High-Resolution DEM Extraction from Terrestrial LIDAR Topometry and Surface Kinematics of the Creeping Alpine Permafrost: The Laurichard Rock Glacier Case Study (Southern French Alps)

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**Abstract**

The most common landforms associated with the creep of Alpine permafrost are the rock glaciers, the morphology of which reflects the complex processes of the internal deformation of the ice and debris mixture. In the present study, a terrestrial LIDAR device was employed to scan, at a sub-decimeter resolution, the surface of the Laurichard active rock glacier (Southern French Alps). Two points-clouds were generated at one-year interval (Sept. 2005 and Sept. 2006) and processed in order to produce two high-resolution digital elevation models (DEMs) and to compare them. Different methods were used in order to extract small-scale topography, quantify interannual surface changes, and determine the kinematic behavior of the creeping mass. For a better understanding of rock glacier dynamics, the results have also been compared to the geodetic measurements annually over a 20-year period, and to the geophysical evidences of rock glacier internal structure.

**Keywords:** alpine permafrost; French Alps; high-resolution DEM; LIDAR; rock glacier morphology; surface kinematics.

**Introduction**

The long term, steady-state and slow deformation of ice-supersaturated sediments, which generates specific landforms called rock glaciers, is dependent on various parameters such as the ice/debris mixture thickness, the local slope angle, the ice and water content, or the depth of the basal shear zone (Haeberli 1985, Barsch 1992, Arenson et al. 2002, Haeberli et al. 2006). Recent investigations have also suggested that, at an interannual scale, the main controlling factor of rock glacier deformation rate may be the thermal state of the permafrost body (Ikeda 2004, Roer et al. 2005, Kääb et al. 2006).

Previous studies on rock glacier surface kinematics have classically used remote-sensing techniques (Kääb et al. 1998, Kaufmann et al. 2005), which provide a good spatial resolution but only on mid- to long-term trends of the creeping activity, or geodetic surveys (Delaloye 2004, Lambiel & Delaloye 2004, Kaufmann et al. 2006), which are often carried out at an annual time-scale but with a limited spatial resolution.

Recent development of the LIDAR (Light Detection And Ranging) technique allows fast and accurate acquisition of the topography with very high resolutions. Using terrestrial devices, several millions of points may be acquired in one day, and entire slopes ($\approx 10^4 \text{ m}^2$) and landforms may be scanned. Therefore, it appears a promising tool to produce high-resolution digital elevation models (HR-DEMs) that have, until now, rarely been used to study surface changes and related processes in the glacial (Bauer et al. 2003, Avian & Bauer 2006) or periglacial geomorphology.

In this study, a medium-range terrestrial LIDAR was employed during two successive years to scan the surface of a rock glacier.

The investigated landform is the Laurichard rock glacier in the Southern French Alps (Fig. 1), which is a 500 m long, tongue-shaped, active rock glacier. As it is surveyed since 1979 with annual geodetic measurements of 28 marked blocks (Francou & Reynaud 1992), its mean surface velocities are known to range from 0.2 m/yr at the root and at the front to 1.2 m/yr in its steepest central part.

Figure 1. Location of the Laurichard rock glacier, in the Southern French Alps.

Beyond the necessity to test the applicability of the terrestrial LIDAR on a very rough and complex terrain, the main goals of this study were to perform multi-scale morphometric measurements, to quantify the interannual surface changes, and to determine the kinematic behavior of the creeping mass.
Acquiring High-Resolution DEM in an Alpine Environment

Data acquisition

The device (Iliris-3D, Optech; wavelength: 1500 nm) used in the present study is able to acquire 2500 points per second, with a centimetre accuracy (8 mm at 100 m) and at a maximal range of about 1000m. The limiting factors that can reduce the LIDAR measurements quality are the presence of non-reflective surfaces, such as snow, and the occurrence of very humid or foggy atmospheric conditions.

