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Observation and modelling of the Saint-Etienne-de-Tinée landslide using SAR interferometry

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Abstract

SAR interferometry has been shown to lead to accurate large-scale surface displacements mapping. The study of the "La Clapière" landslide, located in Southern France on the left bank of the Tinée river, was carried out in order to demonstrate the capability of interferometry to monitor displacements of small spatial extension. In a first study, six different interferograms have been derived from ERS-1 SAR images acquired during the Commissioning Phase. The coherence of the associated images was shown to remain significant over most of the surface of the landslide during the two weeks of the survey. The interferograms, generated on a massively parallel computer, clearly evidenced deformation fringes associated with the landslide. They were remarkably similar, and indicated steady-state displacements over at least 12 days. The displacement field derived from the interferograms was modeled and shown to be characterized by a non-uniform displacement gradient from the top to the bottom. It also revealed a significantly faster motion of the western part of the landslide. The amplitude of the motion was shown to be in good agreement with ground measurements. Furthermore, the interferograms allowed us to evidence a small-scale instability which could not be observed with discrete ground measurements. Finally, we present preliminary results obtained on the same site with images acquired during the second Tandem mission. It provided the opportunity to extend the study of the landslide, which displacements are too high to be observed with images acquired on the standard orbital cycles of 35 days.

Keywords: SAR differential interferometry - Deformation field - Saint-Etienne-de-Tinée landslide - Massively parallel processing - Tandem.

Introduction

Landslides can be a major threat to populations in mountainous areas. Even when they occur away from inhabited areas, they can be a significant hazard and have a serious economic impact by blocking roads and rivers. The "La Clapière" landslide is a good example. It is located near Nice, in Southern France, on the left bank of the Tinée river. This landslide, which extends over a few km^2 between 1100 m and 1700 m, is bounded at the top by a high lobate scarp (fig.1). It is also characterized by an active scree slope on the NW part. A competent layer, known as the barre d'Iglière, produces a sub-horizontal mechanical discontinuity at mid-level in the landslide.

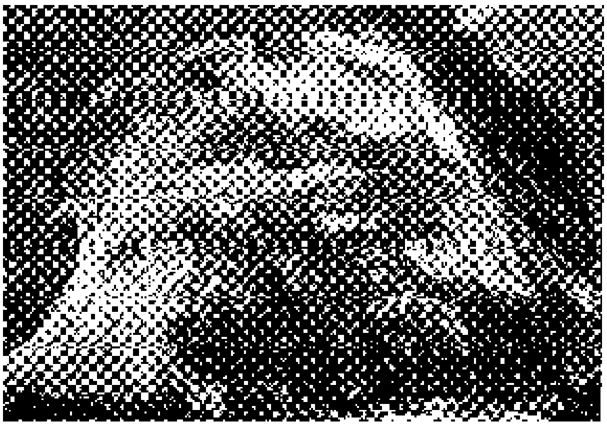

***Figure 1**: The "La Clapière" landslide*

It threatens to obstruct the valley, and then may lead to an overflow of the upstream village of Saint-Etienne-de-Tinée. This hazard has been mitigated with significant road and tunnel construction. It has also been monitored by laser-ranging since 1982. Such a permanent monitoring requires the deployment and servicing of several tens of laser reflectors as well as daily measurement operations. We propose in this paper to apply the technique of SAR interferometry (Zebker et Goldstein, 1986 ; Gabriel *et al*., 1988) to this landslide, in order to demonstrate its capability for studying small scale deformations. In particular, we compare the characteristics of SAR monitoring derived from this analysis to those of ground measurements

Interferometry

In a first study, we constructed six interferograms with images acquired by ERS-1 with a 3-days repeat cycle, on descending orbits, on August 20, 23, 26, 29 and September 4, 1991.The interferograms are generated on a massively parallel computer (Connection Machine 5). The effect of topography in each interferogram is removed using a 5 m x 5 m Digital Elevation Model

(DEM) of the site provided by Institut Géographique National of France (Massonnet *et al.,* 1993 and 1995). The resulting differential interferograms are then projected from SAR geometry to DEM geometry. They correspond to a contour map of the component of the surface displacement field in the direction of the line of sight of the satellite. Significant phase variations associated with the landslide can be detected on these interferograms.

