InSAR assets in ground movements survey on abandoned coalfields

Atouts de l'InSAR pour le suivi des mouvements de terrain dans les zones minières abandonnées

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Abstract. Rising groundwater in abandoned mines may result in ground movements at the surface overlying underground works. Feedbacks on several abandoned coalfields show that ground uplift is generally observed, reaching in some cases several centimetres or more. Although such ground movements, slow and associated with slight slopes, are not expected to generate surface damages, the survey of potential ground movements on abandoned coalfield is necessary, especially to confirm the end of mining-induced subsidence. The most common used method for this mission is levelling. A retro-analysis of ground movements, based on Interferometric Synthetic Aperture Radar (InSAR) technique, covering more than 20 years after mine activity ceasing, has been realised on the French abandoned coalfield of Nord-Pas de Calais. This analysis aimed to extend ground movements detection capabilities in areas not covered by levelling as well as compare InSAR analysis to levelling data for evaluating the robustness of satellite-based displacement measurements. InSAR analysis was able to highlight ground movements of a few millimetres per year, with the same order of precision than classical levelling methods. The observed ground displacement patterns expand well beyond the coalfield, indicating the influence of non-mining-induced phenomena, such as local geology and surface morphology. Our findings underline the operational capability of space-borne InSAR for monitoring abandoned coalfields.

Résumé. La remontée des eaux souterraines dans les mines abandonnées peut entraîner des mouvements de terrain à la surface recouvrant les travaux souterrains. Les retours d'expérience sur plusieurs bassins houillers abandonnés montrent qu'un soulèvement est généralement observé, atteignant dans certains cas plusieurs centimètres ou plus. Bien que ces mouvements lents et à très grand rayon de courbure ne soient pas susceptibles de générer des dommages en surface, la surveillance de ces mouvements de sol reste nécessaire, notamment pour confirmer la fin des affaissements d'origine minière. La méthode la plus couramment utilisée pour cette mission est le nivellement. Une rétro-analyse des mouvements du sol, basée sur la technique InSAR (Interferometric Synthetic Aperture

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Radar), couvrant plus de 20 ans après la cessation de l'activité minière, a été réalisée sur le bassin houiller abandonné du Nord-Pas de Calais. Cette analyse visait à étendre les capacités de détection des mouvements du sol dans les zones non couvertes par le nivellement, ainsi qu'à comparer l'analyse InSAR aux données de nivellement pour évaluer la robustesse des mesures de déplacement par satellite. L'analyse InSAR a permis de mettre en évidence des mouvements du sol de quelques millimètres par an, avec le même ordre de précision que les méthodes classiques de nivellement. Les déplacements du sol observés s'étendent bien au-delà du bassin houiller, indiquant l'influence de facteurs non induits par l'exploitation minière, tels que la géologie locale et la morphologie de surface. Nos conclusions soulignent la capacité opérationnelle de l'InSAR spatial pour la surveillance des bassins houillers abandonnés.

1 Introduction

The Nord-Pas de Calais coal basin is located in the North of France. It extends from East to West on approximately 100 km for a width of 10 to 20 km (figure 1). The basin was exploited between 1750 and 1990, for a total production of 2400 Mt. Coal extraction, down to more than 1000 m deep, and along superimposed seams, has generated subsidence that, in some places, reached cumulatively more than 20 m.

