Velocity field of the "La Clapière" landslide measured by the correlation of aerial and QuickBird satellite images

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[1] Two displacement maps of the "La Clapière" landslide (France) have been derived over two periods of 4 years (1995–1999 and 1999–2003) by correlation of aerial photographs and a QuickBird satellite image. The movement of the landslide ranges from 2.5 m to 20 m per year. Those values have been validated over 13 points monitored by conventional tacheometric measurements. Three areas with significant differences in velocity field have been mapped. Limits of those areas are in good agreement with in situ observations. Velocity maps show the low long term temporal variability of the landslide movement and its spatial variability. The optical correlation method using images derived from various sensors (airborne and spatial) is a promising technique for improving the spatial resolution of velocity field observation of landslides over several years. *INDEX TERMS:* 0933 Exploration Geophysics: Remote sensing; 1204 Geodesy and Gravity: Control surveys; 1824 Hydrology: Geomorphology (1625). **Citation:** Delacourt, C., P. Allemand, B. Casson, and H. Vadon (2004), Velocity field of the ''La Clapière'' landslide measured by the correlation of aerial and QuickBird satellite images, *Geophys. Res. Lett.*, *31*, L15619, doi:10.1029/2004GL020193.

1. Introduction

[2] Presently, most of the techniques for monitoring landslide displacement are derived from measurements of reference stations. Conventional geodetic techniques (triangulation, tacheometry) and extensometry techniques remain to be the most commonly used [*Angeli et al.*, 2000]. GPS measurements can be an alternative [*Jackson et al.*, 1996]. The database of movement provided by these techniques is available only for major landslides for a time span not exceeding 20 years for laser measurements and less than 15 years for GPS. Moreover, due to spatial and temporal heterogeneities of the displacements, such ground based measurements are not sufficient to describe fully the velocity field of a landslide. Remote sensing imagery is a powerful tool for landslide monitoring because it offers a synoptic view that can be repeated at different time intervals. Differential SAR interferometry (DINSAR) has shown its capability for deriving high accuracy maps (at centimeter level) of landslide displacement [*Fruneau et al.*, 1996]. However, this technique is affected by severe geometrical and environmental limitations. Moreover, the SAR image database is limited to 1991, and later.

[3] In the recent years, new techniques based on correlation of satellite optical images for the processing of deformation maps have been developed [*Van Puymbroeck et al.*, 2000]. Those techniques have been successfully applied to the measurement of coseismic deformation [*Michel and Avouac*, 2002; *Vadon et al.*, 2002]. However, due to the small spatial extent of landslides, high resolution optical satellite imagery (SPOT 1–4, LANDSAT) can be rarely used on those targets. In this paper we show how aerial images acquired at different times and very high resolution satellite images (QuickBird) can be correlated to create high spatial resolution displacement maps over long periods on the "La Clapière" landslide. Those maps are compared with laser measurements and discussed relative to INSAR data.

2. "La Clapière" landslide

[4] The "La Clapière" landslide is located in the French Southern Alps (Figure 1), on the boundary of the Mercantour massif. This landslide covers an area around 100 ha between 1100 and 1800 m of elevation (Figure 1). The landslide affects the hercynian basement rocks composed mainly by migmatitic gneiss [*Follacci and Guardia*, 1988]. A subhorizontal bar of metadiorite, called the Iglière bar, crosses the landslide at an average elevation of 1350 m (Figure 1). This landslide is largely fractured with three characteristic directions of faults [*Guglielmi et al.*, 2000] which are N10-30°E, N90°E and N110-140°E. A major fault with a N20 direction divides the landslide by the middle. The landslide is bounded at the top by a main scarp of 60–80 m height which forms two lobes [*Follacci*, 1987]. Two secondary scarps are developed within the landslide. One with a N120 direction is located at an average elevation of 1500 m and another one is developed along a N90 fault since 1987 just under the top NW lobe (Figure 1). Two smaller landslides are superimposed on the major one at the top of the NE lobe and at the toe of the landslide.

