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THE INTERFEROMETRY TECHNICS APPLIED ON RESIDUAL SUBSIDENCE ANALYSIS MEASUREMENT OF CLOSURE COAL MINES, EXAMPLE FROM NORD – PAS – DE CALAIS COAL MINE, FRANCE

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ABSTRACT: This paper describes the residual movements associated with deep coalmines (France). The Nord-Pas-de Calais basin has been monitored since 10 years by traditional method. The interferometry technics are applied on Nord-Pas-de-Calais coal basin. In this study, both differential SAR Interferometry (DINSAR) and Persistent Scaterrers Interferometry (PSI) are used to estimate the induced deformations during 12 years (1992 to 2004) after the end of exploitation. 88 images of ERS scenes, distributed on two adjacent tracks, are processed, using DIAPASON software for DInSAR and GAMMA-IPTA for PSI. The area undergoes high temporal decorrelation due to the high amount of vegetation. Deformations are well detected; they present low amplitude with a maximum rate of only 1 cm/year during 7 years after the end of the exploitation. They show a good agreement with the traditional methods of levelling. A robust methodology can be developed to use Interferometry for surveying surface above abandoned mines.

KEYWORDS: coal mines, subsidence, residual, interferometry

RÉSUMÉ: L'article décrit les mouvements résiduels induit par l'exploitation de mines de charbon profondes (France). La surface est suivie depuis plus que 10 ans par la méthode de nivellement classique. La méthode d'interférométrie a également été utilisée dans le basin du Nord et du Pas-de-Calais, les deux techniques (SAR et PSI) ont été utilisées pour estimer les mouvements résiduels durant 12 ans (1992-2004) après l'arrêt de l'exploitation. 88 images de ERS ont été analysées en utilisant le code DIAPASON pour la méthode DInSAR et le code GAMMA-IPTA pour la méthode PSI. La zone étudiée est caractérisée par une couverture végétale très dense, ce qui induit une forte décorrélation temporelle. Les mouvements ont été bien détectés, ils présentent une amplitude de 1 cm/an pendant les 7 ans après l'arrêt des travaux miniers. Les résultants de l'interférométrie ont montré une cohérence avec les mesures par la méthode de nivellement traditionnel. Une méthodologie robuste peut-être développée pour suivre les mouvements induits par les exploitations minières abandonnées.

MOTS-CLEFS: mines de charbon, subsidence, résiduel, interférométrie

1. Introduction and objective

Subsidence of the ground surface induced by mining is an environmental problem in many countries. To study the magnitude of total and residual subsidence, traditional survey methods are generally used. Recently interferometrics methods have been employed to determine depression due to water pumping. These techniques can be a useful tool to survey the surface of large area with low cost. The objective of this study is to know the precision and the potential of the interferometrics techniques to measure residual subsidence of closer abandoned mines. Charbonnages de France use high precision levelling methods to measure the vertical movements having a magnitude less than centimetres. The Nord and Pas-de-Calais coal basin has been also monitored by differential interferometry SAR (DINSAR) and Persitent Scatterers Interferometry (PSI). Indeed, these methods provided, in accurate area, a precision of displacements less than centimeter. In this study, both (DINSAR and PSI) are used to estimate the induced deformations during 12 years (1992 to 2004) after the end of exploitation. 88 images acquired by ERS satellite are processed, using DIAPASON software (CNES-Altamira Information) for DINSAR and IPTA (GAMMA software) for PSI. The area undergoes high temporal decorrelation due to the high amount of vegetation. The evaluation of atmospheric artifacts is also difficult. Nevertheless, deformations are well detected; they present low amplitude with a maximum rate of only 1 cm/y during 5 to 7 years after the end of the exploitation. The results obtained by the interferometrics methods are then compared to traditional levelling measurements.

2. Mining subsidence

The underground excavation induces the bending and the deconsolidation of the overlying strata. The induced displacements are transmitted on the surface and generate a subsidence trough (figure 1). This subsidence trough extends on the surface above the exploited area; its volume remains less than the extracted one due to the bulking effect. Figure 1 indicates schematically the geometry of the subsidence profile. The mains characteristics of the subsidence trough are: influence angles (or limit angle, γ) and maximum subsidence amplitude Am.