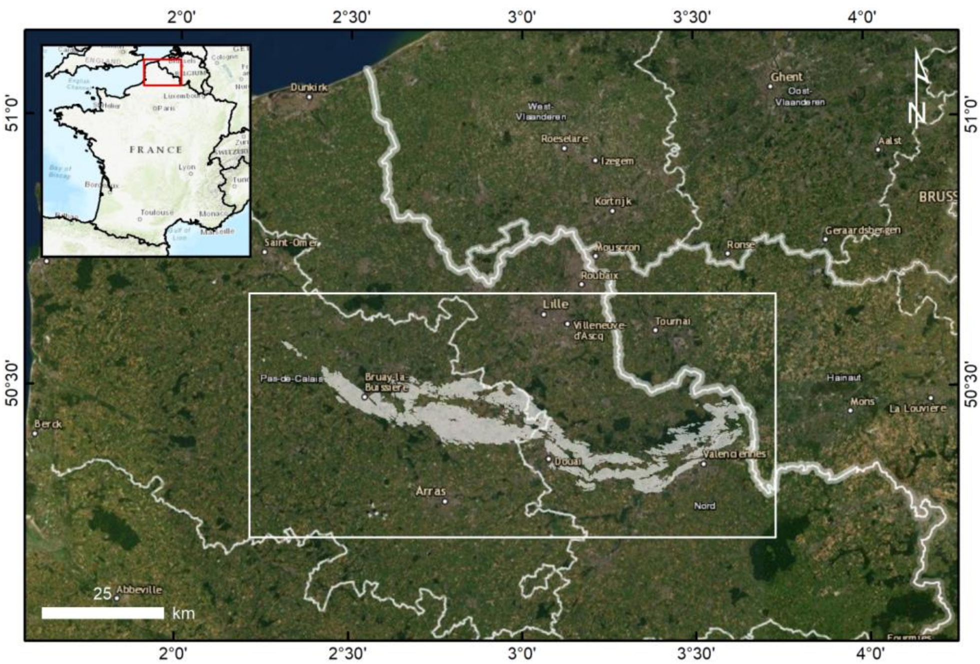


Fig. 1. Location and configuration of the Nord-Pas de Calais coalfield (underground mining works in grey)

At the end of the exploitation, the termination of pumping operations initiated a progressive flooding of underground works, which will last in the case of the Nord-Pas de Calais basin more than one century. This flooding process may result in ground movements at the surface overlying underground works. After a transition phase, lasting a few years, during which residual subsidence occurs, ground uplift is generally observed [1, 2]. This uplift finds its origin in two mechanisms:

1. The dilation of underground caved works under pore pressure rise: this mechanism constitutes the main source of the uplift phenomenon, and will be related to the volume of underground works;
2. The swelling of clay material present in the overburden: the contribution of this second mechanism is much smaller and will concern essentially the first hundreds of meters below the surface.

Feedback on several European abandoned coalfields [3] shows that this uplift can reach several centimetres or more. Largest uplifts are generally observed on places where largest subsidence occurred during exploitation. Their kinetic is directly related to the one of rising groundwater. In some cases (as observed for the Lorraine Coal basin in France), a small reactivation of subsidence might be observed before heave, due to the rearrangement of equilibrium found after residual subsidence. Although of much smaller intensity than subsidence during exploitation, these ground movements induced by water recovery are not negligible.

In the framework of its missions, the Post-mining Department of the French Geological Survey (BRGM) has the mandate of surveying these potential ground movements. The most common used monitoring technique is levelling, performed at a given frequency. On the Nord-Pas de Calais coal basin, five levelling lines of several kilometres long, which were implemented during exploitation for the monitoring of subsidence, are used for the post-mining survey and measured on a yearly basis.

The levelling lines provide high precision (of a few millimetres) measurements of ground movement. However, this technique stays spatially limited and does not offer the opportunity to detect ground movements at the coalfield scale. Mining-induced ground movement might occur also at places not covered by levelling.

Mine water recovery is a process that can last several tens of years. With the goal to optimise the long-term survey, an InSAR retro-analysis of ground movements, covering more than 20 years after mine activity ceasing, has been realised on the Nord-Pas de Calais coalfield. Our work aims to:

1. Extend ground movements detection capabilities in areas not covered by levelling;
2. Compare InSAR analysis to levelling data to evaluate robustness of displacement measurements by spaceborne geodetic techniques;
3. Investigate the impact of non-mining-induced factors on measured ground movements.

2 Methodology

Spaceborne InSAR is a technique for processing of SAR images acquired from Earth Observation satellites. The interferometric processing of a sequence of SAR acquisitions imaged from approximately the same location at different dates allows the measurement of ground displacements, with a precision of a few millimetres. Such multi-temporal InSAR analysis is applicable for monitoring wide areas, while permitting the retro-analysis using already archived SAR data. The above facts make spaceborne InSAR a relevant technique to detect and monitor mine induced ground deformation.

In the current study, we aim at detecting motion rate typically of the order of several millimetres per year (5 mm/yr or less, as expected by levelling campaigns), expanded over several kilometre distances. For this purpose, the entire archive of the European Space Agency's (ESA) historical ERS and ENVISAT as well as the Copernicus Sentinel-1 SAR missions (in descending acquisition geometries) were used, covering an area of approximately 5500 km^2:

1. ERS mission – 246 images covering the period 1995-2000; three adjacent tracks were necessary to cover the entire coalfield;
2. ENVISAT mission – 141 images covering the period 2002-2010; three adjacent tracks were necessary to cover the entire coalfield;
3. Sentinel-1 mission – 164 IW TOPSAR images covering the period 2015-2018; a single track was enough to cover the entire coalfield. Noteworthy is the fact that the repeat cycle of Sentinel 1 mission is 6-12 days (compared to 35 days for ERS and ENVISAT). For a given time span, Sentinel 1 provides a temporally denser archive resulting into more robust InSAR results.

