Potential and limitation of ERS-Differential SAR Interferometry for landslide studies in the French Alps and Pyrenees

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Abstract:

Potential and limitation of ERS Differential SAR Interferometry for landslide analysis in the French Alps and Pyrenees is estimated. Geometrical constraints are a little stronger in the Alps than in the Pyrennes. By combining both ascending and descending ERS orbit, we show that around 5% of the total area cannot be imaged and only 50% can be imaged on both orbits. As most of the areas are below the tree line, state surface variation between acquisitions lead to dramatically loss of coherence. Only images acquired with high temporal repetitivity (1 day or 3 days) are suitable for landslide studies. Then, a landslide called “La Valette”, placed in the southern French Alps is studied using 15 differential interferograms produced from SAR images acquired by ERS 1 and ERS 2 satellites between 1991 and 1999. Velocity maps of “La Valette” landslide have been established. Four domains characterized by their own velocity field have been detected. Three of them can be distinguished from aerial photographs and field analysis. Slow velocity of a resistive bar located near the top of the landslide has been detected on SAR interferograms. Between 1991 and 1996, evolution of the limits of the landslide has been observed both in the upper and in the lower part, by a back erosion corresponding with the main scarp and a progress of the main body of the landslide. The average velocity of the landslide between 1991 and 1999 decreased from 1cm/day to 0.2cm/day in agreement with ground based measurements.

I] Introduction

Study of the spatial and temporal evolution of the velocity field is a way to better understand the parameters that control slow landslides (some centimeters per week over several years). Kinematic studies are usually realized by punctual techniques (leveling, lasermeter, GPS) which are not able to assess spatial heterogeneities. In the last few years, Differential SAR interferometry (DINSAR) has proven its capability for mapping different kinds of surface deformation such as earthquakes, volcanoes and anthropic deformations like mining induced subsidence or water pumping. However only isolated cases of successful applications of DINSAR for landslides studies have been achieved. In order to be observed, small velocity landslides (of the order of centimeter or less per year) have to be located above the tree line [10] or studied by JERS-1 satellite (in L-band), less sensitive than ERS to loss of coherence in relation with the vegetation cover. [8]. For faster velocity landslides (up to few centimeters by day) high repetitivity SAR images have to be used [7] [14] [12]. Furthermore geometry of the landslide has to be favorable regarding the line of sight of the satellite.

In the present work, a quantitative and comparative analysis of potential and limitations of ERS SAR Interferometry for landslides study in medium mountains is achieved in French Alps and in French Pyrennes. Then a successful case of a landslide located study by ERS DINSAR in the Alps is presented.

II] Study sites

Two areas have been selected in France. The first site of is located in the South of French Alps (Figure 1) near the Mercantour massif. The area covers around 11500 km^2. The altitude, representative of medium mountain, ranges between 1000 m and 3500 m.

The second site is located in the middle of Pyrenees Massif across the France and Spain boundary. It covers 9500 km^2. Altitude ranges between 800 and 3300 meters. The two areas have been selected because they contain numerous mapped landslides.

Despite difference in geological history, altitude distribution of the two areas is similar (Figure 2a). A slight shift is just observed. On the two sites, most of the altitudes, are below the tree line altitude which is around 2300m.

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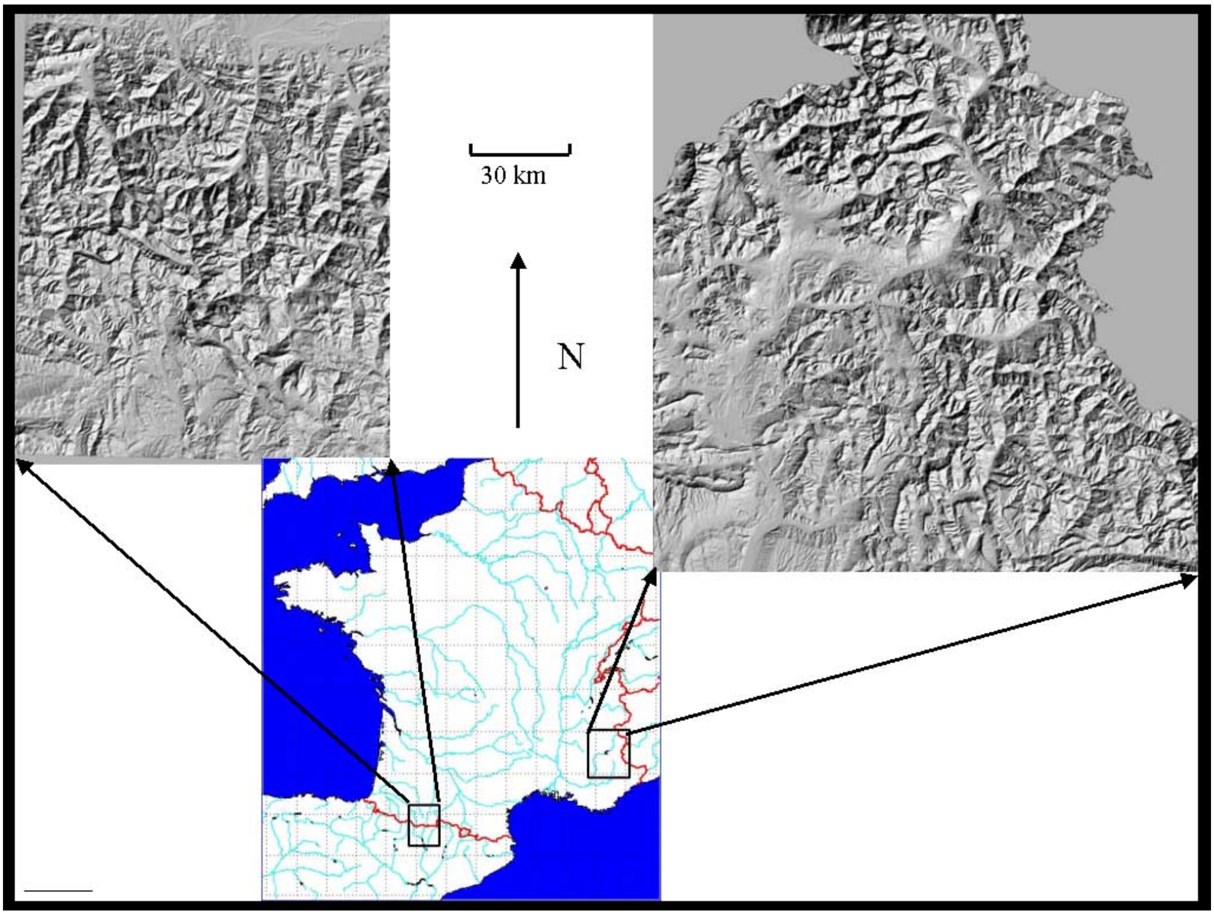