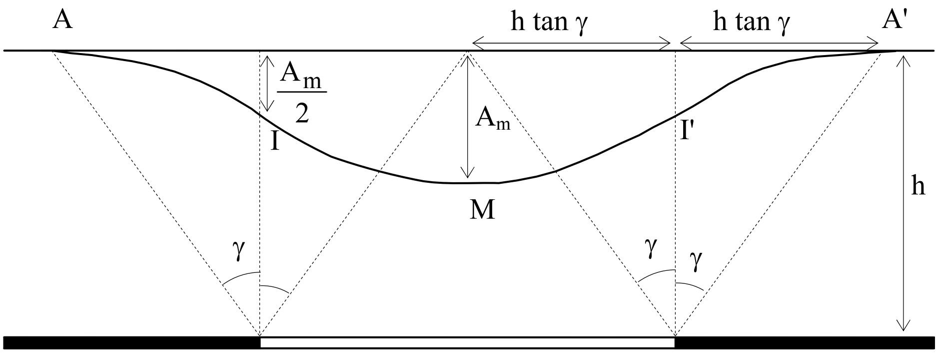
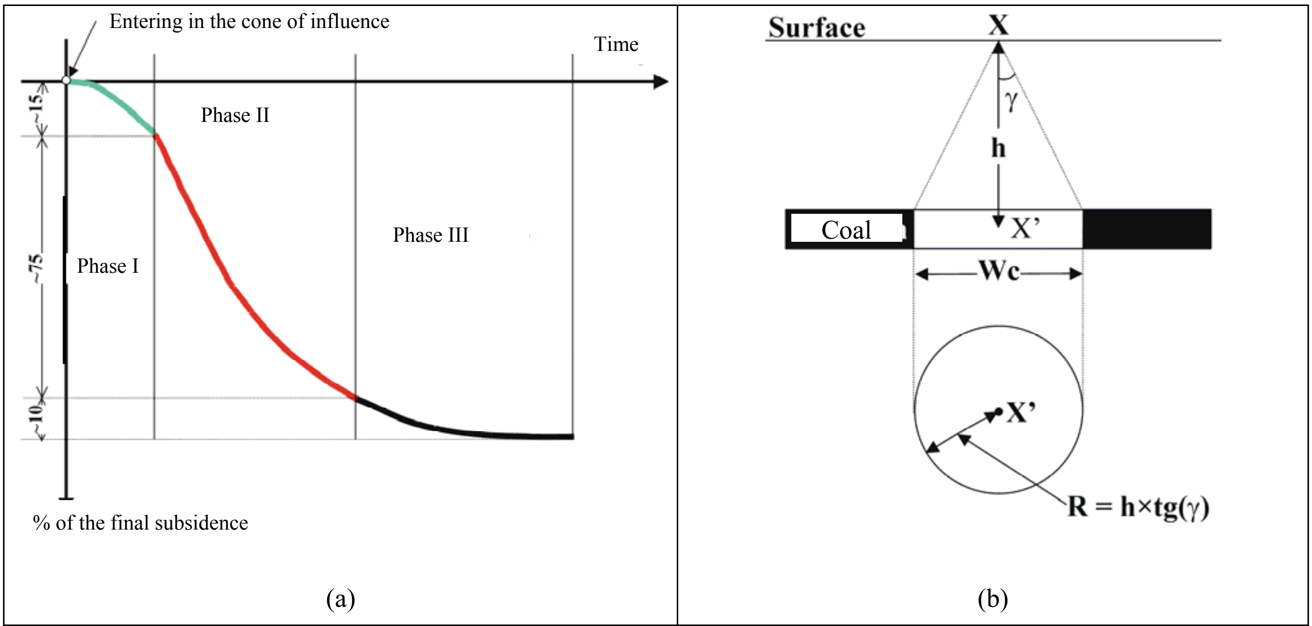


Figure 1: Theoretical subsidence trough above a single panel at critical width in horizontal seam (after Proust, 1964)

The final subsidence can be divided into three phases as illustrated in figure 2, (Wojtkowiak, 1997). Phase I known as initial subsidence, corresponds to the period when the face of extraction penetrates the cone of influence of a considered point located on surface. The influence angle and the depth of the considered point define this cone, until passing to the vertical of this one. This phase is generally associated to 10 to 15 % of final subsidence. Phase II known as principal or accelerated subsidence, corresponds to the period when the face of extraction moves away from the vertical of the point, until it leaves the cone of influence of this point. In the United-Kingdom coalmine, 97 % of final subsidence is reached at this stage. From the bibliography, the corresponding value of subsidence (phase I to II) varies between 90 to 95 % of Am (Whittaker and Reddish, 1989).



