# GEOMATICS TECHNIQUES APPLIED TO GLACIERS, ROCK GLACIERS, AND ICE-PATCHES IN SPAIN (1991-2012)

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ABSTRACT. At present there is a wide variety of geomatic techniques available to determine the dynamics of glaciers, rock glaciers and ice-patches. Between 1991–2012, different geomatic techniques: Total Station, Global Positioning System, Close-Range Photogrammetry, and Terrestrial Laser Scanner, were applied to monitor the movement of cryosphere landforms in the high mountains of the Iberian Peninsula. The applied techniques must be adapted to the dynamic conditions of cryospheric environments, and so there is no ideal general technique, and depending on the characteristics of the geomorphological structure to be studied, different geomatic techniques can be used. However, there are situations in which certain instruments cannot be used, GPS-RTK shows difficulties when the presence of vertical walls cause a “multipath” effect. The technique that provides the best result in each case must be chosen, although they can all give good results in measuring and monitoring geomorphological processes. This paper analyses the techniques used and results on vertical and horizontal changes of glaciers, rock glaciers and ice patches in the Sierra Nevada, Pyrenees and Picos de Europa, and differences among them by location and topoclimatic setting. All glacier and rock glacier show a thinning tendency and annual variations in the flow velocity. In addition to the specific dynamic analysis, the geomatic techniques can be used to detail scales and volumes changes and perimeter of the analysed landforms.

*Key words:* Cartography, climate change, geomatics, rock glaciers.

## Introduction

The cryosphere is made up of different elements whose most important characteristic is the dynamic related to the ice landforms. Glaciers, rock glaciers and ice-patches are ice masses or frozen bodies moving downslope at changing rates depending on local (emplacement, topography) and global (climate) factors. The velocities of frozen bodies are related to mass balance thermal change, and their dynamism is related to their current physical behaviour depending on melting or aggradation, and ice creep. Rock glaciers are an efficient indicator of permafrost environments, and are paleoindicators for the reconstruction of Quaternary periglacial environments in the Atlantic and Mediterranean mountains from preserved relict forms. Their nature as indicators, both of present and past climates, has helped in the development of numerous morphogenetic, morphodynamic and regional studies, and in the development of a inventory of rock glaciers in many mountains worldwide.

The study of glaciers using topographical techniques has been conducted since the XIX century, and more recently it has been applied to rock glaciers. Advances in geomatic techniques have made possible the incorporation of the techniques of *Global Positioning System-Real Time Kinematics* (GPS-RTK) and *Terrestrial Laser Scanning* (TLS) to study glaciers and rock glaciers (Eiken *et al.* 1997; Bauer *et al.* 2003; Lambiel and Delaloyé 2004; Kenner *et al.* 2011; Avian 2012). These techniques give greater precision, and require less logistical effort and time, leading to lower costs and greater quality in field studies (Bauer *et al.* 2003).

In this study, we center our attention on the monitoring of glaciers and rock glaciers in Spain, considering the latter as frozen bodies deformed by flow and characterized by the existence of ridges, furrows and a steep front with a slope of greater than 35º, although there is great controversy regarding the genetic interpretation and origin of ice in rock glaciers (Haeberli *et al.* 2006; Berthling 2011). Rock glaciers are displaced downwards at annual flow velocities varying from centimeter to meter values (in the most extreme cases) (Konrad *et al.* 1999; Haeberli *et al.* 2006), carving out arches and furrows that express in their surface the frozen body flow and deformation. This dynamic flow has been interpreted as creep and gelifluction, which generates the ridges and grooves associated with the emergence, thinning, and compression or stretching of the frozen body. Rock glaciers are also related to thermal processes such as differential thermal diffusion, frozen heave with segregation ice processes or thermokarst, in accordance with the internal classification processes generated by the upwelling of fines in the front area (Whalley and Martin 1992; Kääb *et al.* 2003; Kääb and Weber 2004; Haeberli *et al.* 2006). Many questions remain on the rheology and dynamics of rock glaciers, in recognition of the complexity of the processes involved, but without any agreement on which processes (creep deformation or thermodynamic changes) are dominant in each case (Haeberli 2000; Haeberli *et al.* 2006; Berthling 2011). This means that more detailed field knowledge of rock glaciers is needed in order to improve the environmental and paleoenvironmental interpretation of periglacial sites in temperate mountains, given the absence of other well preserved glacial or periglacial forms in marginal environments and transition between periglacial and nival domains. In high mountain marginal periglacial environments, and in particular in the mountains of the Iberian Peninsula, rock glaciers are a useful environmental and dynamic indicator, and are also the most characteristic active periglacial landforms found here (Serrano *et al*. 1999, 2006, 2010).