Fig. 1 : Location of area of interest

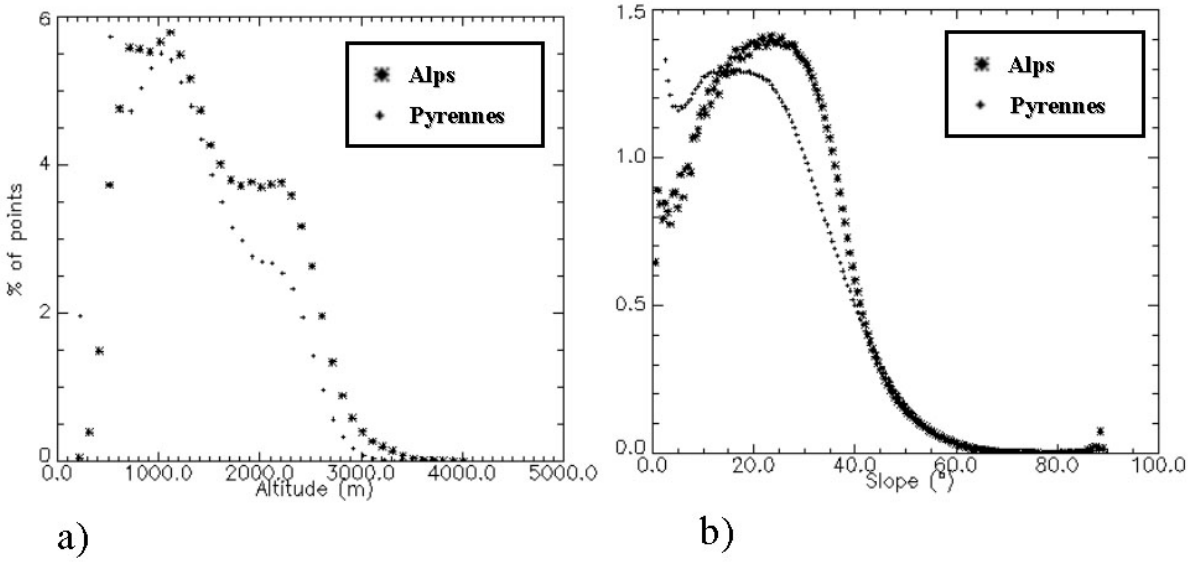

Fig. 2 : a) Elevation distribution b) Slope distribution

III] Limitations

1) Geometrical constraints

In order to estimate the real potential of DINSAR, the first point is to estimate the geometrical visibility of the areas. Indeed due to its side-looking acquisition mode, SAR images are subject to geometrical distortions [11]. Areas affected by overlays or shadows could not be imaged by the sensor. Those types of distortions are very sensitive to topography and more specifically to local slope along the line of sight. On figure 2b we can observe the topographic distribution and slope for our areas of interest. Slope values are slightly higher in the Alps. Simulation of visibility for has been made on ascending ERS orbit for both areas (Table 1). Due to its higher slopes Alps site is less visible than Pyrenees (69% for 75%). However for the two sites more than 25% of the total area is masked on SAR images.

	Visible	Shadow	Overlay
Alps	69	15	15
Pyrennes	75	13	12

Table 1: Visibility simulation of descending ERS orbit

A way to overcome this limitation is to combine ascending and descending ERS orbit over the same area. Figure 3 shows a visibility map on the two sites for ascending and descending orbit. This combination allows to reduce the percentage of masked area to 5% in the Pyrenees an 7 % in the Alps (Table 2). It can be noticed that only 54% of the total area for Pyrenees and 40% for the Alps can be imaged by both ascending and descending. Furthermore foreshortening effect is not taken into account, then efficient area is less than that presented in this study.