Wc: Critical width of mining area, h: depth of seam, γ: influence angle

Figure 2: (a) Typical evolution of a subsidence profile with time; (b) cone of influence of a point located on the surface

Phase III, known as residual subsidence (also named differed or delayed subsidence) constitutes the final phase of subsidence. It continues after the extraction phase or when the front of the face is completely out of the area that influences the considered point. Residual subsidence represents only some fraction of the total subsidence. After this last phase, subsidence is supposed finished and surface is stabilized.

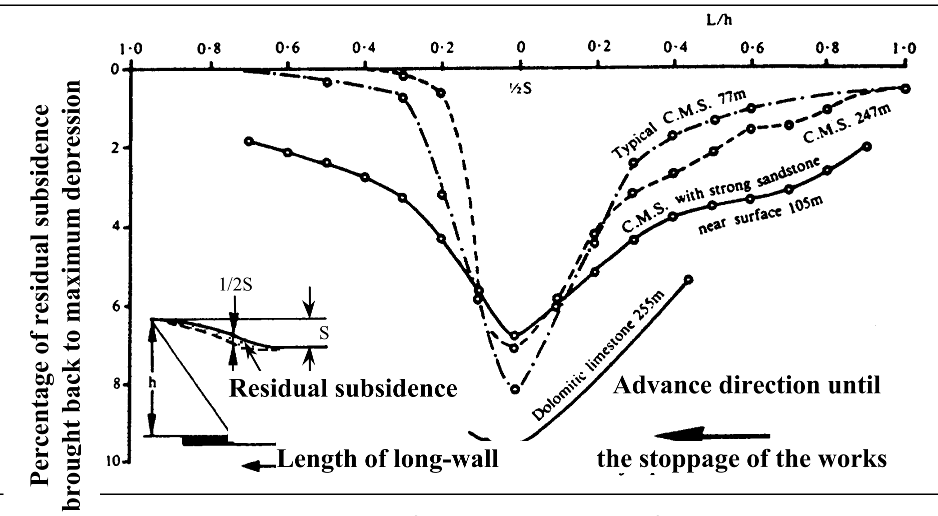
3. Residual subsidence

3.1. Amplitude and shape of residual subsidence

The amplitude of residual subsidence is generally about 1 to 10 % of final subsidence (figure 2). This value is largely allowed by the whole French and foreign authors. The amplitude depends on many factors: thickness of the mined seam, depth, backfilling and goaf methods as shown in figure 3. The amplitude of residual subsidence is maximum in the vicinity of the inflection point of the subsidence trough. On both sides of this point, the amplitude of residual subsidence decreases significantly. Generally, residual subsidence decreases with the mine depth. We can highlight, during the last two or three years of residual subsidence phase, that the amplitude of subsidence is negligible. The settling speed is decreasing over this duration. A great part of residual subsidence is given at the end of the first year (40 to 90 %), sometime before, (80 % after one month in a USA mine).

3.2. Duration of residual subsidence

Table 1 presents bibliographical data related to the duration and amplitude of the residual subsidence phase (Al Heib et al., 2005). We specified for each case the treatment method (goaf, backfilling) and the nature of strata. The duration of the residual subsidence phase is variable from months to years, i.e. about 3 to 4 months when the exploitation is carried out in an already disturbed zone (several seams, goaf...). There are some isolated cases resulting from geological contexts and/or particular exploitation, for these cases, the duration of residual subsidence can appreciably be raised and spread out over one period of 4 to 6 years.



imal subsidence ; L : length of long-wall ; h : depth of underground excavation

Figure 3: Residual subsidence for various coverings according ratio length exploited/depth (after NCB, 1975)