[5] Distancemetric measurements are regularly acquired since 1982 by laser ranging. Among the 50 targets deployed over the landslide, 20 have recorded continuous data over the period of interest (1995–2003). This dataset shows average velocities of 10 or 20 mm/day. Distancemetric registration points out a seasonal response of the landslide characterized by acceleration of movements correlated to snow melting [*Follacci*, 1987].

[6] Remote sensing has already been used for characterization of "La Clapière" landslide. DINSAR has shown over short periods (between 3 days and 9 days) in August–September 1991 a clear movement pattern [*Fruneau et al.*,

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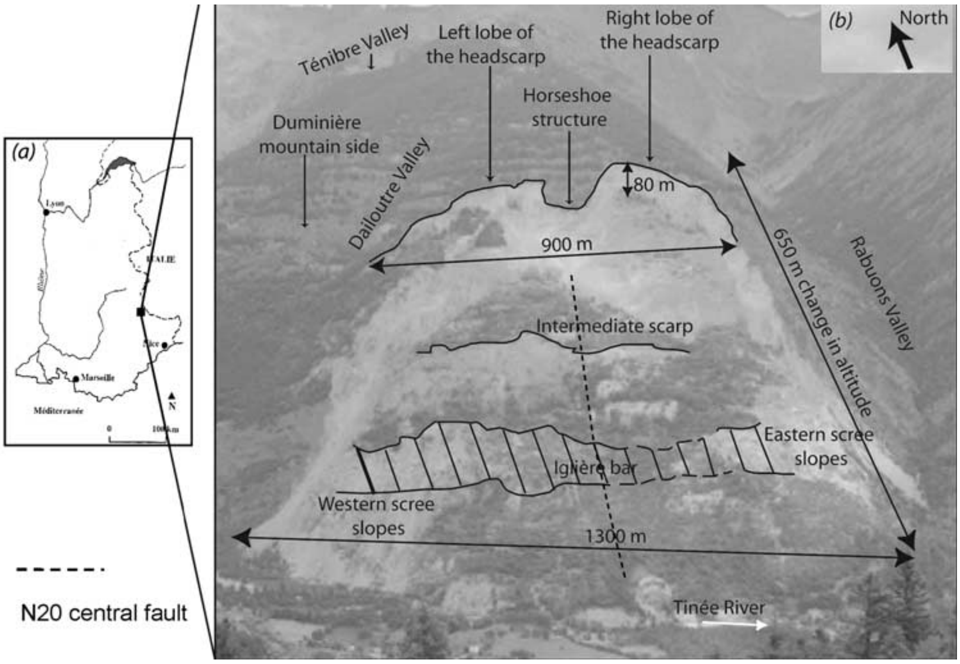

Figure 1. (a) Geographic location of the "La Clapière" landslide (44°15′20 N–6°56′37 E) (b) Major geomorphologic characteristics.

1996]. Those values have been validated by laser measurements [*Carnec et al.*, 1996]. However due to high rate of displacement and vegetation state, no long term deformation measurements can be obtained by this technique. Photogrammetric analysis has been applied on aerial images acquired between 1983 and 1999 [*Casson et al.*, 2003]. In this previous study, only motions of main geomorphological structures have been analyzed.

3. Data, Methodology and Results

[7] For this study, two stereoscopic pairs of aerial images acquired 4 years apart (25 June 1995 and 4 June 1999) have been used. The images have been acquired near vertically at a constant altitude of about 5000 m. Each image covers about 36 km^2. In addition, a very high spatial resolution image (0.6 m) has been acquired by the QuickBird satellite on 6th September 2003, with an off nadir View Angle of 9.3 degrees that induces limited geometric distortions. With these data set, we have obtained the displacement field over 2 consecutive periods of 4 years: between 1995 and 1999 by correlating 2 aerial images and between 1999 and 2003 by correlating the 1999 aerial photograph and the QuickBird image. To be correlated successfully, the images have to be exactly in the same geometry, so an orthorectification procedure has been applied on both aerial and QuickBird products. In order to orthorectify the images, 2 Digital Elevation Models (DEM) have been processed from the stereoscopic aerial images (1995 and 1999). Using the corresponding DEM, orthorectified aerial images resampled at a spatial resolution of 1 m have been generated [*Casson et al.*, 2003]. The QuickBird image has been orthorectified using the 1999 DEM [*Grodecki and Dial*, 2003]. The image has been undersampled to 1 m in order to have the same spatial resolution than the aerial images. All the images have been projected into a Lambert II conic conform projection.