	Always visible	Visible only on descending orbit	Visible only on ascending orbit	Never visible
Alps	40	29	24	7
Pyrenees	54	21	20	5

Table 2: Visibility simulation on ascending and descending ERS orbit

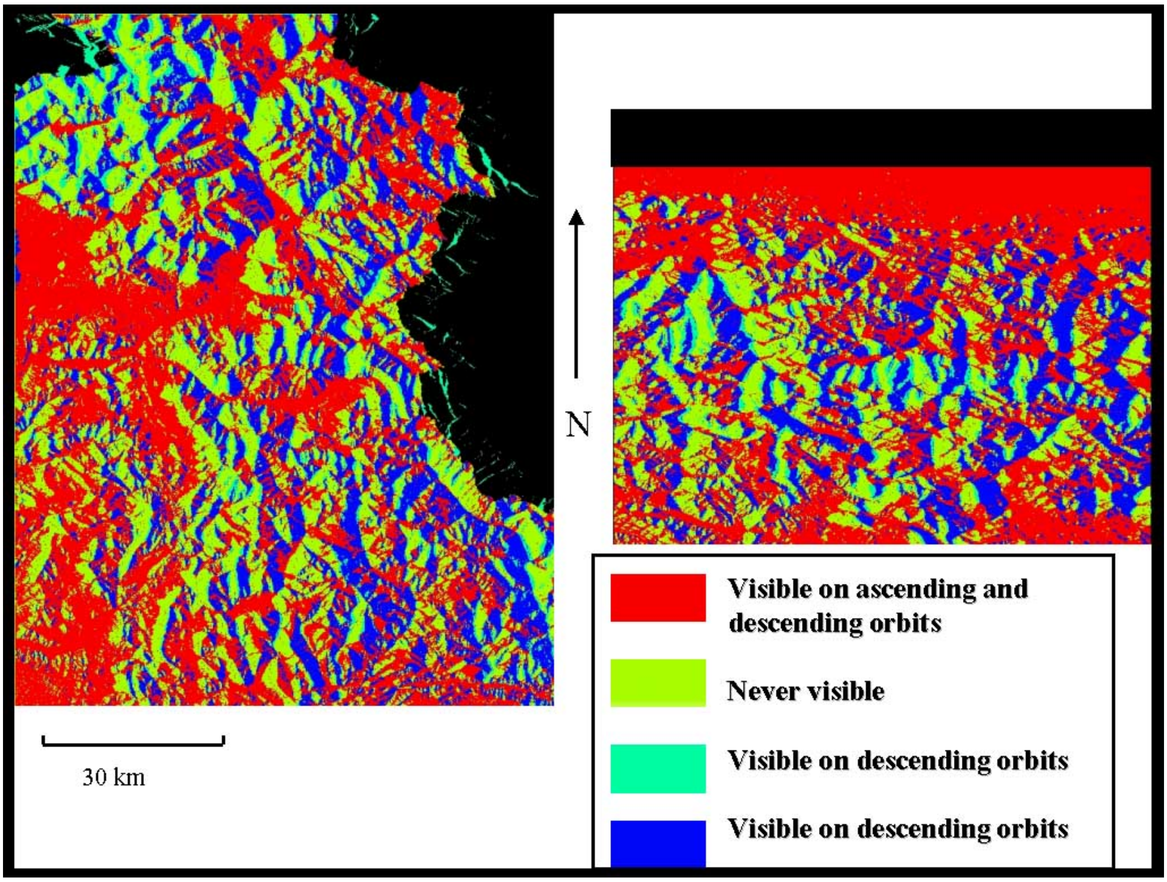

Fig. 3 : Simulation of geometrical visibility for ERS images

2) State surface effect

Variation in surface state between the two images acquisition lead to loss of coherence. As the coherence loss is primarily associated to vegetation, in mountains areas the coherence is higher at higher altitude. Under a threshold of 0.4, loss of coherence does not allow to analyze interferograms. On figure 4 we can observe the loss of coherence with time in the Alps and in the Pyrennes. As major part of our area of interest is located below the tree line, loss of coherence is severe for image time spanning larger than 3 days.

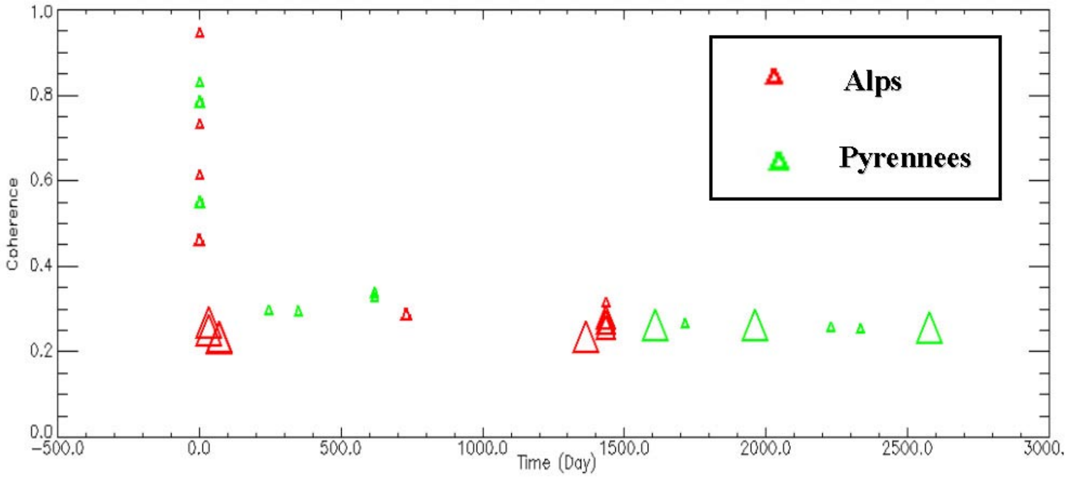

Fig. 4 Loss of coherence with time. Size of triangle is proportional to baseline values