Table 1: Duration and amplitude of residual subsidence phase (after Aissaoui, 1999)

Cases	Mining conditions	Residual subsidence
U.K. (Many basins) Whittaker and Reddish, 1989	Long-wall method and plastic layers	Less than 12 months; 5-6 % of the total subsidence
UK (Durham Coalfield) Orchard and Allen, 1974	Tow mines with high resistance strata	1) 8 % of total subsidence after 4 years, and 9 % after 6 years. 2) 6.8 % of total subsidence after 4 years
West Germany Kratzsch, 1983	Many mines using long-wall method	5 years, with 75 % from the first year
Australia (Whittaker and Reddish, 1989)	Long-wall with caving method	3 to 7 months
India Singh et Saxena (1989) Saxena , 1991	Long-wall in virgin ground	10 months to 15 month for 10 to 30 % of total subsidence
	Long-wall method - in extracted zones.	2 to 4 months; 5 to 10 % of total subsidence
USA Hasenfus et al. 1988	Long-walls method	10 % of total subsidence 1 month and 12 % after 17 months
France: Nord-Pas-de-Calais	Plastic strata; in already extracted zones.	99 % of total subsidence after 3 to 4 years
France: Provence, Lorraine And Blanzy	Resistant strata; in already extracted zones	2 to 3 years

Except some specific context (Heitfeld et *al.* 2006), residual subsidence does not generally affect the surface constructions because the residual horizontal strains, which are more prejudicial, are practically small. We don't have specific study undertaken on the damage that mining works can induce during residual phase. We can however roughly estimate the horizontal strain and the tilt starting from relations established for the active phase. Maximum residual subsidence reaches only a small proportion of maximum subsidence (about 10 %) in active phase (Al heib et al. 2005). The residual maximum strain and tilt result from those in active phase in the same proportion. Since the horizontal strains reach in active phase, 0.1 to 3 mm/m (more rarely higher values), the order of magnitude of the additional horizontal strain, will be 10^{-2} to 10^{-1} mm/m in residual phase.

4. Case study: Nord and Pas-de-Calais Basin

The basin is located at the centre of the powerful coal belt, which joins together the Ruhr basin (Germany) to the basin Kent (England). It extends from West to East on about 120 km. The exploitation began in 1720 to finish at the end of 1990. The exploited coal seams are numerous; their thickness are low and variable, ranging between 0.5 and 2 meters. The depth of the exploitation increased according to time, of 200 m to 1100 meters. Geology is marked by the presence of several faults of more or less important rejections. The grounds of surface consist of more or less chalky marls (to 20 m of depth), beyond, one notes the presence of a white layer of 50 m thickness chalk. The overburden is characterized by a plastic behaviour (deformation spread out in time). Mining work is in the course of submergence, but the water level, is very low compared to the level of final submergence.

Charbonnages de France has the complete cartography of the exploited veins on the whole basin at 300 meters below the surface. This database also contains the years of exploitation as well as the exploited thickness and thus makes it possible to locate the last exploited zones and to consider the awaited compressing rate. This step was carried out during previous work undertaken by INERIS (Degas, 2001) and allowed to draw up cartography of the zones which are most sensitive to residual subsidence.

4.1. High precision levelling data

Since 1991, the French National Geographic Institute (IGN) realizes precise measurements each year. These five high precision levelling lines are usually measured in the beginning of October, except in 1999 where two campaigns have been carried out during spring and autumn in order to reveal seasonal effects. Two years (1992 and 1995) are missing. Three zones were then monitored initially (Wallers/Arenberg, Billy-Montigny and Estevelles/Carvin/Courrières), which were later extended to Lens and Bruay-la-Buissière in 1998 (figure 4).