The InSAR processing implemented is the interferometric stacking, which is based on the estimation of the average displacement rates by examining a set of successfully unwrapped differential interferograms [4, 5, and 6]. Processing was performed using the GAMMA software packages [7]. Considering the large amount of data that had to be managed, calculations were implemented on a Virtual Machine (VM) of the European Space Agency (ESA) Grid Processing on Demand (G-POD) service (https://gpod.eo.esa.int/).

For the co-registration of SAR scenes an iteration process applying initially image matching followed by Enhanced Spectral Diversity approach [8, 9]. The ALOS Global Digital Surface Model (AW3D30) (http://eorc.jaxa.jp/ALOS/en/aw3d30/) was used to compensated for the topographic component. Multi-looking factors both in range and azimuth were considered leading to interferometric outputs at 60m spatial resolution. More details on the interferometric methods used can be found in [10], [11], [12] and [13].

3 Results

Displacements are measured along the radar beam's Line-of-Sight (LOS). It is assumed that ground motion is occurring essentially along the vertical direction, and given that the area is practically flat, the vertical motion can therefore be reliably deduced from the LOS measurements. Slight deviations could be introduced due to differences in the incident angle between ERS/ENVISAT and Sentinel-1 observations.

The displacement rates are expressed in millimetres per year over the considered period, with local reference point at the town of Lille, far enough from the coalfield influence. As expected, the density of InSAR results is much higher in urban and suburban areas compared to vegetated lands (forest and/or agricultural fields), mainly due to temporal decorrelation effects.

3.1 ERS and ENVISAT observation periods (1995-2000 and 2002-2010)

A significant subsidence reaching approximately 4 mm/year can be noticed in the central region of the coalfield during the ERS observation period (1995-2000) (figure 2). This phenomenon occurs a few years after the end of the exploitation and might be attributed to residual subsidence. During the following period, ENVISAT observation (2002-2010), the subsidence in this central region is lower but still present (at 2 mm/year), despite the fact that residual subsidence is expected to end few months to few years after exploitation [14].

An increase in subsidence rates can be observed on some isolated areas during the ENVISAT period, e.g. more than 12 years after the end of coal exploitation. This observation points out a clear and significant impact of non-mining-induced phenomena on measured ground movements. This result is developed in paragraph 3.3.