3) Atmospheric artifact

Variation in atmospheric conditions in the lower part of the atmosphere (troposphere) between the 2 acquisition dates of the image changes the radar signal time delay. This change produces a rotation of the phase which could mask part of the deformation signal. Two types of tropospheric artifacts could occur in mountainous area. First, a global change of the atmosphere, will produce low frequency artifacts which could be correlated with topography. In this case, they can be easily removed by statistical approach or modeling [4] or approximated by a single polynomial function for their lower frequencies. The second one is due to local heterogeneities of the atmosphere [13]. These high frequency artifacts can not be removed on a single interferogram. We can see on figure 5a that due to the size of the heterogeneities (few tens of meters to kilometer) the artifact can be interpreted as landslide motion signatures (represented in black circles). In that case the only way to detect this artifact is to use various independent interferograms. Indeed, this effect in not temporally correlated.

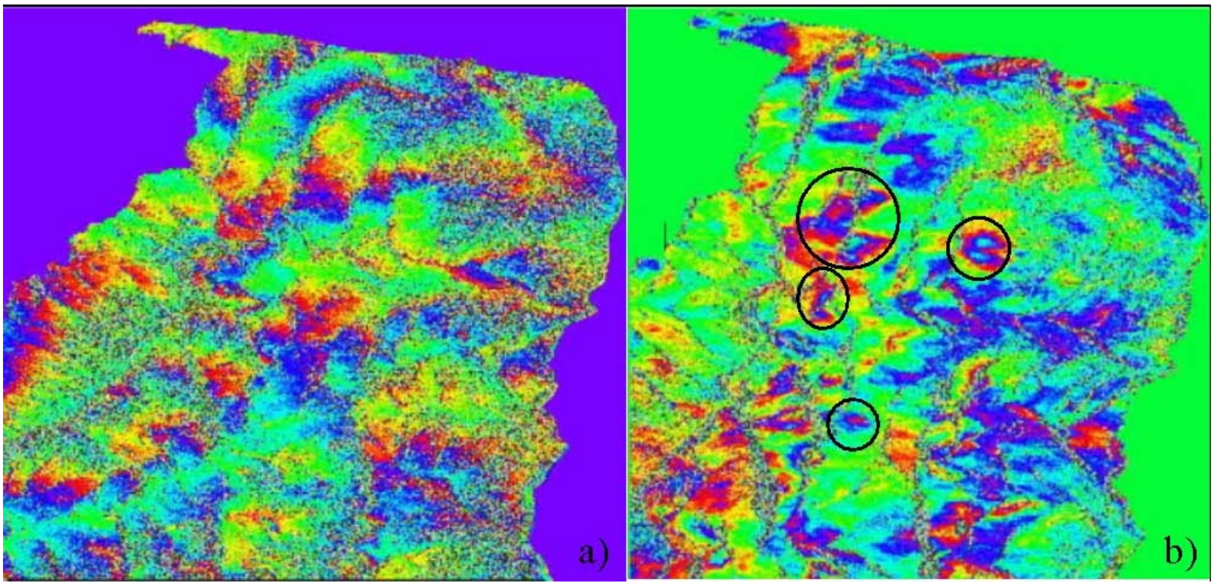

Fig. 5 : Example of tropospheric artifact a) Low frequency artifact correlated with topography b) in black circles, local heterogeneities.

IV] Example of application in the Alps : The Lavalette Landslide

1) Geology and History of the “La Valette” landslide

The “La Valette” landslide is located in the southern French Alps, at the north of the Mercantour massif. The slope involved in the landslide movement is placed near the village of Barcelonnette, on the right side of the Ubaye valley, in the catchment of the La Valette stream. The bottom of the local lithological is formed by the callovo-oxfordinan “Terres Noires” formation, thick about 300 meters and mainly composed by highly stratified black marls. This geological formation is known as to be very sensible to physical weathering processes, causing erosion, locally voluminous solid transport and promoting surface instability [1]. The Helmintoid flysch nappes of the Ubaye-Embrunais composed by Senonian sediments rest with a tectonic contact on the autochthonous “Terres Noires”. On the lower part of the slope, about to 1500 m of altitude, a layer of clayey würmian morainic deposits covers the “Terres Noires”.