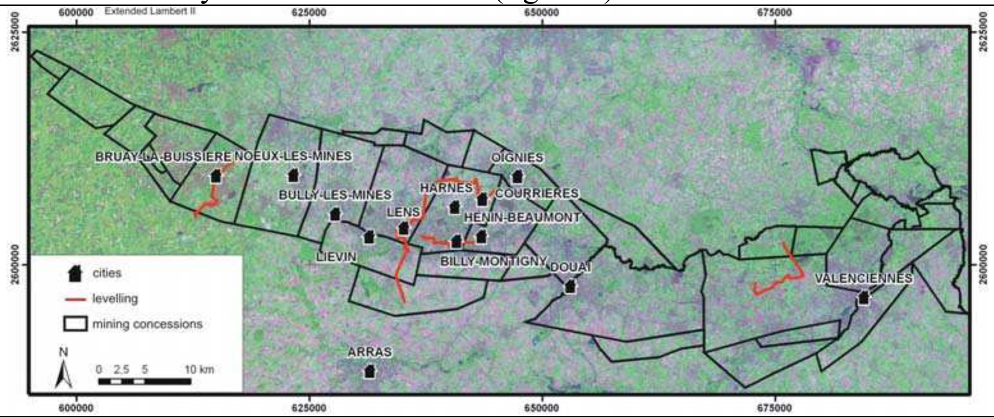


Figure 4: Leveling monitoring of the Nord and Pas-de-Calais coal basin.

This precise levelling allows to identify different areas showing surface displacement and some depressions are clearly observed. Displacements reach four centimetres for almost points of the Billy-Montigny line in eight years (figure 5).

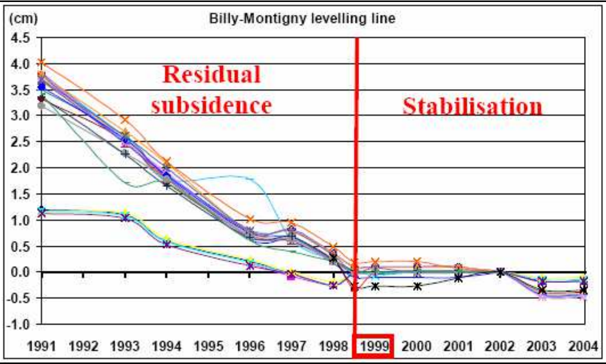


Figure 5: Example of the Billy-Montigny leveling line. The stabilization of the residual subsidence is clearly observed after 1999.

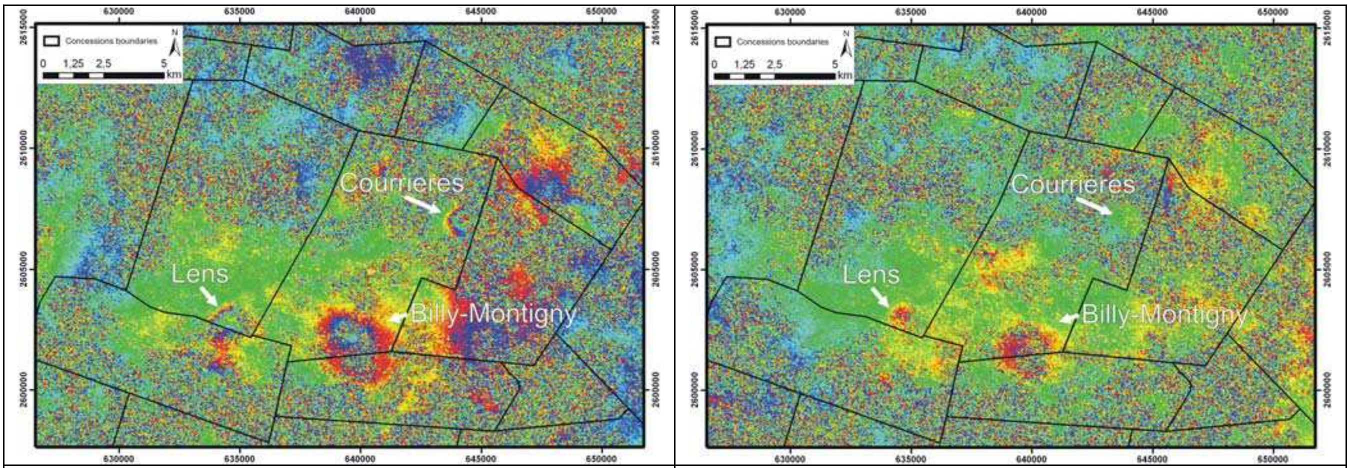
Concerning the Estevelles/Carvin/Courrières line, some points with a six centimetres amplitude can be identified between 1992 and 1999, but only in the restricted area of the “Cité Saint Paul”.
Some points in surrection are also highlighted in particular for the line of Estevelles/Carvin/Courrières where the movements reach two centimetres for a period of seven years (92-99). After 1999, the stabilisation of the majority of the leveling points of the three studied lines is observable. Only a few points of the “Cité Saint Paul” sector (Estevelles/Carvin/Courrières lines) still present subsidence of low amplitude (0.25 centimetres per year). Some points of the Lens and Billy-Montigny levelling lines present new displacement between 2002 and 2004 reaching amplitude of the order of the centimetre over this period.