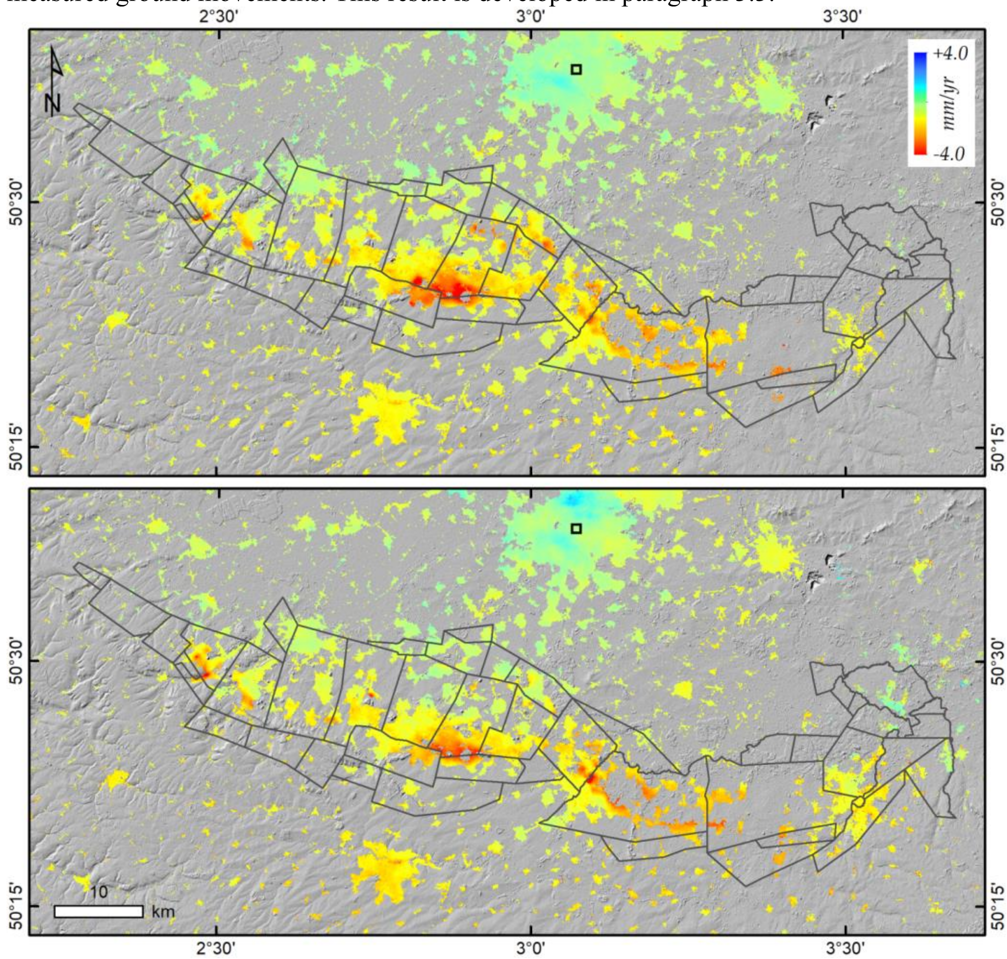


Fig. 2. InSAR ground displacement rates during ERS (1995-2000) (up) and ENVISAT (2002-2010) (down) observation periods. Selected local reference point shown as square. In background a hillshade based on the AW3D30 DSM heights. Black polygons correspond to mining concessions (see Figure 1).

3.2 Sentinel-1 observation period (2015-2018)

Subsidence is still observed over the main part of the region reaching in some places up to 5 mm/year (figure 3). At the eastern part of the coal basin subsidence is still ongoing, while extending much farer than the mining works influence, especially towards the southeast. Other areas with no relation to the coalfield show also significant subsidence, however, they cannot be attributed to mining-induced effects. Specific natural areas, such as riverbeds, are characterised by high subsidence rates, while a very localised uplift pattern is recognised within the urban area of Valenciennes (figure 4).

All these observations point out the influence of natural and/or non-mining-induced anthropogenic phenomena. These phenomena should be taken into account when interpreting the origin of ground movements in the coal basin.

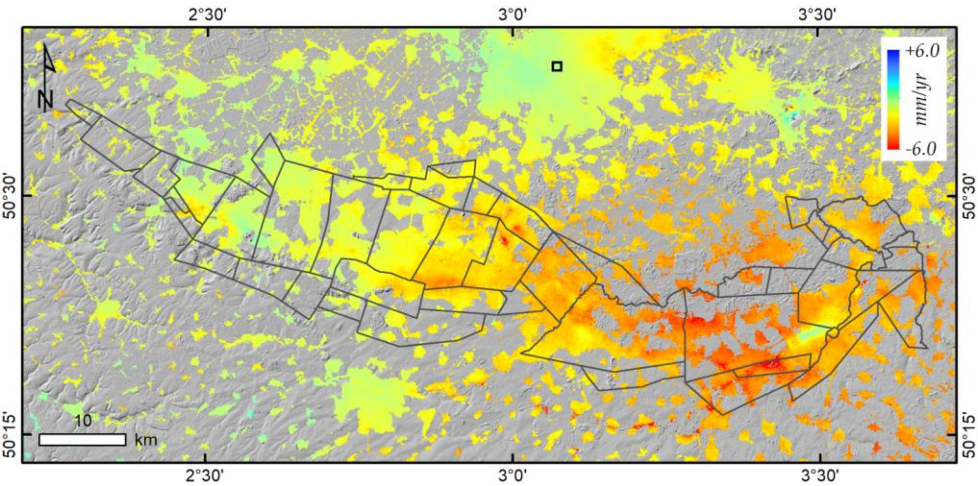


Fig. 3. Sentinel-1 InSAR ground displacement rates for the period 2015-2018. Selected local reference point shown as square. In background a hillshade based on the AW3D30 DSM heights. Black polygons correspond to mining concessions (see Figure 1).

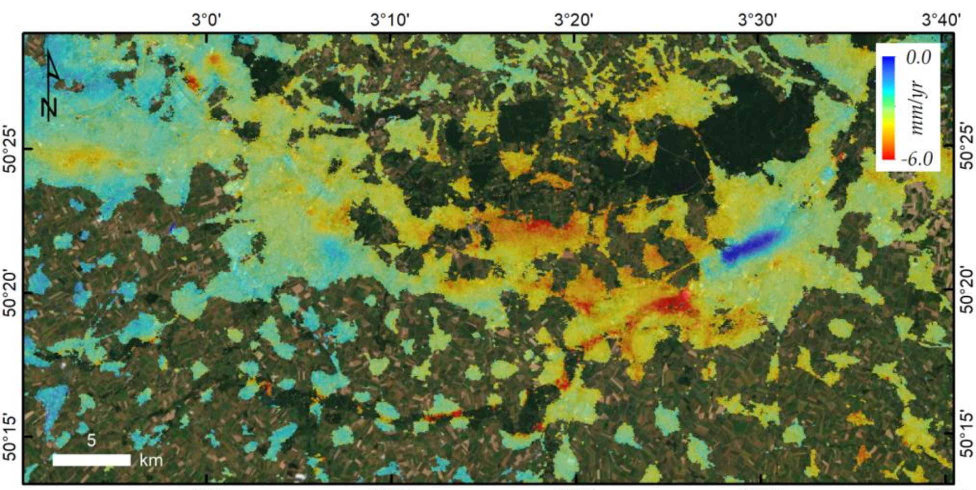


Fig. 4. Subsidence along a channelled river and localised uplift in urban area of Valenciennes, as shown by Sentinel-1 InSAR results (period 2015-2018). Satellite imagery layer in background (source ESRI basemaps).