[8] To find the ground displacement which occurred between two images, a local window of some number of pixels width is defined on the oldest orthorectified image. Then, the corresponding window is searched on the youngest orthorectified image by maximizing a correlation function [*Vadon and Massonnet*, 2002]. The starting point of the search is the expected position of the window if no displacement has occurred between the two acquisitions. The measured shift is directly related to the ground displacement between the two acquisitions by the pixel size. The main parameters of the process are the size of the local window and the maximum expected displacement between the images. This process is repeated for each pixel of the oldest image. The result is composed by 3 arrays which have the size of the correlated images. The first one contains the shift in lines for each pixel, the second one contains the shift in columns and the third indicates the quality of the correlation.

[9] The choice of the local window size is a compromise between desired accuracy of the shift, and the acceptable Signal to Noise Ratio. When the size of the window increases, the computed displacement represents an averaged value over the whole window, but the noise is reduced. Independently from this choice of image window size, the variation state of the surface, such as vegetation growth, or colluvium movement caused by the large time spans between the acquisitions decreases the quality of the correlation. In order to limit the loss of coherence, a 31 × 31 pixels correlation window has been used. So, each deformation value of the image is an averaged displacement over 961 m^2.

[10] The method itself has no limit in precision. Correlating similar images which are just translated one compared

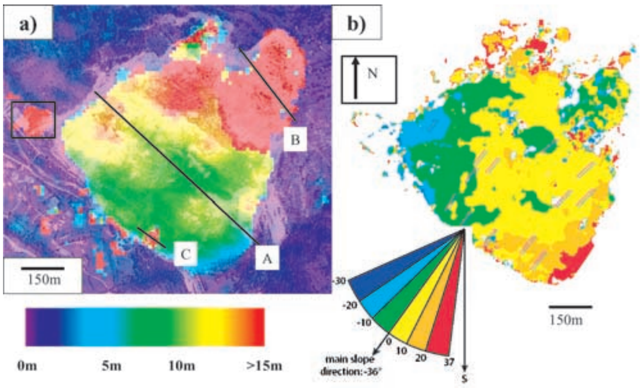

Figure 2. Displacement map obtained by correlation between aerial photographs acquired in 1995 and 1999. (a) Horizontal amplitude (b) Orientation. Displacement vectors measured on ground by laser telemetry (pink arrows) and by correlation (blue arrows).

to another and which are well sampled, with low noise, can lead to precisions of up to 0.001 pixels. But in practical terms, this accuracy is never reached. As far as sampling is concerned, we must accommodate data as it is delivered. As far as similarity is concerned, this implies that better correlation will be obtained using instruments as similar as possible (same spectral sensitivity), with geometry as similar as possible (same point of view) and illumination as similar as possible (same season, same time in the day). The practical absolute accuracy is estimated on known fixed areas (out of the landslide) on which the shift has to be null. In our case the average displacement is lower than 2 pixels (i.e., 2 m, Figure 2).

[11] Due to the Lambert II conic conform projection, the shift in lines corresponds to the motion along north-south direction and then shift in columns gives motion in the west-east direction. Figure 2 shows the horizontal displacement of the landslide observed between the 1995 and 1999 aerial photographs. The limits of the landslide are clearly visible with a near-uniform displacement value of 0 m outside the landslide and an average displacement of around 10 m inside (Figure 3a). Furthermore, internal spatial variation of displacement can be clearly observed (Figure 3). Finally, two areas of high displacement can be distinguished, the first one (B) is located in the northeast headscarp area of the landslide (Figure 3b). Its extent is about 135 000 m^2 showing a displacement of about 60 meters in 4 years. The second area (C) of small spatial extent (4000 m^2) and low velocity (15 meters in 4 years) is located in the toe of the landslide (Figure 3c).

