure 6). However, interferometric application was unsuccessful in non-urban areas because, in all likelihood, of vegetation growing and surface humidity variation. This example shows the opportunity of using DInSAR for surveillance in urban area. In the meantime, it also shows the limitation of the technique in non-urbanized areas.

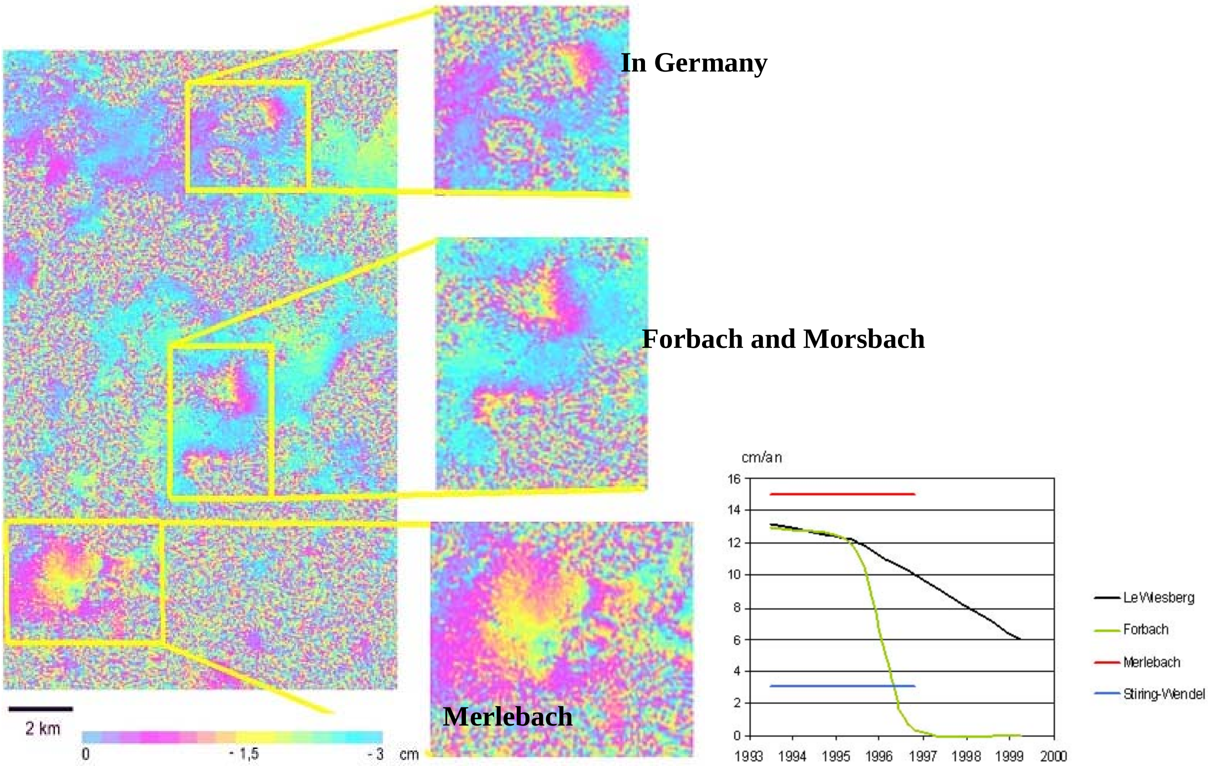

Figure 6. Interferometric map obtained using two images acquired in 1993 between June and August, and maximal displacement rate observed above four cities between 1993 and 2000. Two curves after 1997 stop because measurements were too noisy. Adapted from (Carnec and Raucoules, 2000).