3.3 Influence of non-mining-induced phenomena

Large and long-term geological processes, such as tectonic activity or post-glacial rebound, might generate ground movements reaching up to 1 cm/year in the Nord-Pas de Calais region [15]. However, the most important natural factor remains local geology. Figure 5 shows the geology characterizing the Nord-Pas de Calais region. The coalfield is located close to the boundary between upper Cretaceous (green colour, mainly at the SW of the coal basin) and lower Eocene (orange colour, dominating the north-eastern part of the coal basin). The eastern part of the coal basin is also characterized by an important amount of alluvial deposits (light grey colour). Highest subsidence rates are essentially observed in this part of the coal basin during the Sentinel-1 observation period (cf. Figure 3), one of the most remarkable example being along the channelled Sensée riverbed.

No further attempts were made to interpret these naturally induced (non-mining related) signals, given the focus of the current work.

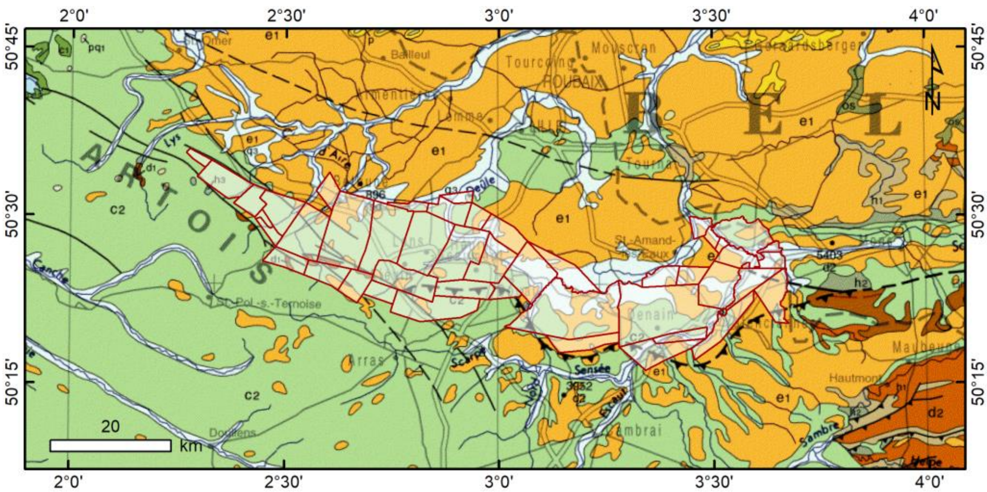


Fig. 5. Geology of the Nord-Pas de Calais coalfield area (BRGM 1/1.000.000 scale geological map, source http://infoterre.brgm.fr). Mining concessions are shown as dark red polygons.

Anthropogenic activities might also result in significant ground movements. Figure 6 shows a detail view of the central part of the coal basin, where the highest ground displacement rates are identified on open pit quarries, often associated with old coal extraction waste heaps. Other anthropogenic factors such as ground water pumping for domestic use or forgotten underground stone quarries might also induce ground movements.

Fig. 6. Correlation between highest observed displacement rates (period 2015-2018) and anthropogenic activities (quarries, red rectangles) in the study area.

4 Intercomparison between InSAR and levelling

The location of the five levelling lines used for ground movement surveys on the coal basin is shown in figure 7. As previously mentioned, they do not allow for a complete coverage of the coalfield, whereas some of them are located within the underground works influence zone. Each levelling line measurement is referred to benchmarks located at both ends of the line. Measurements are carried out once per year, with precision at the order of a few millimetres.

Two of the levelling lines indicate a continuous subsidence since the beginning of the measurements (examples of the Billy-Montigny and Lens levelling lines, figure 7), at a rate of 1 to 4 mm/year. Two others do not show clear trend, with lower displacement rates (Bruay and Estevelles-Courrières levelling lines). The last one shows apparent continuous uplift since the beginning of the measurements (Wallers-Arenberg levelling line).