4.2. Differential and persistent scaterrers interferometry

Since the beginning of the 1990’s, the utility and the effectiveness of the radar interferometry treatments for the monitoring of the topographic surface movements, in particular in mining areas, were shown with many recoveries (Carnec et *al*., 2000; Raucoules et *al*., 2002; Raucoules et *al*., 2003; Colesanti et *al*., 2005). Two methods are used here for this study: differential interferometry radar (DInSAR) and Persistent Scatterer Interferometry (PSI), with CNES Diapason and GAMMA Remote Sensing IPTA software respectively. The satellite data used in this study are coming for ERS-1 and ERS-2: 88 scenes distributed on two frames are available with an approximately three months periodicity between 1992 and 2002. Unfortunately, due to the zero-gyro mode of ERS-2, interferometric processing could not be carried out after 1999.

4.3. DINSAR and PSI results

According to the last areas exploited, we focused this study on the centre of the coal basin, around the important conurbation of Lens. In addition, this area presents the advantages to be monitored by three levelling lines. The major of studied area presented important temporal decorrelation difficulties. The presence of an important part of fields and forests as well as a low urban density leads to low coherence, which limits the use of DInSAR. Nevertheless, the area of Lens provides a quite good coherence and concentrated our attention. We thus clearly could highlight three principal zones of movements localized on the towns of Courrières, Billy-Montigny and Lens. They show a depression phase between 1992 and 1996 with a deformation of about four centimetres over this period, corresponding to one centimetre per year velocity (figure 6).



A. B.

Figure 6: Identification of subsiding areas with DINSAR. A.: 6623-25504 interferogram (21/10/1992-31/05/1996) highlighting three principal subsidence areas. B.: 8837-21362 interferogram (28/12/1996-22/05/1999) showing only two subsidence areas still active after 1996.

After 1996, no interferometric fringes can be observed on the Courrières area. But we can’t exclude that small movements remain with amplitude under the detection threshold of the method. On the other hand, both zones of Lens and Billy-Montigny still present movements between 1996 and 1999 (end of the exploited data). The subsidence rate of these areas, initially of about 1 centimetre per year, decreases after 1996 and reaches 0.5 centimetres per year. Thus, the total subsidence is then of about 6 centimetres over the whole 1992 to 1999 period. The PSI method allows confirming the results obtained by DInSAR and to identify more precisely the moving areas. Indeed, although the three zones quoted previously are again identified and present the same order of magnitude of deformations, a new area at the North of the Courrières city appears active. Located in the “Cité Saint-Paul”, this one shows an average velocity of about 1 centimetre per year all along the considered time period (figure 7).

4.4. Discussion and methods comparison

DInSAR measurements are compared to precise levelling data provided by Charbonnages de France in areas where both are available. This could be carried out only for the zones of Courrières and Billy-Montigny, because the levelling of Lens becomes available only since 1999. They are in good agreement, and show same areas of displacements with the same order of amplitude. On Courrières area, DInSAR method provides clear results on the city and highlights a subsidence of about one centimetre per year. But, on the other hand, it does not provide any result for the “Cité Saint-Paul” due to a too low temporal coherence. However, some PS pixels have been found in the “Cité Saint Paul”, and can be compared with levelling points in a 150 meters neighbourhood. They present very good agreement and proved the effectiveness of this method in low temporal coherence areas (figure 8).