The small-scale morphology of the rock glacier, composed of extensive (longitudinal ridges) or compressive (transversal convex ridges and furrows) flow structures, has made it imperative to multiply the angles of view. Hence, during the two field campaigns (September 2005 and September 2006) four stations and 14 to 17 scenes (between 1 and 4 per station) were necessary each time to scan the whole surface of the rock glacier and to minimise shadowed areas (Fig. 2). In addition, five fixed points, outside the rock glacier, were measured with DGPS (Differential GPS), enabling a centimeter precision for the georeferencing of each DEM.

With a mean resolution of 7 cm (it varies according to the distance between the LIDAR and the target) two clouds of 10–15 millions points were generated.

Data processing

The raw datasets, that consist in x, y, and z coordinates (reflectance and colorimetric information have not been used), have to undergo several processing steps before being usable for further treatments. The PolyWorks (© InnovMet-ricss 2005) software, dedicated to the processing of 3D point clouds, was hence used to:

1. align and adjust the scenes together, thanks to common overlapping areas,
2. reduce the redundancy where a high density is not necessary,
3. grid the data to obtain either a polygonal model or a regularly spaced model,
4. georeference one polygonal model, thanks to using the DGPS points by the manual recognition of the blocks, and
5. align the two polygonal models on their common stable parts.

Finally, three types of processed data are available for further analysis: initial point clouds (17 in 2005, 14 in 2006, plus the 2 final aligned ones); two polygonal models (one per year); and two regularly-spaced models (one per year, at resolution of 0.5 and 1 m).

The Use of High-Resolution DEM to Quantify Rock Glacier Morphology and Surface Kinematics

Morphometric analysis of the rock glacier

Because of the presence of snow on the upper part of the rock glacier during the 2006 campaign, only the 2005 data were used.

First, a detailed map of the main morphological features has been established and verified in the field (Fig. 3). Interesting elements, such as the limits of the different flowing units or the variable roughness of the surface, can be extracted.

Second, the use of morphometric parameters has allowed a fine quantitative description of the rock glacier topography. Slope, microtopography ($\mu_z$) after Kääb (2005), and roughness ($\rho_z$) index were computed along the main flow line by the following formulas:

$$\mu_z = \frac{\sum_{n=2}^{n-2} z_n}{5}$$

$$\rho_z = \frac{\sum_{n=10}^{n-10} z_n}{21}$$

This allows several parts with homogeneous morphometric characteristics to be distinguished (Fig. 4):

a) the scree slope at the contact between the rock wall (slope >37°) is marked on its upper part by a deep concavity, which actually corresponds with the “randkluft” of the rock glacier (massive ice is commonly observed);

b) the upper convex part of the central slope where transversal microtopography is almost absent due to high, extensive flow;
the lower concave part of the central slope, which is characterized by a high roughness, related to the presence of numerous large boulders and, at the bottom, by transverse ridges and furrows;

d) the gently sloping tongue of the rock glacier shows several ridges, and the roughness index suggests smaller boulders.

As a rock glacier is commonly interpreted as a creeping mixture of debris and ice (Haeberli 1985, Barsch 1992), it may be assumed that those morphometric measurements partly reflect the dynamics of the landforms.

Long-term deformation of the rock glacier

The digitizing of contour lines obtained through photogrammetric restitution of 1975 aerial photos (topographic map IGN 3436ET, 1:25000) has provided a DEM (at a grid resolution of 10 m) of the rock glacier region. The comparison between this 10 m DEM (which displays quite poor accuracy of +/-5m) and the 2005 HR-DEM allows us to roughly estimate the characteristics of the Laurichard rock glacier flow (Fig. 5). It appears that the frontal zone has advanced by about 11 m, displacing a volume of rock and ice of approximately 50,000 m$^3$ in 30 years. An interesting feature is the clear inflexion of the flow towards its right, in a local valley axis.

Interannual comparison of HR-DEM

Due to the coarse detritic cover of the rock glacier, made up of decimeter to meter-sized boulders without fine material, the surface roughness appears to be greater than the spatial resolution of the HR-DEM. Furthermore, the variability of the point density, from place to place and from one HR-DEM to the other, may lead to an heterogeneous quality of the reproduction of the surface by the models. Thus, as a smoothing of the “noisy” blocky surfaces would have induced an additional inaccuracy and would have limited the detection of infra-meter surface movements, direct comparisons were performed by two different means.