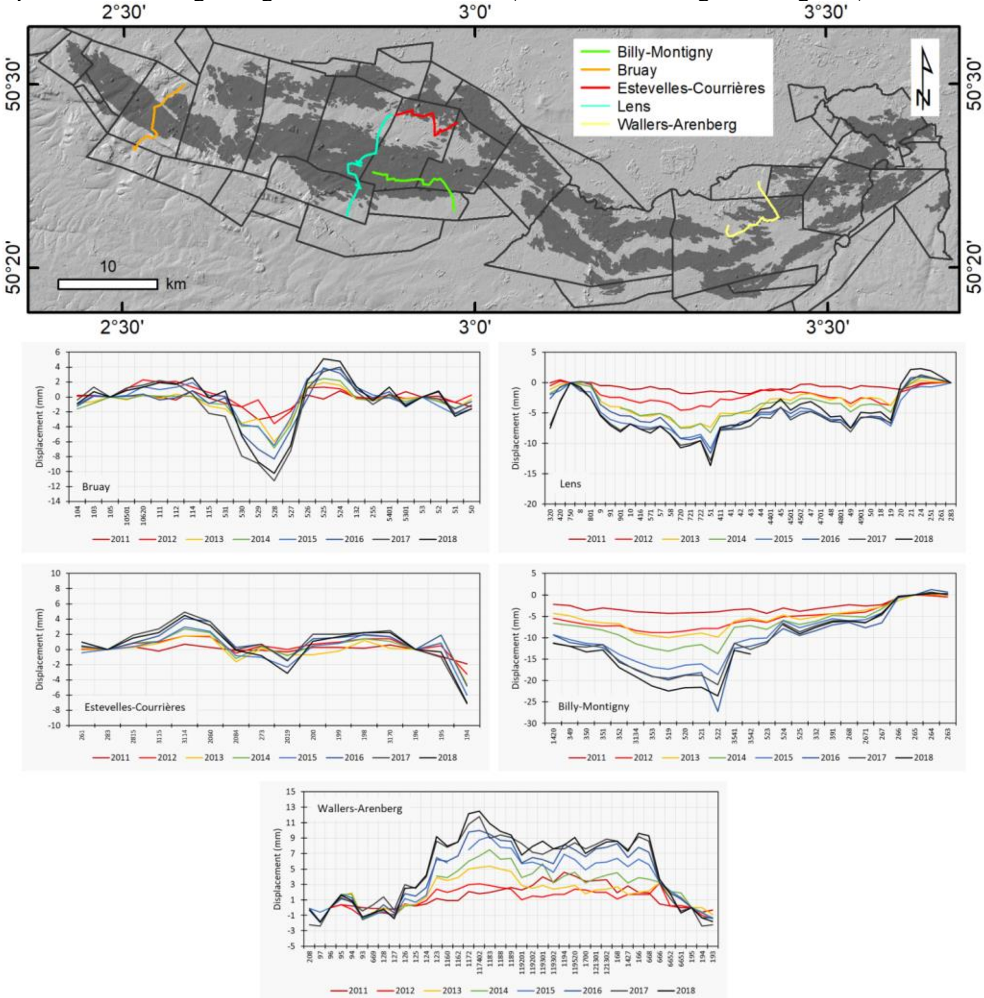


Fig. 7. Location of the five levelling line in the Nord-Pas de Calais coal basin and the corresponding vertical displacement measurements for campaigns between 2011 and 2018.

The inter-comparison between InSAR displacement rates and levelling has been done for the period 2015-2018 covered by Sentinel-1 mission data.

The results presented in the former paragraph, particularly through figures 3 and 5, show the strong influence of non-mining-induced factors, especially geology, on the origin of measured ground movements. Hence, the potential mining-induced contribution (that could be associated with rising groundwater) to these already very small movements, cannot be distinguished from that associated with non-mining-induced phenomena.

The following proposed interpretation considers then the measured ground movements as the sum of all factors likely to generate ground movements, without being able at this stage to distinguish them. The impact of non-mining-induced phenomena, however, appears to be preponderant.

Figure 8 presents InSAR displacement rates in the surroundings of the Wallers levelling line. Alluvial deposits are particularly presents in the sector where this levelling line is implemented. Figure 8 shows that the benchmarks at both ends of the levelling line are also affected by ground movements during the observation period. Subsidence rates at the levelling benchmarks up to 4.3 mm/year are measured. This relative movement of the levelling benchmarks generates an offset, which must be corrected when interpreting levelling data.

Moreover, the middle part of the Wallers levelling line appears to undergo slower subsidence than its ends, with displacement rates less than 3 mm/yr. Therefore, what was interpreted as uplift based on levelling (Figure 7) is in fact the result of subsidence being faster at its ends where the reference benchmarks are located (Figure 8).

