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Detection of mining related ground instabilities using the Permanent Scatterers technique—a case study in the east of France

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Ground stability is a major concern for land use planning and both natural and anthropogenic risk assessment, especially in urbanized areas. Space-borne differential radar interferometry provides a unique tool able to give a synoptic view of ground deformation with centimetric to millimetric vertical precision. Approaches for combining a wide range of radar images such as the permanent scatterers (PS) technique allow the estimation of the deformation history of single buildings. The PS approach has been exploited to investigate a test site particularly exposed to ground deformation hazards, namely the iron mining basin in Lorraine (France). In this Letter, a specific focus was set on the case of Roncourt, where precursor signs of a collapse affecting an area of $\sim 300 \times 300\,m^2$ have been identified.

1. Introduction

The iron mining basin in Lorraine (France) covers an area of more than $1680\,km^2$ from Nancy to the border with Luxemburg. The iron ore has been intensively exploited since about 1870 at a depth of several tens of metres using the chamber and pillar method under existing infrastructures. As a consequence, several ground deformation phenomena have been observed at the surface (Deck *et al.* 2003).

Three major types of deformation can occur over abandoned mine cavities (Cui *et al.* 2000, Bennani *et al.* 2003): (1) a sudden collapse can take place when the progressive degradation of the roof of a cavity (generally not deeper than 50 m) reaches the surface; (2) a sudden deep collapse in wide mine works can induce surface faulting and tremor; and (3) subsidence bowls with a diameter up to several hundreds of metres can arise.

All the types of deformation mentioned can damage severely existing buildings and should, therefore, be monitored.

The monitoring of ground deformation by means of classical methods such as optical levelling or Global Positioning System (GPS) can reveal deformations with sub-millimetric to centimetric precision on localized areas. However, to provide data

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on a reasonably dense two-dimensional (2D) benchmark grid, conventional techniques require the test area to be very small, otherwise cost and measurement time are no longer affordable. Moreover, a regular (both expensive and time consuming) intervention on the site is required and a retrospective study of a specific deformation event is usually not possible, since monitoring networks are often implemented after the major events themselves.

Synthetic Aperture Radar (SAR) images provide an alternative and complementary method to investigate ground deformation phenomena. In particular, differential SAR interferometry (DInSAR) can give a synoptic view of the deformation events projected along the sensor–target line of sight (LOS) on areas of hundreds to thousands squared kilometres (see e.g. Massonnet and Feigl 1998 for a review).

The results of a multi-image interferometric study (permanent scatterers (PS) analysis) performed involving a full archive of European Remote Sensing Satellite (ERS) SAR images on the Lorraine iron mining basin are presented. A specific focus is set on the Roncourt area, where collapse precursor signs have been clearly detected in PS deformation time series. The comparison with optical levelling data has been carried out as well.

2. Data processing and results

In this study, a set of 57 descending mode ERS-1/2 SAR data (track 337, frame 2619, including 10 Tandem pairs), covering the time span June 1995–April 2000, has been processed. The three most suitable Tandem pairs were exploited jointly using a multi-baseline approach (Ferretti *et al.* 1999) to reconstruct a digital elevation model with an estimated vertical standard deviation of ~12–15 m.