The “La Valette” landslide started in 1982 with a deep fracture which opened just at the contact between the “Terres Noires” and the flysch nappes [3]. The landslide developed first as a rock fall and a rotational slide involving the rocks of the Autapie - Pelat nappes between 1900 and 1600 meters of altitude just under “Rocher Blanc”. This caused the disorganization of the below less resistant “Terres Noires”, with the superimposed morainic deposits, and their slow destabilization, leading to a progressive advance of the clays and marls terrains in the gorge of the “La Valette” stream, cut in the “Terres Noires”. This layer of sliding material reaches actually a thickness of about 25 meters. The instability involves now the slope from 1900 m of altitude down to 1200 m, with an extension of about 2000 meters in length and to 450 meters in width at the top of the landslide. The landslide motion is constantly monitored since 1988 by “Restauration des Terrains en Montagne” Service (RTM) by means of laser geodetic ground measurements made every three weeks on a section placed in the middle part of the landslide (Figure 6a). Two main events occurred in spring 1989 and in autumn 1992 with velocity peaks of 50 cm/day. Apart from them, the motion is quite homogeneous, with some seasonal variations and maximum displacement amounts of 10 cm/day.

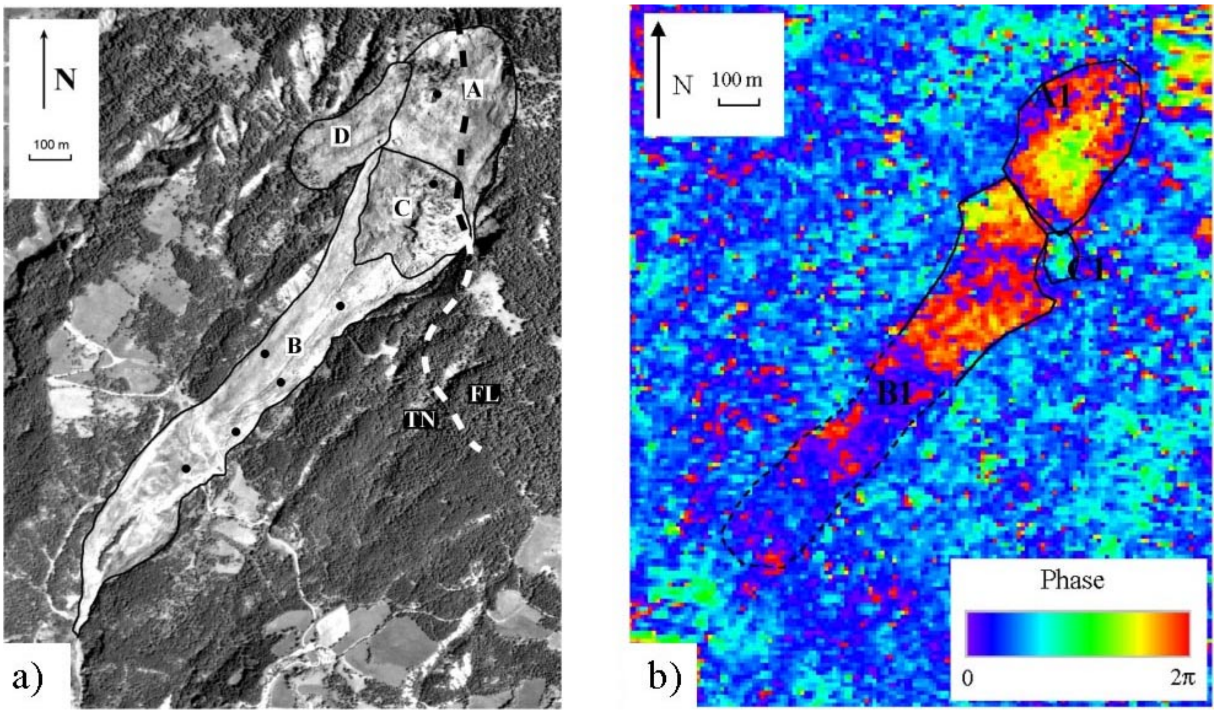

Fig. 6 : a) Aerial photography of La Valette b) 22-23 October 1995 1 differential interferogram

2) Motion analysis

A) Data set

Thirty SAR images acquired by the European remote-sensing satellites ERS-1 and ERS-2 between 1991 and 1999 have been used. Because of the specific orientation of the investigated slope, only images acquired in descending orbits have been processed. Furthermore, due to the relatively fast landslide motion (between 1 and 3 cm by day over the studied period), radar images with a high repetitiveness have been chosen, acquired in the TANDEM phase (1 day time interval) and in the Commissioning phase (three days passes). From those images, 15 interferograms exhibiting a sufficient value of signal to noise ratio to study the landslide have been retained. The differential interferograms were produced with the technique of the two-pass differential interferometry with Digital Elevation Model subtraction [9], using a DEM provided by the National Geographical Institute of France (IGN). The interferograms have been processed with a 10 m x 10 m pixel resolution.

B) 1 day motion

In a first step, we focus our analysis on the 22-23 October 1995 TANDEM differential interferogram (fig 6b). This differential interferogram exhibits a significant phase variations associated with the landslide. Indeed, the boundary of the area in motion are clearly visible. Three areas can be isolated based on the variation in the fringe shape.

- The zone A1 in the upper part of the landslide is characterized by a circular shape of the fringes with a maximum deformation of 1.7 cm. The upper part of this area is limited by the crown and the main scarp of the landslide, the nearly linear bottom limit is clearly delimited by the extension of the outcrop observed on aerial photograph.
- The lower part (zone B1) corresponds to the main body of the landslide, the deformation is weaker, with a maximum value of 1.1 cm, and it seems to be homogeneous and regular. In this part of the landslide the movement is mainly translational, with a direction parallel to the slope.
- Finally a small area (of around 100m x100m) in the eastern part (zone C1) affected by a lower almost null, rate of deformation, compared to the surrounding moving areas is observed. This isolated area is related to the 'Rocher Blanc', which is a competent outcrop, rooted in the landslide.