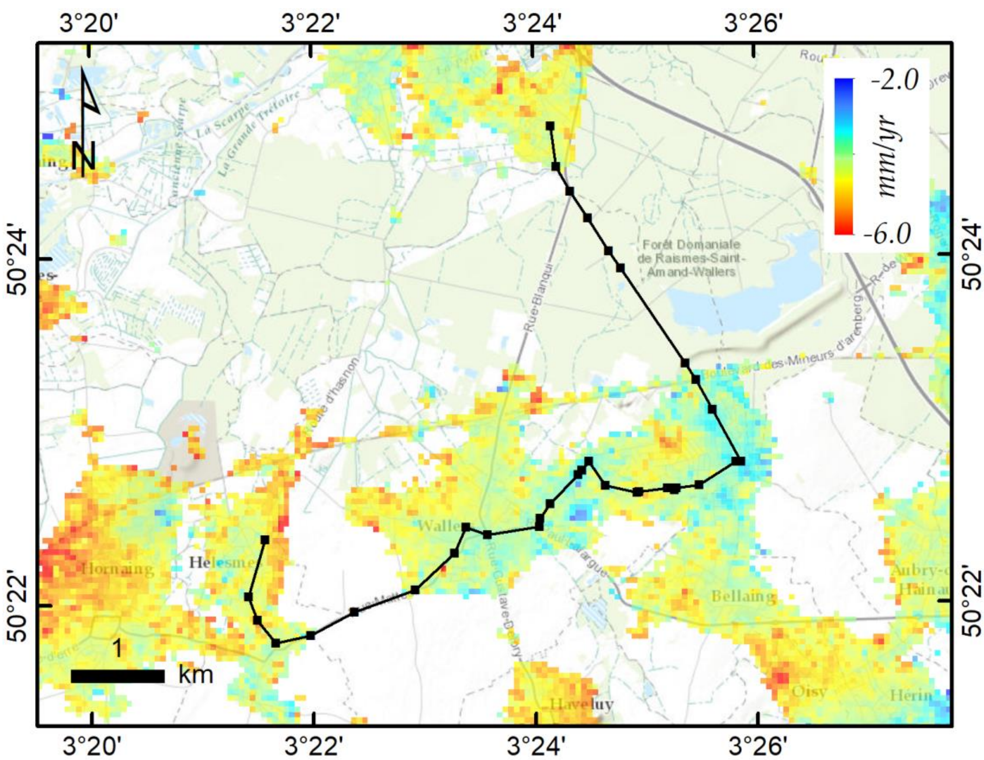


Fig. 8. InSAR ground displacement rates in the Wallers levelling line area, Sentinel-1 period (2015-2018). World topographic map in background (source ESRI basemaps).

This intercomparison points out that differential motion between benchmarks at both ends of a levelling line (i.e. one exhibits a relative motion respect to the other), shall introduce not only an offset but also a distortion in the produced displacement profile. This is clearly visible on the Bruay levelling line (the westernmost line in the coalmine basin; see figure 7) for which a difference of about 1 mm/yr is observed between both ends (figure 9).

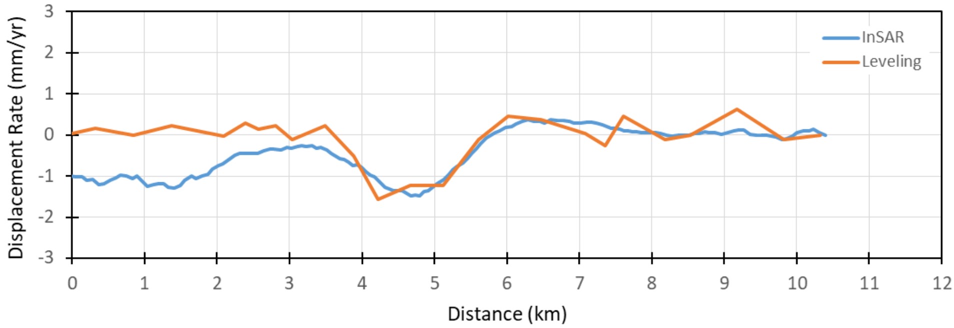
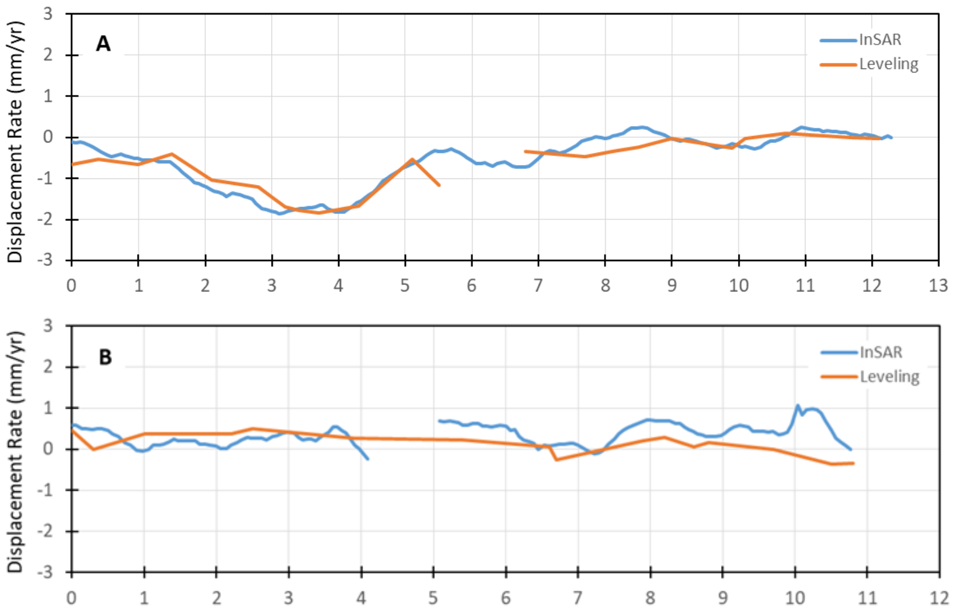