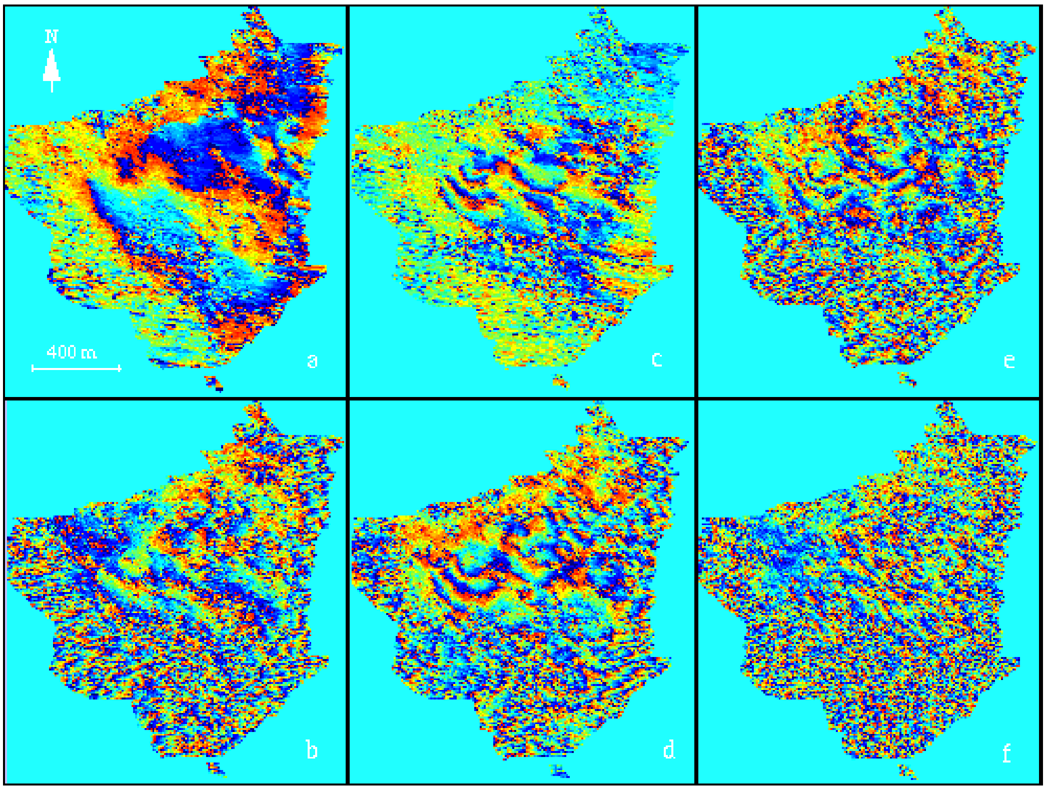

Figure 2*: Geocoded differential interferograms.* ***(a)*** *23-26 pair (3 days). Bperp= 43 m.* ***(b)*** *26-04 pair (6 days). Bperp= -298 m.* ***(c)*** *20-29 pair (9 days). Bperp= -4 m.* ***(d)*** *26-04 pair (9 days). Bperp= 248 m.* ***(e)*** *23-04 pair. Bperp= 291 m.* ***(f)*** *20-04 pair. Bperp= -301 m*

Figure 2 shows the 6 interferograms. The 3-days interferogram (fig.2a) provides the clearest picture of the landslide, due to its small baseline and a very short time interval. Its boundaries are well described, especially the northwestern part and the 2 lobes at the top. The others present fringes with a lower SNR, because of larger baselines and larger time intervals. All computed interferograms are shown to be similar. The number of fringes increases linearly with the elapsed time between the various image acquisitions, while their overall geometry remains the same. This suggests that the observed landslide motion is stationary over the period surveyed. On all six interferograms, NW-SE trending fringes attest of a downhill movement characterized by a gradient of displacement from the top to the bottom of the landslide, the motion decreasing towards the bottom. A full phase rotation is equivalent to a displacement gradient of 3.9 cm along the landslide average steepest slope. The fringe intervals are not constant over the landslide, suggesting both downhill and lateral variations of the displacement gradient. This gradient changes from top-to-bottom, especially in the SE part: the gradient is very low between the intermediate scarp and the "barre d'Iglière" and seems to increase below this layer. This is consistent with the hypothesis that this layer behaves as a competent layer that blocks the movement and maintains some coherence in the upper part of the massif. From the active scree slope towards the SE, i.e. towards the right side, one observes a progressive increase of the fringe separation, indicating a decrease of the displacement gradient. This variation occurs near the N20° faults that cut the landslide.

Modelling

Since interferograms measure only one component of the displacement (its projection on the slant-range), recovering the 3 components of the displacement field requires some a priori hypotheses on the mechanical behaviour of the landslide. Synthetic interferograms have been computed for two different sliding models which represent the most important types of slope failure: rotational and translational slips (Bromhead, 1986 ; Giani, 1992). In rotational slip, the sliding surface has a spoon shape, and can be approximated by a circle in vertical cross-section. With translational slip, the failure surface tends to be planar and roughly parallel to the slope.