The installation of surface rods and the monitoring of their movement by means of topographical survey or GPS-RTK and the generation of a *Digital Elevation Model* (DEM) from *Terrestrial Laser Scanner* (TLS) data reveal their displacement, which is highly variable over time and space. Knowledge of their exact movement and temporal and spatial variations are important parameters related to the presence of permafrost, to estimate their age, the rates of potential erosion, or the collapse processes associated with the disappearance of frozen bodies and mountain permafrost. All of these measurements help to understand the dynamic diversity of high mountain landforms in the Iberian Peninsula (Fig. 1). The displacement rates are highly variable between glaciers, rock glaciers and other landforms related to the presence of seasonal or permanent ice in glacial or marginal periglacial environment. In these cases the processes and landforms are closely related to topoclimatic factors.

The aim of this study is the comparative analysis of geomatic techniques applied to the monitoring of rock glaciers and glaciers in the Iberian Peninsula, their problems and use, together with the results obtained by means of these different techniques in different landforms (glaciers, rock glaciers, protalus lobes and ice patches) with the aim of identifying their similarities and differences.

## Study area

The high mountains of the Iberian Peninsula with perennial ice and frozen bodies are only located in the Pyrenees and Cantabrian Range (Picos de Europa) in the North, and the Sierra Nevada in the South (Fig. 1). The three mountains system have very different environmental conditions derived from their altitude, latitude and geographical positions, varying from Atlantic to Continental and Mediterranean high mountain with transitional environments in the Pyrenees and Cantabrian Mountains. The loss of ice mass is common to most mountains, and especially in the temperate high mountains of the Iberian Peninsula. The retreat of glaciers results in a transition from ice bodies to ice patches, with melting of non-moving residual ice masses, and glacial environments are often replaced by periglacial environments. Marginal ice and frozen bodies are today a research field of increasing interest.

The Sierra Nevada, to the south of the Iberian Peninsula, is formed by a high ridge reaching 3483 m a.s.l. in the Mulhacen peak (Fig. 1). On the high mountains of the Sierra Nevada there is one relict glacier ice mass, one active rock glacier and around 40 relict rock glaciers mostly located above 2800 m a.s.l. (Gómez-Ortíz *et al.* 2001, 2002). Relict ice masses are located on the North side of Veleta peak (3394 m). The Corral del Veleta rock glacier is located at the head of the old cirque of the Guarnón (the Sierra Nevada, 37º 3’ N, 3º 21’ W, 3100 m a.s.l.). It is made up of thick accumulations of blocks from rockfalls of the cirque wall that have become a glacier-derived rock glacier (Gómez-Ortiz *et al.* 2008). The interest in this rock glacier lies in its latitudinal position (37º 3’ N, the southernmost of Western Europe) and its site, in relict glacial ice from the *Little Ice Age* (LIA), which is currently degrading (Gómez-Ortiz *et al.* 2008).

The Pyrenees is a complex mountain range 400 km long with an Atlantic climate at the West and Mediterranean one in the East, reaching 3404 m a.s.l. In the Pyrenees there are at least 21 glaciers (Martínez de Pisón and Arenillas 1988; ERHIN 2008), 14 rock glaciers (Serrano and Agudo 1997; Serrano *et al.* 1999) and thousands of relict rock glaciers, which were initially interpreted as highly complex retreat moraines, and later as relict rock glaciers (Serrat 1979; Soutadé 1980). The detailed study of Pyrenean rock glaciers is recent (Cazenave-Piarrot and Tihay 1983, 1986; Martínez de Pisón and Arenillas 1988; Hamilton 1988; Serrano and Rubio 1989; Agudo *et al.* 1989; Serrano *et al.* 1991, 1995), and has led to the confirmation of the current movement of the Argualas, Posets, Besiberri, Maladeta and Bastampé rock glaciers (Cazenave-Piarrot and Tihay 1983, 1986; Serrano *et al.* 1995, 2006, 2010; Chueca and Julián 2003; González-García *et al.* 2011) and the possibility of current movement in another nine rock glaciers (Serrano *et al.* 1991, 1999; Martí and Serrat 1995; Serrano and Agudo 1997, 2004). The Argualas (2590 m a.s.l.), Maladeta (2910 m a.s.l.) and Posets (2875 m a.s.l.) rock glaciers in their respective massifs have been under analysis since 1991, as well as the glacier of La Paul (2830 m a.s.l.) in the Posets massif (Serrano *et al.* 2011a) (Fig. 1).