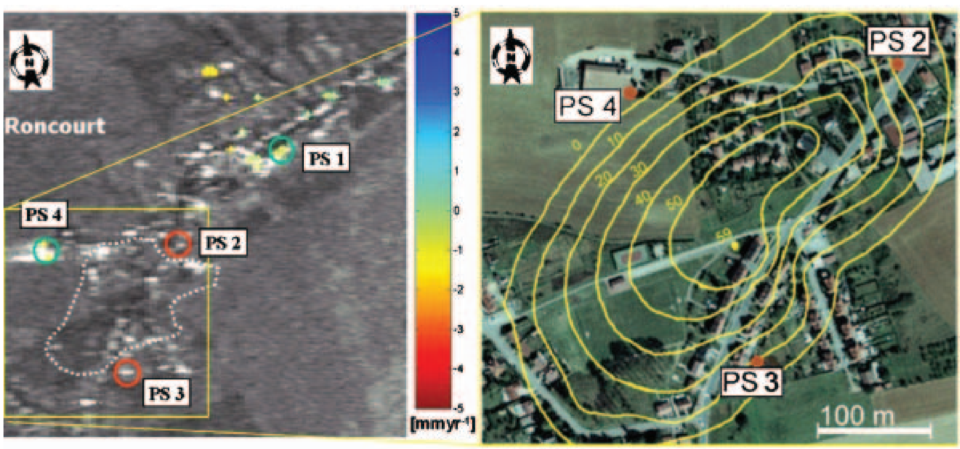
Whenever carrying out deformation measurements starting from SAR interferograms, only the projection along the sensor–target LOS (d_{LOS}) of a potentially three-dimensional (3D) (easting, northing, height) displacement vector (d) is recorded. In particular, d_{LOS} can be obtained as the scalar product between d and the so-called sensitivity versor u (Massonnet and Feigl 1998, Colesanti *et al.* 2003a). In the centre of the area investigated in this study, u has the following components, $u=(u_E,u_N,u_H)=(0.42,-0.11,0.9)$ and shows large sensitivity with respect to vertical deformation typical of ERS-1/2 SAR interferometric data.

A preliminary test based on the analysis of single interferograms (conventional DInSAR, see e.g. Carnec and Delacourt 2000) did not allow one to highlight the ongoing deformation phenomena due to the dense vegetation cover inducing rapid decorrelation with time. To circumvent this problem, the PS technique has been used.

The PS technique is an advanced processing tool allowing the joint exploitation of series of interferometric SAR images all referred to a unique master acquisition. It focuses the attention on privileged radar targets (the so-called PS) only slightly affected by both temporal and geometrical decorrelation. The different contributions to the interferometric phase (residual topography, ground deformation, atmospheric disturbances, imprecision in the orbital data) are separated on a pixel-by-pixel basis exploiting their different behaviour in a time–space–acquisition geometry (i.e. normal baseline) domain. Information from isolated phase stable radar targets (i.e. individual buildings and/or rocky outcrops), even if surrounded by incoherent image pixels, can be extracted as long as the number of images and the PS spatial density are large enough (at least 15–20 images and $5\,\mathrm{PS\,km^{-2}}$). A detailed description of the PS technique can be found in Ferretti *et al.* (2000, 2001). The first comparison of PS results with GPS and levelling records is reported in Colesanti *et al.* (2003a) and highlights clearly the millimetric precision of PS displacement measurements. More details on a formal precision assessment of PS results and further examples can be found in Colesanti *et al.* (2003b).

The PS analysis has been carried out as a 'blind experiment' without any *a priori* information, apart from the geographical coordinates of a few ground control points. A test area of ~24 km × 34 km was investigated. Despite the rural environment, the average PS spatial density resulted in ~60 PS km^{-2}. To identify PS, a simple time uniform (i.e. constant velocity) model for ground deformation has been used. Under the assumption of constant LOS velocity deformation it was not possible to find PS in several very localized test sites within the test area (e.g. part of the village of Roncourt, see figure 1). Nevertheless, statistical indices used to identify in advance probable PS, in particular the (amplitude) dispersion index discussed in Ferretti *et al.* (2001), indicated clearly the presence of image pixels expected to show PS phase stability. This suggested that very likely the constant velocity model was inadequate to fit the local LOS ground deformation dynamics. Indeed, assuming a fourth order polynomial to model its temporal evolution (Colesanti *et al.* 2002, 2003b), additional PS (e.g. 2 and 3 in figure 1) could be found where expected in Roncourt. The corresponding time series show LOS displacement effects with a strongly time non-uniform behaviour.