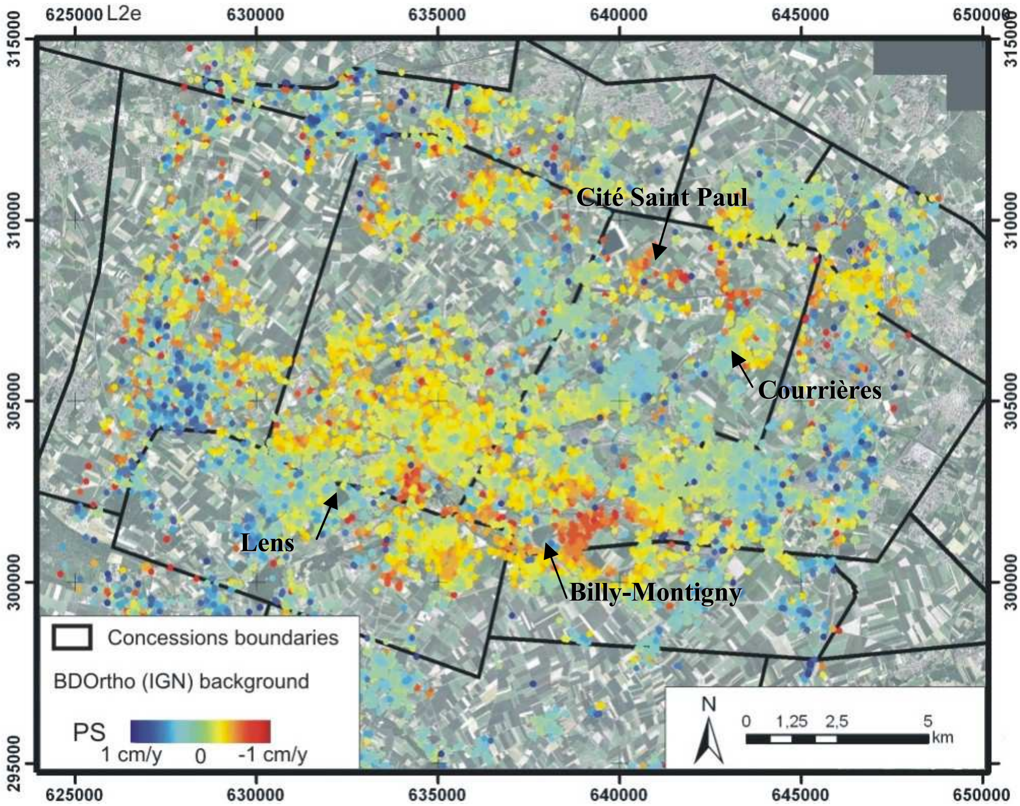
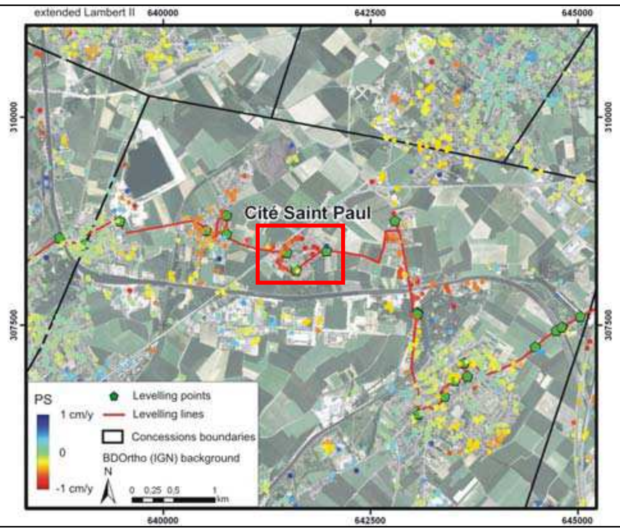
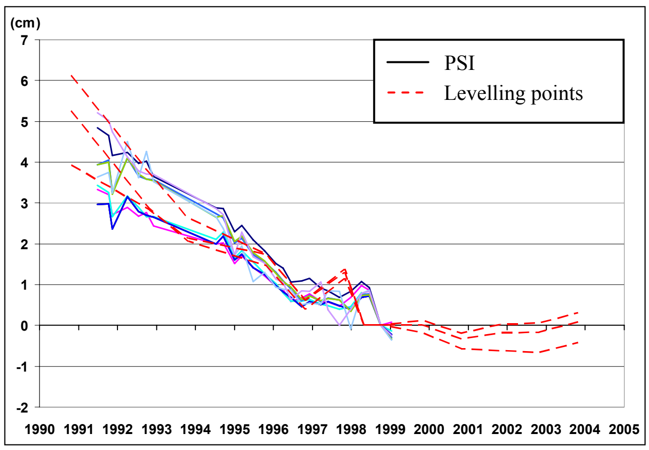


Figure 7: PS average subsidence rate between 1992 and 1999.