[12] Due to the date differences between the two image acquisitions (4 years), the surface state could have dramatically changed. In those areas, (black box on Figure 2a), the correlation coefficient is low and then, the associated shifts are not representative of the real displacement of the objects (around 10% of total pixels in our case).

[13] In order to validate our results, a comparison between displacement values obtained by optical correlation measurement with conventional tacheometric measurements acquired by the "Centre d'Etudes Techniques de l'Equipement de Nice" has been performed. The motions of 13 targets located on the landslide (Figure 2b) were

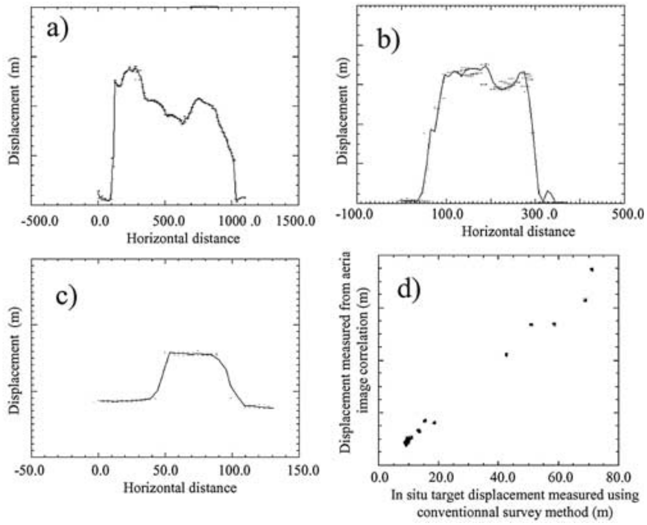

Figure 3. Displacement profiles (a) Crossing the landslide (b) Crossing the north-east lobes (c) Along the bottom landslide, (d) Correlation between in situ displacements measured by tachometry on targets located on Figure 2 and by correlation technique.

recorded between 1 July 1995 and 1 July 1999. The small temporal shift (1 month) in the acquisition period between the two techniques is assumed to be negligible compared to the large time span of the original observations (4 years). Figures 2b and 3d show that our results (both in amplitude and direction) are in good agreement with the in situ horizontal measurements.

[14] Shifts between IGN 1999 aerial photo and satellite QuickBird image acquired in September 2003 have also been calculated. Figure 4a shows the north-south shift between the two images. The limits of the landslide are clearly visible and the order of magnitude of the deformation over the 1999–2003 period is similar to the movement observed during 1995–1999 (Figure 4b). However, the number of areas with low correlation values has increased. That can be explained by the different characteristics of the two sensors. QuickBird and aerial images do not have the same initial spatial resolution, so QuickBird has been

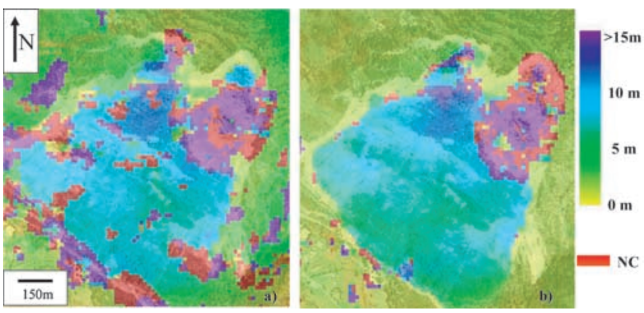

Figure 4. North-south deformation map (a) between 1999 and 2003 from aerial and QuickBird image (b) between 1995 and 1999 from aerial images. NC corresponds to no significant displacement areas because of poor quality correlation values.

undersampled before the correlation process. Furthermore, radiometric sensitivity and acquisition season and time are different, which, as discussed earlier, is not ideal. In our case the accuracy of measurement has been estimated to 6 pixels in north-south direction. Furthermore, due to geometry of acquisition of QuickBird images, the column displacement component is noisier than the line displacement component.