The three areas mapped from SAR Interferometry are analyzed from field trip and aerial photograph interpretation. Discrepancies observed in the boundary of the areas indicate that morphology is not always directly related to the landslide motion or under the threshold of detection of SAR interferometry [4] or affected by a non stationary deformation behavior.

C) Seasonal variations on 1995-1996 interferograms

After the analysis of motion features on one interferogram, the temporal variation of the landslide over one year has been studied, using 6 TANDEM differential interferograms with images acquired between July 1995 and April 1996. (fig. 7). The six differential interferograms exhibit a significant phase variations associated with the landslide which confirm that the landslide is in activity all the year.

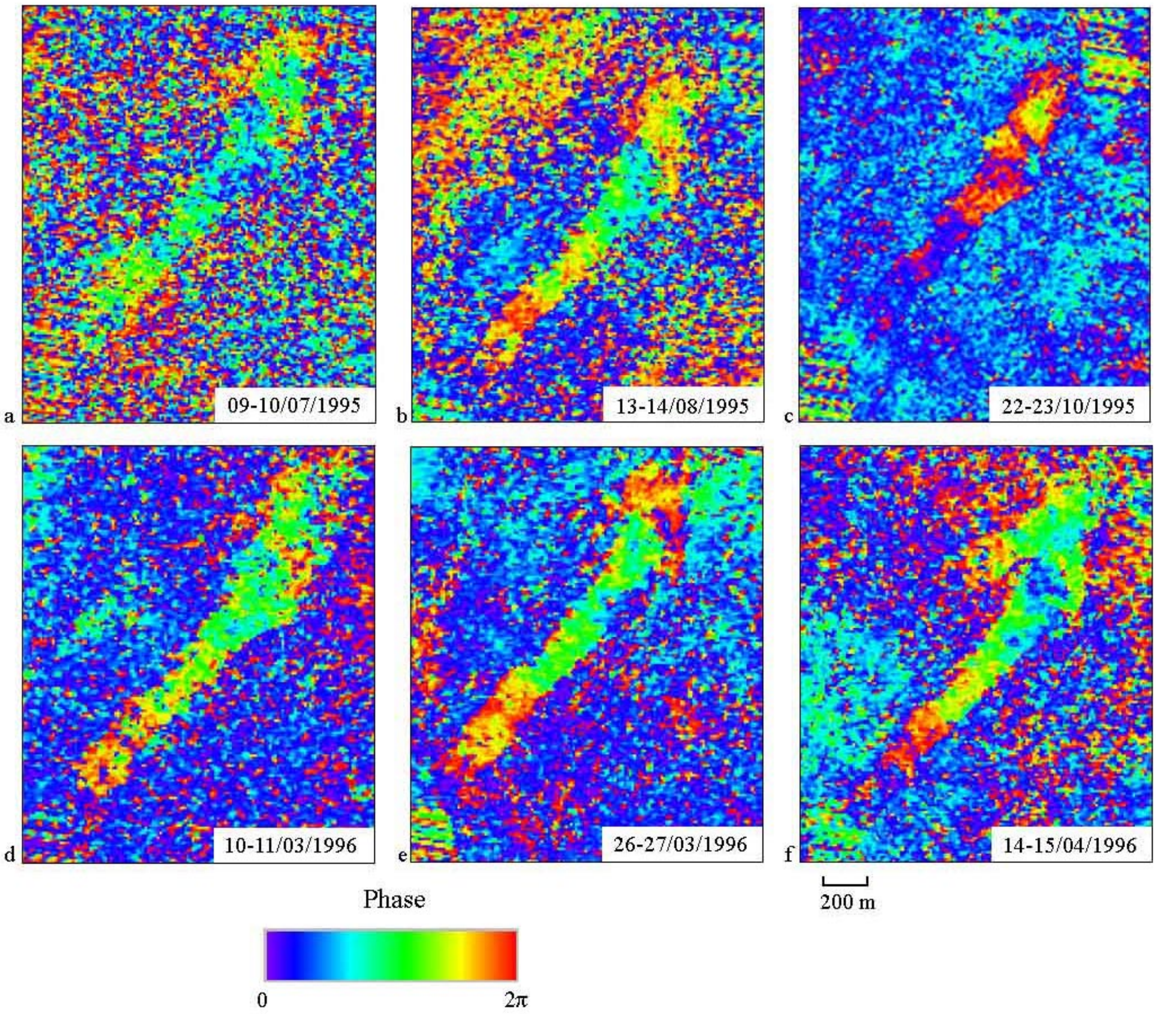

Fig. 7 : Multitemporal interferometric series from July 1995 to April 1996.