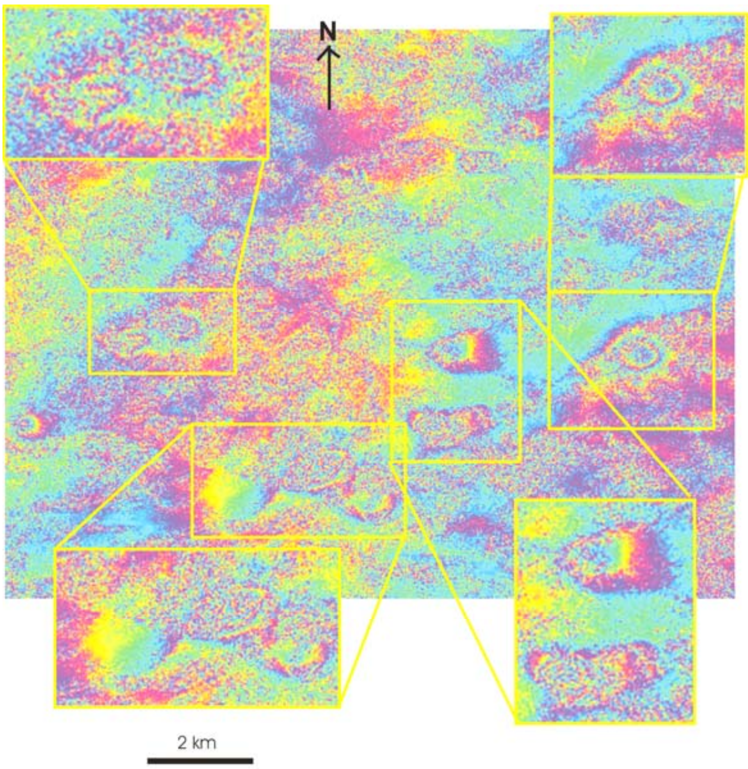

Figure 7. JERS-1 interferogram on the mining area of la Lorraine (same sector that Figure 6). Acquisition dates 24/03/1993 - 11/03/1994. 1 fringe ~ 11.5 cm of vertical deformation. Additional subsidence bowls undetected on figure 6 are observed. Adapted from (Raucoules at al., 2005b).

However, an experiment has been carried out using JERS (figure 7, Raucoules at al., 2005b) data from the Japanese Space Agency. This satellite was equipped with a sensor working with L-band (22cm wavelength), instead of C (5.6cm wavelength) as for ERS or ENVISAT. As a result, interferometric measurement is less sensitive to temporal variation linked to vegetation or surface humidity and provide a complement to the C-band interferometry on vegetated areas.

7. Experiments in Paris

A precedent experiment over Paris revealed a deformation around Montmartre hill. This study was performed in the framework of the RESUM project. 30 ERS images acquired between 1992 and 2000 have been processed using an advanced stack technique, based on classical DInSAR (Le Mouelic et al., 2005). DInSAR showed an averaged subsidence of -2mm/yr for this period on the West and South parts of the mound. Compaction over filled up gypsum quarries was the first explanation retained. However, more recently, a 3D geological model showed that unconsolidated backfills above old gypsum quarries are only one of the potential causes explaining the terrain displacement (figure 8). Up to 25m of backfill thickness can be found at this place. Two other factors may also participate: the slope of the terrain and a perched water table on the sannoisian clay on charge toward west, leading to the destabilization of the unconsolidated backfills (Thierry et al., 2004).