With the first method, the PolyWorks software computes the distance between each cell of the 2005 polygonal model and the closest cell of the 2006 polygonal models. A directional constraint is set by a 3D vector which specifies in which direction the comparisons have to be performed. Thus, maps of “directional differences” can be computed for various 3D vectors.

This method shows some of the main components of the surface movement, such as the downstream progression of the ridge that appears to be larger in the main flow axis of the landform (Fig. 8). The larger movement on the right side of the rock glacier seems also to be confirmed, and the fall of blocks from the top of the front or the individual movements of big boulders can be easily detected.

The second method consists in the use of topographic profiles along which 2005 and 2006 surfaces are compared. Vertical changes as well as horizontal differences can then be computed.

Specific patterns of rock glacier movement can therefore be visualized. The frontal advance is detected by the uprising of the surface, which decreases toward the foot of the talus (Fig. 6 A). Erosion by the fall of blocks from the upper part of the front is also perceptible at some places by a lowering
of the surface at the top and a subsequent rising at the foot, which corresponds to the deposit.

This method also permits to quantification of the downstream progression of the ridges (from 0.2–0.6 m/yr on the tongue) and the advance of the latero-frontal talus that appears to range from 0–0.6 m/yr (Fig. 7).

Discussion on the Rock Glacier Dynamics and Discussion

The rock glacier advance

The latero-frontal edges of the rock glacier were frequently perpendicular to the line-of-sight of the LIDAR, and this has locally improved the quality of the HR-DEM and facilitated surface changes quantification on those specific sectors.

Hence, measure of the horizontal movement of visible boulders allows the drawing up of vertical profiles of the advance of the rock glacier edges (Fig. 8). Those show an increase of the advance rate toward the top of the front, as well as marked ruptures that are visible at different levels in the profiles.

Although this kind of measurement has to be carefully interpreted due to the roughness of the surface and to individual boulder movements that may introduce noise in the values, several remarks can be made concerning the advance of the rock glacier.

First, the linear to parabolic shape of the vertical profiles is similar to those observed by Kääb & Reichmuth (2005) on the front of two rock glaciers. For the Murtèl case, they found that its frontal part is affected by a downslope creep of a surface layer (which acts as a “conveyor belt”) and a thaw settlement that reveal an excess ice content of about 60%–70%.

Second, the presence of a non-moving layer is observed within the vertical profiles of the right side of the Laurichard rock glacier. This may approximately correspond to the level of the bedrock (as suggested by surrounding evidence) and may be interpreted as evidence of the presence, immediately above, of a shear zone (Arenson 2002) where a large part of the total deformation occurs.
Implications for the long-term geodetic survey

The annual measurements with the LIDAR device have suggested that the flow of the rock glacier may partly turn to its right, following a local valley axis. Between 1975 and 2005, the right side of the rock glacier advanced by about 14 m (+/-5 m) in that direction, and the corresponding 2005–2006 advance was around 0.3 m on the top of the latero-frontal talus.

Therefore it can be assumed that the surface changes observed with the long-term geodetic survey along the main axis of the rock glacier (Fig. 10) will reflect this specific behavior.

As a consequence, the small mean lowering of the surface (indicated by the calculated slope compensated variation of surface, data from 1986 to 2006) which accompanies the local compression of the tongue has to be interpreted in different ways. It may be a consequence of the global dynamics of the rock glacier, as well as an impact of the thaw settlement that would be associated to the global warming of the last two decades.

Conclusion

The terrestrial LIDAR technique has been employed to produce two high-resolution DEMs of the Laurichard rock glacier in two successive years. The morphology of the landform has been analyzed, thanks to mapping and to morphometric parameters. The depicted flowing structures clearly reveal the creep of the ice and debris mixture. This has also been studied through interannual comparisons of the HR-DEM, which allows general or detailed quantification of the surface kinematics of the rock glacier. By comparing with the results of a long-term geodetic survey, it appears that more detailed studies, for example with a regular (every 5 years) survey of the rock glacier, are necessary to develop models of the rock glacier dynamics.

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References