The 3 areas defined on the 22-23 October interferogram are still observed. However, on the interferograms in fig. 7a, 7d and 7f, a little lobate-shape sector developing on the north-western side of the landslide has been recognized. It corresponds to the zone D described in the above aerial photograph interpretation. Its evolution seems to be quite independent from the main body of the landslide, being apparently affected by a non stationary motion, where it is characterized by an acceleration with respect to the rest of the year. In fact, only during this period its amounts of displacement are comparable with the displacement of the main body composed of sector A and B (fig. 6). The non stationnarity of the rate of deformation of this part of the landslide can be due some external factors, such as the presence of water. An hydrogeological study of the landslide slope made from [5] shows that most of the sources present in the landslide gushes out in the eastern side. They have been canalised by the RTM Service in order to try to decelerate the landslide motion. No canalisation has been carried out in the western part. So we can assume that this part is more sensible to hydrological variation which can lead to the non stationnarity of the landslide. But other factors such as the less important volume can be invoked. For the other parts of the landslide, the movement of the upper zone (A1) is not always correlated with the movement of the lower one (B1) (fig. 6), probably because of the different mechanisms controlling the motion. Nevertheless, the maximum displacement rate reached in both sectors in the days corresponding to the interferograms studied is the same, 2.2 cm/day. Furthermore, confirming the field observation, inside the sector B itself some heterogeneities in the motion occur, with the slowest velocities at the toe of the landslide.

On the eastern part of the landslide, the sector C is always affected by a slower motion ranging from 0 to 0.4 cm/day which confirms the rooting behavior of the 'Rocher Blanc'.
No evidence of correlation between seasonal meteorological data and variation of rate deformation has been observed. On this landslide this observation has already been over large period [6]. But due to small data set of interferograms (6 couples over 1 year) a final conclusion is difficult.
Since 1993, the 'Restauration des Terrains de Montagne', are monitoring the landslide by leveling measurements (laser geodetic measurements over some points shared out in the landslide slope). The ground data collection is not regular, and in some cases few months can occur between two acquisitions. In order to make a comparison of 1 day motion with SAR interferometry, assumption of a stationary motion between 2 ground based acquisitions has been made. Nevertheless, a good correlation between the two methods of investigation is obtained (fig. 8).

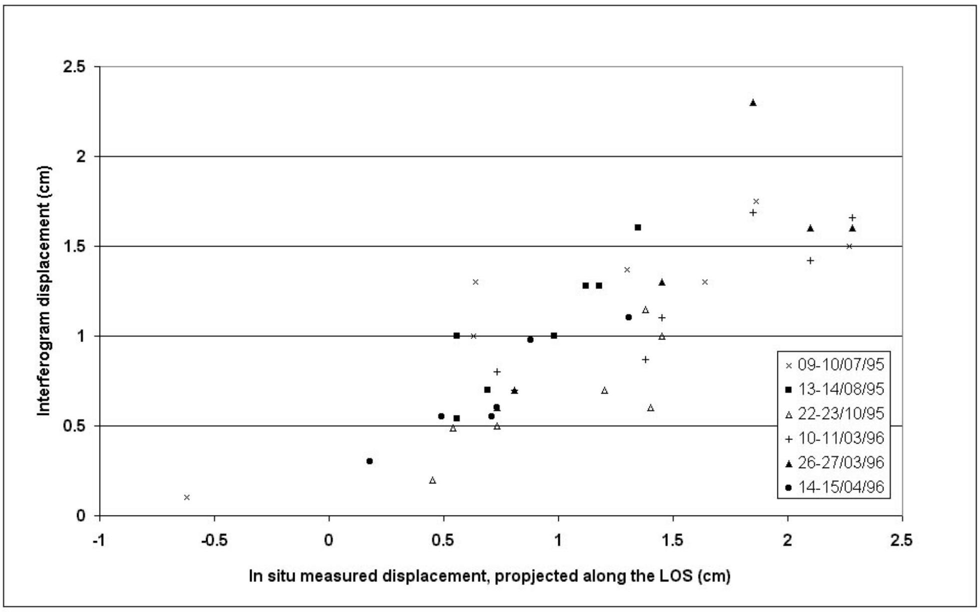

Fig. 8. Comparison between the ground based measurements (y-axis) and the SAR interferometric values (x-axis) for the 1995-1996 interferometric set.

In conclusion, the multitemporal analysis of the six interferograms from July 1995 till April 1996 shows that the landslide motion is not stationary on a one year scale, varying in the time and in the space over the whole landslide. The reason of these heterogeneities is not clearly understood, probably influenced by the water content coming from source, rain falling and snow melting. But the heterogeneity of the deformation rate between the observed areas suggests that the 3 areas defined previously are representative of 3 partly independent behaviors of the landslide.

D) 9-years variation of the landslide motion

The general evolution of the landslide motion over 9 years has been followed by means of some interferometric couples dating from 1991, 1995, 1996, 1997 and 1999 (fig. 9). On the 6 new differential interferograms motion associated with the landslide is evidenced. However, the 1991 SAR images have been acquired during the commissioning phase (3 days apart). Change in the vegetation state due to large time span and 3 days of deformation values (respect to the 1day interferogram) leads to a decrease of the coherence value. Therefore, both deformation rate and motion boundaries are more difficult to estimate (fig. 9a). The two interferograms dated 1997 show a gradient of deformation a little lower than the previous year, according to the RTM punctual ground data. The shape of the landslide is clearly detectable in fig. 8b, while in fig. 8c the lower part of the moving zone is not easily distinguished from the noise, probably due to the loss of coherence and to the slow motion. The average velocity of the landslide is of 1cm/day from 1991 to 1995 and increases to 2cm/day during 1996 and 1997. Since this date, its velocity decreases to 0.2cm/day in the lower part.