Rotational model

The surface displacements associated with this model are similar to the simple tilt of a rigid block. As already shown by Peltzer *et al*. (1994), we observe that the fringe separation, is not sensitive to the curvature of the sliding surface and only depends on the rotation of the block. With such a model, the interferogram analysis appears therefore not to be efficient to estimate the depth of the sliding surface, a parameter which controls the behaviour of the landslide and the related hazard. In any case, this type of model does not seem to describe the St-Etienne-de-Tinée landslide since it shows fringes with a regular spacing interval and cannot account for the observed non-uniform gradients displayed by the interferograms.

Planar model

A preliminary model based on the 20-29 interferogram was proposed in a previous study (Fruneau et Achache, 1995). In this model, elastic deformation along 3 major discontinuities (faults trending N20°) was superimposed on a uniform gradient of displacement from top-to-bottom. A rigid block of a few hundred meters was also included in the eastern part, between the "barre d'Iglière" and the intermediate scarp. However, when the amplitude of the displacements is rescaled assuming a constant velocity field, this model cannot account for the fringes observed on the new 3, 6 and 12 days interferograms derived in the present paper.

Using these additional interferograms, we derived a new model in which elastic deformation along the major structural discontinuities is modelled by progressive lateral decrease of the top-to-bottom displacement gradient (Fruneau *et al*., 1995b;

Fruneau, 1995). Figure 3a displays synthetic fringes produced by such a displacement field with a gradient ranging from 1.5 cm/100 m in the west of the slide to 0.5 cm/100 m in the east above the barre d'Iglière and 1 cm/100 m below the barre. This variation of the gradient of displacement from the top to the bottom was introduced to further improve the fit between observed and synthetic fringes in the eastern part of the landslide. It may be associated with a swelling of the topography above the "barre d'Iglière" and is consistent with the mechanical behaviour of this layer which holds back the upper part of the landslide. This interferogram (figure 3a) can be compared with the 23-26 interferogram (figure 2a). The displacement field of figure 3a can, then, be rescaled by factors 2, 3 and 4 and the resulting fringes (figure 3b, c and d) can be readily compared with the 6, 9 and 12 days interferograms of figure 2b, c and e, showing a satisfactory agreement. Furthermore, this modelling confirms the stationarity of the displacements.

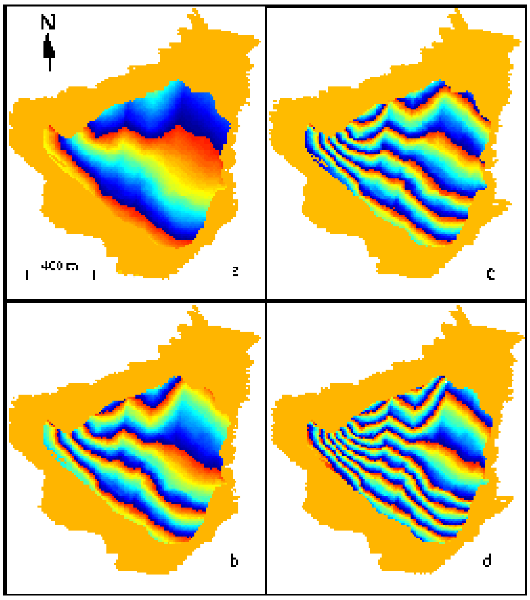

***Figure 3**: **(a)-**Synthetic interferogram. A top-to-bottom gradient of displacement is gradually decreased across the landslide from 1.5 cm/100 m in the NW to 0.5 cm/100 m in the SE. This interferogram should be compared with the 3 days interferogram of figure 2a. **(b)-**The displacement field is increased be a factor 2 with respect to figure 3a. To be compared with the 6 days interferogram of figure 2b. **(c)-**The displacement field is increased by a factor 3 with respect to figure 3a. To be compared to the 9 days interferograms of figure 2c and d. **(d)-**The displacement field is increased by a factor 4 with respect to figure 3a. To be compared to the 12 days interferogram of figure 2e.*

Figure 4 displays the difference between modelled and observed fringes of the 23-26 pair. We observe a nearly uniform phase value over the area of the landslide, indicating a good agreement between the two interferograms over most of the sliding zone. At the eastern top of the slide, figure 4 displays significant phase variations over a small area. This evidences a small unit in the landslide which movement is rapid, and which has not been taken into account by the uniform translational model.