4. Discussion

[15] Two parts characterized by different amplitude of movements can be pointed out on displacement maps. On the NW part of the N20 central fault movements appear more faster than on the SE part, particularly under the Iglière bar. This is in agreement with the hypothesis of *Follacci* [1987] who suggests that this landslide is composed of different parts limited by structural and lithologic features. A similar observation has been already realized with DINSAR [*Fruneau et al.*, 1996]. This distribution remains stable over the 8 years of the study. This suggests that the registered motions are mostly controlled by deep processes rather than superficial ones. The two superimposed landslides (B and C), identified on velocity maps, appear independent of the major structure. The top NW lobe is the most active part of the la Clapière landslide [*Casson et al.*, 2003] with movements of more than 70 m in 4 years. It over rides progressively the middle part of the landslide. Displacements of the area at the toe (C) of the landslide are around 23 m between 1995 and 2003. Precise limits of the sliding area can be deduced from the velocity map. This area can be considered as a rigid shallow slide moving on a deeper mass.

[16] The velocity maps obtained by optical correlation can be compared with those obtained with DINSAR by *Fruneau et al.* [1996]. From DINSAR data, velocity maps can be computed on the whole landslide with a spatial resolution of about 8 m for a period of 9 days from data acquired in August and September 1991. At global scale, the results obtained with radar data are similar to the results obtained with optical correlation. The NW part of the landslide moves faster than the SE one. These two areas are separated by a linear structure clearly visible on radar data, and more diffuse on the optical data. However, detailed observation of the two high-velocity structures (B and C) described above cannot be distinguished on the radar data. The lower structure is certainly too small to be detected, and is also covered by vegetation which results in a loss of coherence on differential SAR interferogramms. The upper structure close to the headscarp is moving too fast to deliver a signal on the radar data.

[17] The optical correlation technique is thus complementary to DINSAR. Practically, measurement of displacement of about 0.1 pixel to hundreds of pixels can be performed with optical correlation. Applied to very high spatial resolution data (1 meter or less), correlation technique can detect motion as low as 0.1 m for 2 images acquired by the same sensor. Those movements occur over a period of a few days on a landslide such as "La Clapière". For DINSAR, loss of coherence in vegetated mountainous areas prevents detection of landslide motion over period larger than few days or deformation larger than few tens of centimeters. Optical methods remain effective over longer period of time (up to 4 years) with resampled images derived from various sources. Moreover, the geometry of optical data, which are generally acquired with an incidence angle close to the vertical, are favorable to the survey of landslides by optical correlation.

5. Conclusion

[18] Optical correlation can be used for deriving deformation maps of landslides which have a near continuous deformation over several years. This technique can be applied either on two images acquired at two periods by the same type of sensor or by different sensors (for example aerial photography and very high resolution satellite imagery). This technique allows the user to map a large deformation field. On the "La Clapière" landslide, the combination of aerial and QuickBird images reveals displacements ranging from several tens of centimeters to 80 meters movements with a pixel spacing of 1 meter over two periods of 4 years between 1995 and 2003. The velocity maps, produced from images at one meter spatial resolution exhibit spatial variations at hundred meter scale. The velocity heterogeneities remain stable in place and in intensity for the two time periods.

[19] Combination of optical correlation with Differential SAR interferometry is a promising method for the study of landslide movement pattern. Limitation of DINSAR (limited data archive starting in 1991, geometrical constraint and loss of coherence due to vegetation) can be overcome using optical correlation. The large temporal archive of aerial images (since 1950 in France), high spatial resolution (better than 1 meter) and launch of new very high resolution optical satellites (QuickBird, Ikonos, SPOT5) can supply images that allow detailed monitoring and observation of recent landslide activity.

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