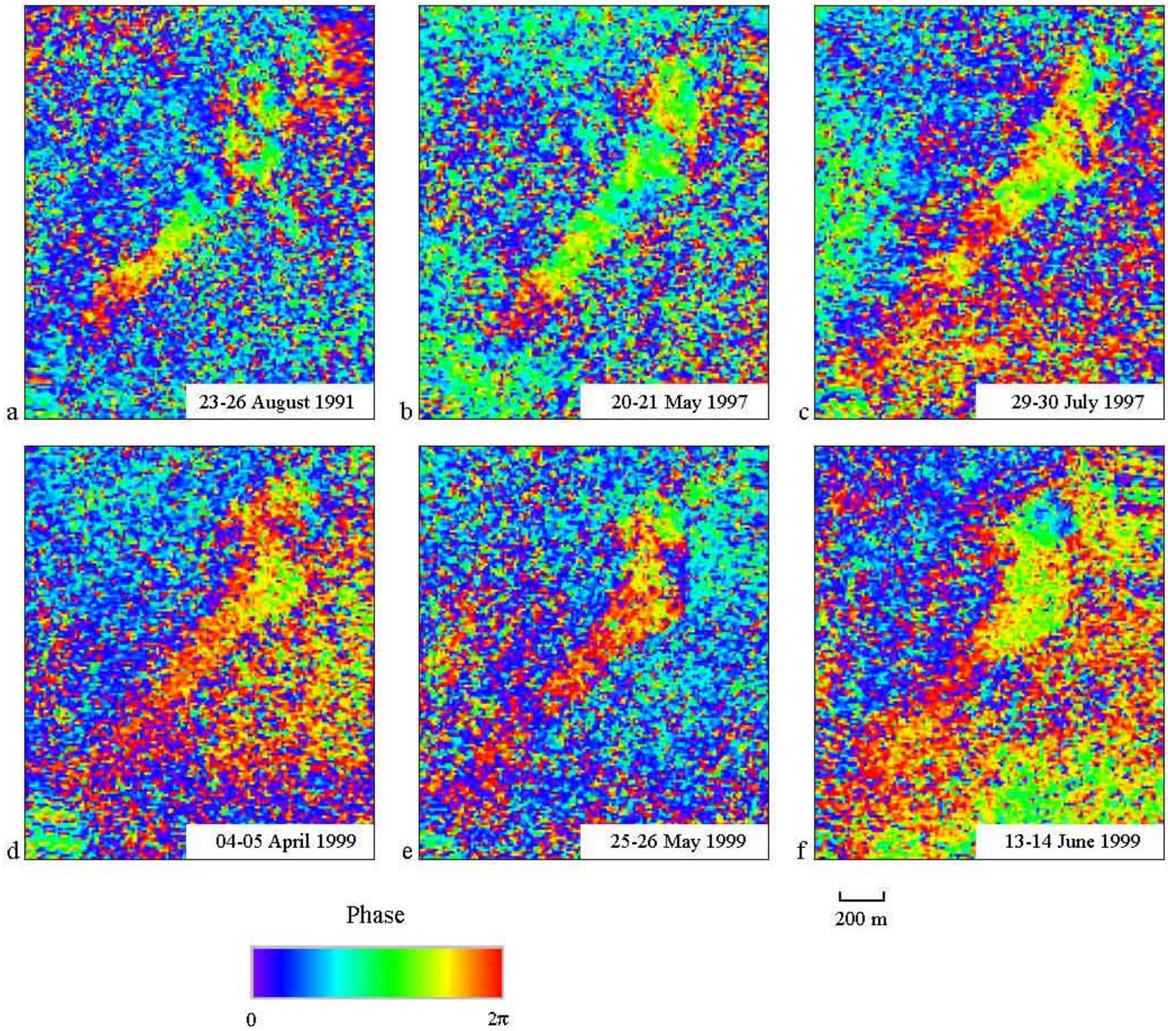

Fig. 9 : 1991 – 1997 – 1999 interferograms

V]Conclusion

Despite severe limitations, the differential SAR interferometry may be a good mean to investigate landslide areas with displacement rates less than a few cm per day. The limitations are nearly the same in medium mountains in the Pyrenees or in the Alps. Landslides should be favourably oriented along the line of sight, atmospheric artefacts should be detected and removed if possible, vegetation variation should be low enough to keep high coherence and high repetition images should be used. In that case this technique can efficiently be used in association with aerial photographs interpretation and geomorphological analysis. Velocity maps of “La Valette” landslide have been established by differential SAR Interferometry, over 9 years between 1991 and 1999. Four domains characterised by their own velocity field have been detected. Between 1991 and 1996, the evolution of the limits of the landslide has been observed both in the upper and in the lower part, by a back erosion corresponding with the main scarp and a progress of the main body of the landslide. The average velocity of the landslide is of 1cm/day from 1991 to 1995 and increases to 2cm/day during 1996 and 1997. Since this date, its velocity decreases to 0.2cm/day in the lower part. On a 1 year scale, 6 ERS-1 ERS-2 TANDEM interferograms exhibit high degree of spatial and temporal heterogeneities of the landslide.

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