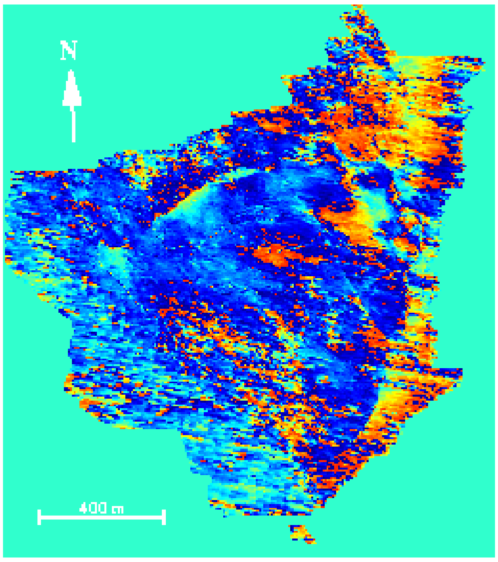

***Figure 4**: Difference between the real and the modeled interferogram.*

Comparison between SAR and ground measurements

The interferometric analysis provides accurate estimates of the displacement gradients in close agreement with existing ground measurements. Figure 5 shows displacement vectors monitored on ground superimposed on displacement vectors derived from our model (which gives a smoother representation that the noisy real interferograms).

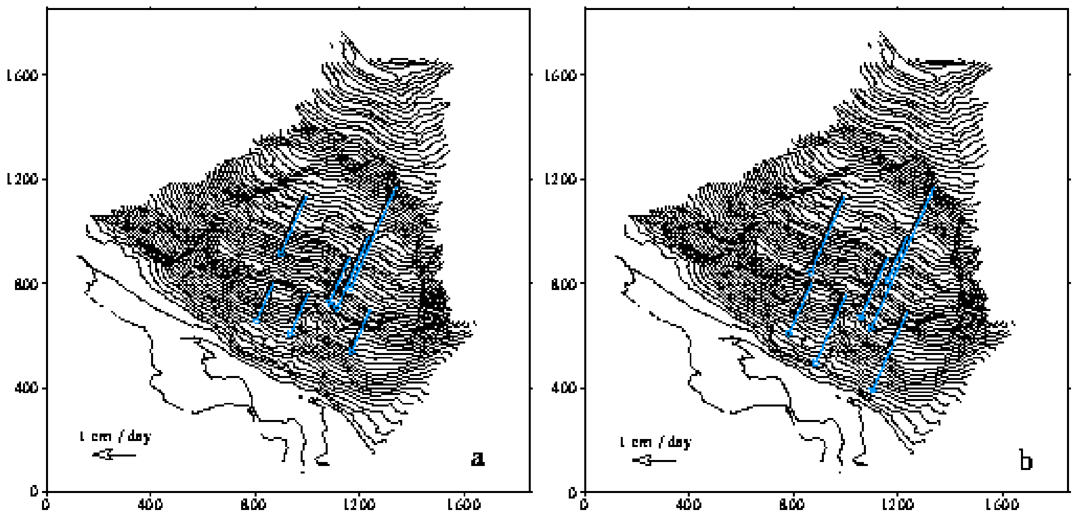

Figure 5: ***(a)-****Displacement vector measured on ground by laser telemetry (bleu arrows) and computed from the model (black arrows) for the 26-04 period.* ***(b)-****Same as figure 5a for the 23-26 period.*

Some discrepancies are observed on figure 5b near the bottom of the slide. This can be explained by the fact that interferometry provides only the gradients of displacement. Then only relative displacements can be evaluated because of the discontinuity of the movements between the landslide and the steady massif and ground reference points are necessary to determine absolute displacements. A constant displacement corresponding to the bottom displacement should be added to our model. In the present case, ground measurements by laser telemetry reveal a systematic offset with the average displacement recorded by SAR interferometry. This offset varies from 2 to 7 mm / day over the duration of the survey and provides an estimate of the absolute displacement at the bottom of the landslide.

This shows the complementarity of ground and SAR measurements.

Tandem mission

The tandem mission allowed us to circumvent the incompatibility between the amplitude of the movements and the repeat period of the standard ERS orbit (35 days). It offered the opportunity to carry-on our study of the Saint-Etienne-de-Tinée landslide.

Two interferograms calculated with images from the second Tandem mission give interessant preliminary results. On the 13-14 august 1995 interferogram (fig.6a), we observe a nearly uniform phase change over the area of the landslide, with respect to the bulbe of the landslide. The phase change is also observed on the second couple (10-11 march 1996)(fig.6b), but is less uniform, and clearly evidences the small block on the upper right part of the landslide, which was already detected on the previous interferograms of the previous study. It confirms the high value of displacement of this block, and then emphasizes its instability.