A.



B.

Figure 8: Comparison between PS displacements and levelling monitoring in the "Cité Saint Paul" area for PS closer than 150m of the levelling point. A.: Localization of the "Cité Saint Paul" area and considered data (red square). B.: Comparison of PS and levelling results where dashed lines represent the levelling points and continued lines, the PS.

Concerning the results for the Billy-Montigny area, we observed depressions of the same order of magnitude for the two methods allowing the validation of the interferometric results in this quite urbanised region.

4.5. Interferograms analysis

After unwrapping, vertical displacements maps are obtained. Spatial profiles, calculated on a 11 pixels large band allow to compare the different subsidence area shapes through time (figure 9). We can then highlight important differences between Lens and Billy-Montigny behaviour. Indeed, the Lens subsidence area shows some quite abrupt slopes at the difference of Billy-Montigny, which looks smoother. These differences may be due to different exploitation types and extent. On the other hand, using numerous profiles allows realizing three-dimensional visualization. The latter is very interesting to clearly visualize the shapes and spatial extent of the subsidence areas and confirm the more smooth slopes of the Billy-Montigny area according to the Lens one.

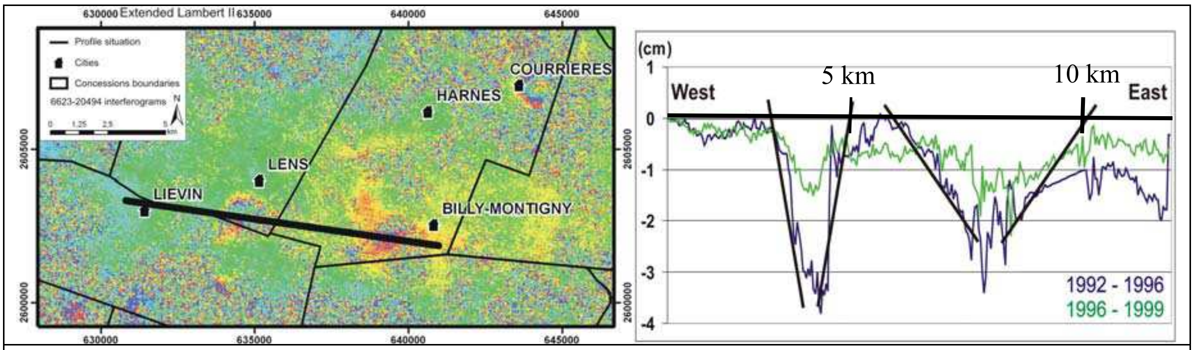


Figure 9: Localization (A) of the profiles (B) obtained from the unwrapping interferograms for two different time period (1992-1996 in blue; 1996-1999 in green)

5. Conclusion

The residual subsidence of Nord and Pas de Calais coal basin is mostly stabilized after less than five years of closure mine. The measured movements using precise levelling method and SAR interfermotry conformed this conclusion. The amplitude of subsidence velocity is less than 1 centimetre per year. The precise levelling method is traditionally used for low topographic surface movements monitoring. It already proved its ability to monitor residual phase deformation and provides very precise order of magnitude. However, this method is limited by its small spatial extent and its expensive cost. DInSAR and PSI offer new possibilities as both gives access to displacements that are of the same orders of magnitude than levelling and allow to investigate areas of larger spatial extension. It is also possible to take benefit from the ERS archive, with images acquired since 1992. In addition, the description of a new moving zone by the PSI shows that this method is particularly effective in areas of low temporal correlation where DInSAR fails and is then complementary. The realisation of profiles, velocity and displacement maps have moreover provided a great help for the analysis of the observed phenomenon.

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