Moving towards the centre of the village the dynamic range of the LOS deformation effects increased and, finally, even assuming polynomial models, the interpretation of the time series became extremely difficult and no PS could be identified with high confidence (area marked in figure 1(*a*)). Coupled with the time series successfully extracted (figure 2), this suggested that, starting from



(*a*) (*b*)

Figure 1. (*a*) Position and average LOS deformation rate (colour code, negative values indicate subsidence) of PS superimposed on a multi-image reflectivity map (non geocoded). Even with polynomial models, no high confidence PS could be found in the area highlighted with the white dotted line due to fast evolving ground deformation. (*b*) Approximate geometry of the collapse event derived from the interpolation of levelling measurement performed in 1994 and in May 1999. The maximum amplitude of the subsidence was estimated at 59 cm. Each contour line represents 10 cm of vertical deformation.

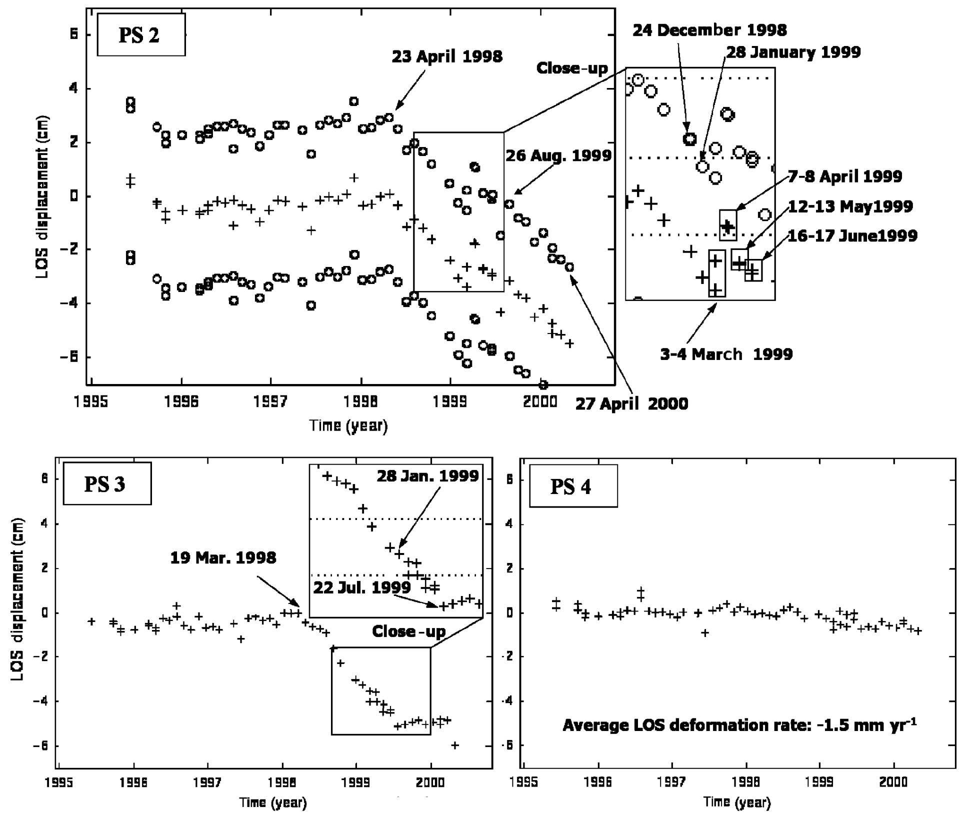


Figure 2. PS 4, outside the area affected by the strong subsidence phenomenon, has a rather flat time series. PS 2 and 3 show clear evidence of a deformation event starting in April 1998, 10 months before the collapse of February 1999. Plotting $\pm\lambda/2$ replicas (to underline the ambiguity of phase measurements) clear signs of aliasing can be recognized at PS 2 in the time span January–July 1999. The distance between the horizontal dotted lines in the close-up boxes corresponds to 2 cm. In the close-up relative to PS 2 the black boxes identify records relative to ERS-1/2 Tandem pairs (one-day time span between the acquisitions).