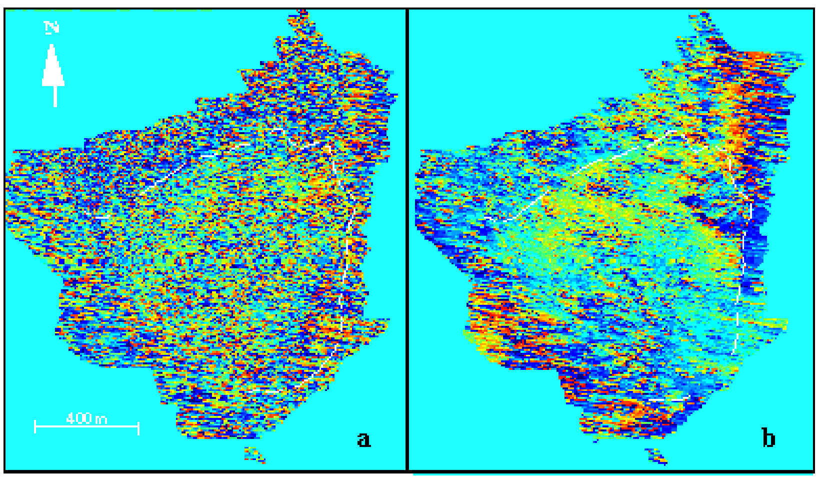

Figure 6*: Geocoded interferograms calculated with ERS-1 / ERS-2 tandem images.* ***(a)****13-14 august 1995 interferogram. Bperp= 50m.* ***(b)****-10-11 march 1996 interferogram. Bperp= 17 m.*

SAR interferometry versus ground monitoring

A higher density of "measurements" can be achieved with SAR interferometry: SAR monitoring provides a continuous displacement field in comparison with discrete ground measurements. It allows, in particular, to delineate the limits between the different units of the landslide. It also allows to detect local instabilities (in this study we detect a small block at the upper east part) which may not be disclosed by ground measurements if it has not been anticipated, so that laser targets can be installed on this particular block (Achache et al., 1995). Furthermore, ground measurements suffer from the problem of representativeness of the global motion by some targets deployed on the site. Ground measurements are very sensitive to local heterogeneities.

The major limitation of SAR interferometry is the loss of coherence between the 2 images due either to changes in the orbital geometry of the two acquisitions, to ground surface changes, or to a too high gradient of deformation. The two orbital tracks have to be within a few hundred meters to preserve the coherence . This limits the number of interferograms which can be produced from satellite images (among the 10 interferograms which could be generated with the 5 ERS-1 images of 1991, only 6 have good coherence). Ground-surface changes also affect directly the contribution of individual ground targets to the phase. Coherence loss then occurs often in the presence of vegetation or surface water. We note that the active scree slope where there is little vegetation remains the most coherent part. Displacements with high values of gradient, such as those associated with the landslide, lead also to incoherence since phase variation across a pixel exceeds one cycle. Orbit cycles of a few days as well as Tandem configuration allows the user to overcome this limitation of ERS data.

Of course, interferometry is limited by its "mono-component vector" evaluation, and by the ambiguous nature of the signal, which is known within one half of the wavelength only. Furthermore, it provides only the gradient of displacements, and hence relative displacements can only be evaluated by remote sensing. Reference points are necessary to determine absolute displacements.

Conclusion

This investigation demonstrates the capability of SAR interferometry to monitor surface displacements at the scale required for landslide monitoring. The constraints of this kind of study are totally different from the ones associated with earthquakes, due to small spatial extension and often the high topography encountered. SAR interferometry demonstrated its capability for studying the deformation over small areas. We were able to construct several interferograms on which the landslide is clearly evidenced. These interferograms show an organized fringe system for an elapsed time as large as 12 days, allowing us to construct a steady-state model of surface displacements valid for the whole period of observation. A simple model of translational slide satisfactorily accounts for the observed interferogram, and suggests the existence of a significant plastic deformation in the vicinity of the N20° structural discontinuities cutting the slide. The influence of the major heterogeneities of the landslide ("barre d'Iglière", intermediate scarp) on its mechanical behaviour can also be constrained by the interferometric analysis. It also provides accurate estimates of the displacement gradients in agreement with ground measurements and even allows us to detect small blocks with enhanced displacement which may represent a potential hazard.

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