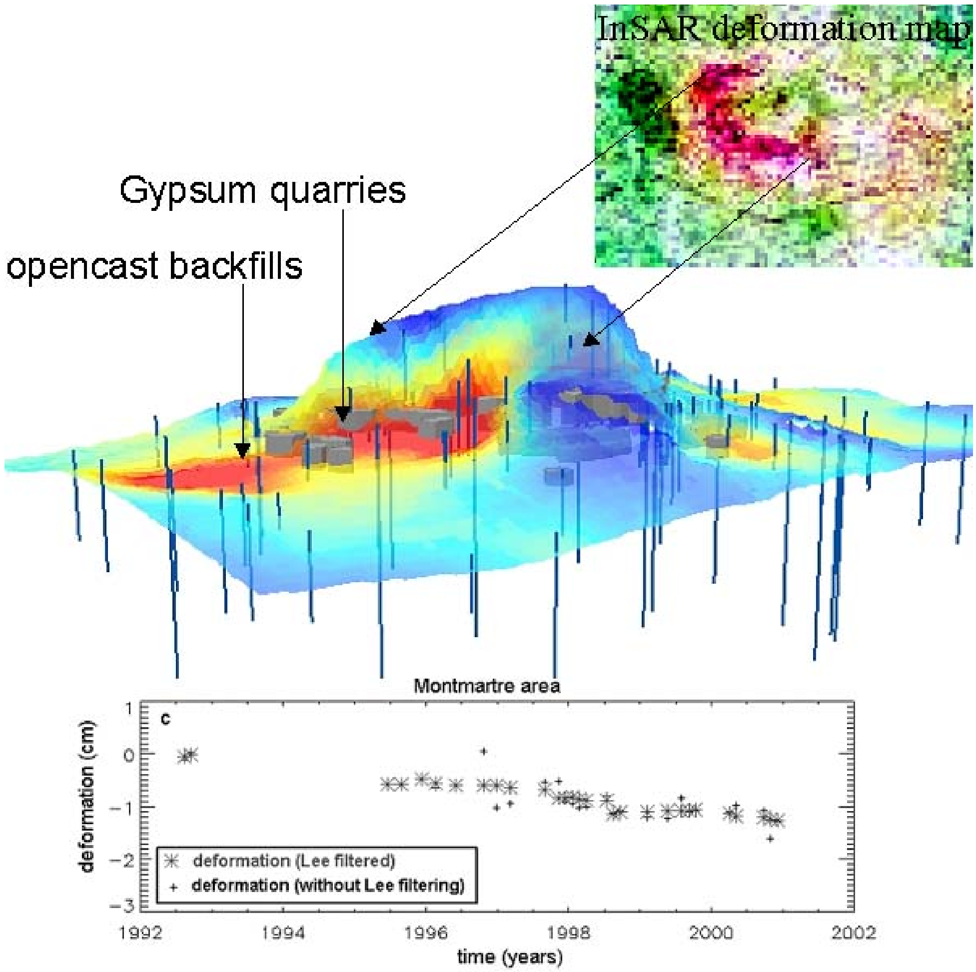

Figure 8. DInSAR map of the mean displacement rate between 1992 and 2000 in Paris, Montmartre mound. A 3D geological model shows that backfills around old gypsum quarries is one of the causes of the deformation in Montmartre. Backfill layer is represented according to its thickness (blue to red) and mapped on a DEM with a vertical exaggeration. The area is 1.5kmx2.2km. Temporal profiles of the deformations occurring in Montmartre area. Plus symbols correspond to the direct output of the least squares inversion method. Asterisks correspond to the values filtered using a Lee filter

with a window of 5 pixels (in time) to reduce the atmospheric component, which is completely random from one image to the next. Adapted from (Le Mouélic et al., 2005).

8. Conclusions

The DInSAR technique presents great advantages for mining and post-mining surveillance. It provides dense and historical deformation maps, precise measurements (mm/yr) and is complementary to field auscultation. Previous studies showed the compatibility of the InSAR measurements with existing *in situ* topometric data. Besides, in certain cases precursor signs of the deformation could also be detected. This remote sensing technique allows the survey of a site with no *a priori* information and no devices on the terrain. Of course, some *in situ* measurements (like GPS) are necessary to validate the InSAR measurements and calculate the absolute deformation field.

Here, one can also notice that the methodology has evolved and is still improved in the framework of research projects. Firstly, individual interferograms were analysed, then interferograms have been stacked allowing to increase the signal to noise ratio. Currently, the PS technique is expected to be the most promising.

It must be noted that the technique can be used only in a favourable context leading to pertinent measurements (data availability, terrain geometry, vegetation, deformation characteristics). Due to the dependence on the launch of a satellite and its characteristics, the method actually suffers from a lack of visibility to insure long-term measurements. Currently, an archive of 15 years of radar interferometric images exits (ERS and ENVISAT from ESA) since 1991. ENVISAT should yet go on some years.

Radar interferometry could also be opportune for other applications such as civil engineering, gas or petrol field surveillance, aquifer system analysis, and in earth science (seismic activity, volcano).

9. Aknowlegdements

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