March–April 1998, intense displacement effects occurred, widely and continuously exceeding the limit posed by the sampling theorem to the detection of unambiguous deformation (as a function of time) at single PS.

As is well known, phase measurements are affected by an intrinsic 2π ambiguity (corresponding, for ERS SAR, to $\lambda/2=2.83$ cm along LOS and 3.1 cm in vertical direction). Therefore, alias affects data characterized by more than $\lambda/4=1.41$ cm LOS displacement in the 35 day ERS revisiting time (aliasing along time of the phase/deformation series).

As discussed below, such a strict limit is generally valid as long as no *a priori* information is available and the PS analysis is carried out without exploiting the possible spatial correlation of the deformation phenomenon at-hand.

The results of the ‘blind’ PS analysis turned out to be perfectly consistent with the fast evolving subsidence event that occurred in Roncourt in February 1999, inducing severe damage to houses. Ground *in situ* investigations revealed a collapse event having a maximal vertical amplitude of 59 cm and extending on a roughly elliptical area (major axis approximately 450 m, minor axis 250 m, see figure 1(*b*)) at a location that matches well with the PS results. The process went on achieving the figure of 72 cm vertical deformation, according to the latest measurements performed in December 2002.

The PS analysis allowed a retrospective study of this ground deformation event. In particular, outside of the subsidence bowl, tens of PS could be identified easily with the time uniform deformation model. Their evolution was well summarized in LOS velocities ranging from 0 to $-1.5\,\mathrm{mm\,yr^{-1}}$ (figure 1(*a*)). Moreover, a set of time series was produced, relative to 10 demonstrative PS immediately around and within the area affected. The positions of those with lowest phase noise among them (1, 2, 3, 4) are highlighted in figure 1 and the corresponding time series are represented in figure 2 (the flat time series of PS 1 is not reported).

Since at individual PS a fine elevation estimate ($\sigma \leqslant 1$ m, Ferretti *et al.* 2001) was carried out (in order to isolate the topographic phase contribution), precise geocoding was possible, allowing one to map the PS on the corresponding structures, exploiting high resolution orthorectified aerial photography. PS 1 showed no evidence of LOS ground deformation whereas PS 4 exhibited a LOS displacement of a few millimetres. On the contrary, PS 2 and 3 showed clear evidence of a LOS deformation phenomenon starting in March–April 1998, thus 10 months before the major collapse event. The aliasing clearly affecting the phase measurements (e.g. PS 2, January–July 1999) did not allow one to derive from these PS time series alone the exact amplitude of the deformation in correspondence and immediately after the major collapse.

After the collapse event, a ground control levelling network was set up in February 1999. The position of two levelling benchmarks matches almost perfectly PS 2 and 4, and a third benchmark is very close to PS 3. This enabled a quantitative comparison between the two types of measurement for the period February 1999–April 2000. To this end it was assumed that ground deformation occurred only in vertical direction. The levelling data (sensitive to vertical displacement only) were projected along the ERS LOS. The levelling benchmark located near PS 4 did not show any sign of deformation, which is consistent with the flat time series depicted in figure 2. Besides delimiting the area affected by deformation, this agreement is relevant also because it confirmed that no systematic bias was affecting the whole set of PS measurements.

On the contrary, the benchmarks close to PS 2 and 3 exhibited more than 15 cm of progressive deformation after the main collapse event. The quantitative comparison between the time series of PS 2 and that of the corresponding levelling benchmark is provided in figure 3. Both in the close-up of figure 2 and in figure 3(*a*), one can appreciate that the LOS deformation evolved too fast in the time span January–July 1999 to allow for an unambiguous monitoring on a single pixel basis. Four phase jumps have been identified. Once correctly unwrapped, a direct comparison with levelling data (projected along the ERS LOS) is possible for the full time span February 1999–April 2000 (see figure 3(*b*)). Starting from August 1999, both measurements (PS and levelling) agree perfectly without any hypothesis on the solution of phase ambiguity (due to a slower evolution of the deformation phenomenon).