Fig. 9. Displacement rate differences along the Bruay levelling line, after adjustment on one of the levelling benchmarks.

Following the adjustment of the InSAR displacement rates to compensate for the referencing differences generated by the movement of levelling benchmarks, displacements rates calculated with both methods fit remarkably well (figure 10). This result shows that InSAR is a perfectly adapted tool to monitor ground displacements with a precision equivalent to that of levelling method.



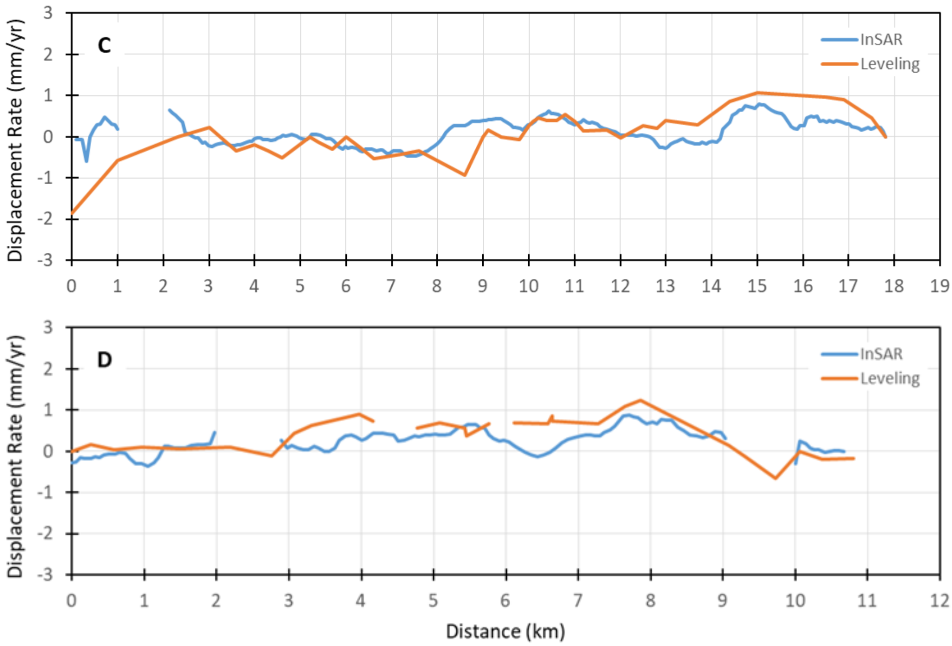


Fig. 10. Comparison of the displacements calculated from Sentinel-1 InSAR and levelling for (a) Billy-Montigny, (b) Estevelles-Courrières, (c) Lens and (d) Wallers-Arenberg levelling lines (see Figure 7).

5 Conclusion

This study demonstrated that the effective monitoring of mining-induced ground movements at the scale of a coalfield requires techniques able to operate at large spatio-temporal scales as well as properly designed to facilitate identification of non-mining related deformation mechanisms, particularly the influence of local geological conditions. Spaceborne InSAR techniques offers the opportunity to examine historical data archives, while covering much larger regions compared to standard levelling methods. By achieving comparable level of precision, InSAR has been proven well suited for revealing ground movements not detectable by local levelling campaigns.

InSAR appears also as a complementary tool to emphasize the impact of non-mining-induced phenomena on levelling measurements, especially on the potential movement of levelling benchmarks. These results highlight the necessity of being cautious when interpreting the origin of damages caused by ground movements.

Our findings underline the capability of satellite InSAR for the operational surveying of ground movements on abandoned coalfields. The ability to cover wide area, the frequency of data availability, the accuracy of the measured displacements and the opportunity to perform retro analysis are strong assets in post-mining monitoring context.

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