3. Discussion and conclusion

The retrospective analysis of a series of 57 ERS-1/2 SAR images was performed blindly to investigate the surface deformation event in the site of Roncourt (France).

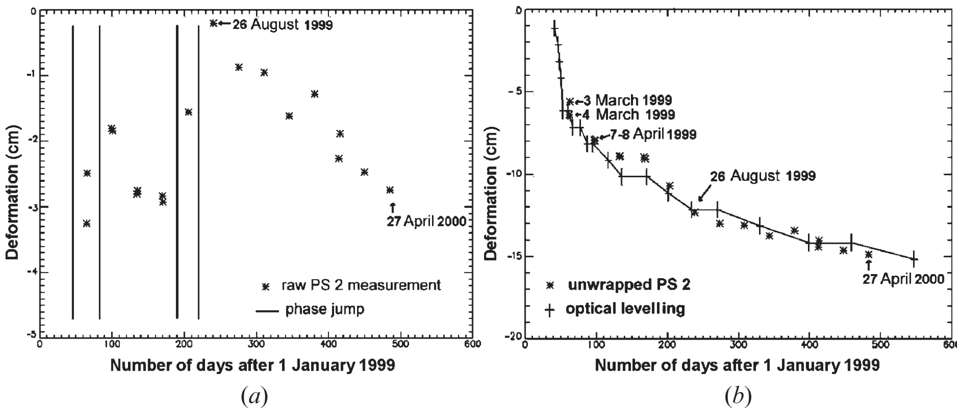


Figure 3. Comparison with optical levelling at PS 2 (after the collapse event of February 1999): (*a*) ambiguous (phase wrapped) PS measurement; and (*b*) unwrapped time series of PS 2 compared with the levelling data.

This site suffered from ground instability due to historical iron mining activity. The PS processing approach was employed to overcome the difficulties linked to the strong temporal decorrelation (due to the vegetation cover) affecting conventional interferograms. Clear collapse precursor signs have been identified in the 10 months preceding the major collapse event, which occurred in February 1999. The comparison with available levelling measurement after the collapse itself shows a good consistency (differences in the order of 1–5 mm) between *in situ* and space-borne measurements.

The PS interferometric approach provided valuable clues about the dynamic evolution of this collapse event, even though, without exploiting auxiliary additional information, the phase ambiguity did not allow the evaluation of the amplitude of such a decimetric deformation.

It is worth pointing out that starting from the spatial correlation of the phenomenon at hand it is possible to prevent or solve aliasing in the PS time series, as long as the spatial gradient of the displacement effect is not too strong. Depending on the local PS spatial density, the applicability limits can be estimated quantitatively with a sparse grid generalization of the simple considerations discussed for individual interferograms in Massonnet and Feigl (1998).

The capability of investigating the deformation before the major collapse itself (when no levelling data were recorded) suggests that a relevant application of the PS technique could be envisaged in the detection of collapse precursors.

Anyway, for achieving operational capability, a shorter revisit time would be often required. Moreover, other collapse events occurred (also in similar geological and mining contexts) without clear evidence of known precursor signs. A deeper analysis of several different cases should, therefore, be performed to generalize the case of Roncourt.

Nevertheless, this study clearly shows the important role that the PS technique as well as other advanced multi-interferogram radar interferometry approaches could play in land use planning and natural or anthropogenic risk assessment. In particular, these approaches could be exploited systematically on large areas ($100 \times 100\,\mathrm{km}^2$) to optimize and drive other ground control methods such as optical levelling and microseismicity techniques (Bennani *et al.* 2003), which can be used locally to set up a real-time alert system.

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