The Cantabrian Range forms a wide set of ridges and massifs of moderate altitude with a strong asymmetry between the Atlantic North slope and the transitional Atlantic-Mediterranean environment to the South. The highest altitudes are located in the Picos de Europa (Torre Cerredo peak, 2648 m a.s.l.), located in the North and Central part of the Cantabrian Range. In the Picos de Europa, there are no glaciers, and nivokarstic processes are dominant. The Jou Negro ice patch (2200 m a.s.l.) has been monitored since 2005, and that of Llambrión (2350 m a.s.l.) since 2011 (Fig. 1). Both are remnants of ice from LIA glaciers (González-Trueba 2006; Serrano et al. 2011b).

## Methods

Precise measurements of the dynamics of landforms in the Spanish high mountains (glaciers, rock glaciers, solifluction lobes, scree and ploughing blocks) have been made since 1991. During the years of work different advances in geomatic techniques have permit us to use different techniques such as Total Station Topographical survey, GPS-RTK, TLS and Close-Range Photogrammetry. Innovation in geomatic techniques gives greater precision, and requires less logistical effort and time, leading to lower costs and greater quality in field studies (Bauer *et al.* 2003). The monitoring of rock glaciers is of special interest for monitoring vertical and horizontal displacements of the frozen body, determining the processes that generate and maintain the landforms, their activity or inactivity and their evolution over time. But in the field the efficiency of techniques varies depending on placement and orography, such that there may be problems in the use of topographical survey, GPS-RTK or TLS. The lack of ideal placements for stations, which makes it impossible to collect suitable visual data or scans, or the existence of vertical walls in its surroundings, thus blocking the direct reception of satellite signals, produce low accuracy or errors in the data (Sanjosé *et al.* 2010). For this reason, when planning the field study and repeat survey of a glacier or rock glacier, the most efficient geomatic technique must be chosen to obtain precise data, which in our case is estimated at around ± 3 cm (Sanjosé 2003).

Our studies began in the area of the Pyrenees with the Argualas rock glacier (1991–2000) (Sanjosé 2003). Later, measurements continued on the Posets (GPS-RTK), Maladeta (GPS-RTK) and Corral del Veleta rock glaciers (Total Station, GPS-RTK, Close-Range Photogrammetry, TLS), solifluction lobes in the Renclusa (TLS), and La Paúl, Monte Perdido, Maladeta and Ossue glaciers (GPS-RTK, TLS) (Serrano *et al.* 2006, 2010). In the Picos de Europa are being studied the Jou Negro (Close-Range

Photogrammetry and TLS), the Llambrión ice-patch (TLS), debris talus and cones in La Vueltona (TLS), and mass movements related to seasonal ground ice (GPS-RTK and TLS).

The different geomatic techniques that have been applied throughout this time and which have led to the determination of rock glacier dynamics were:

- The use of GPS-RTK, which allowed the follow-up of control points (marked by metal rods) distributed over the surface of frozen bodies (Eiken *et al.* 1997; Lambiel and Delaloyé 2004; Sanjosé *et al.* 2007a, 2007b; Gómez-Ortiz *et al.* 2008) with an accuracy of around ± 2 cm, but this technique is not applicable to all cirques. When the walls are close to the measured points the satellite signal is interrupted or there are rebounds of the 'multipath' signal and the required accuracy is too low.
- The methodology used with a Total Station was the direct multiple angular intersection and distances (control points placed on the rock glaciers), in the case of Argualas rock glacier from three fixed stations. On glaciers, using the total station, several transversal profiles are monitored, as well as the outline of the glacier and rock glacier. With this technique the positional precision (planimetric and altimetric) of the control points and profile points was ± 3 cm. The use of the 'reflectorless' total station and the support of photographic images to trace the front of rock glaciers by monitoring relevant fixed points in blocks. This precision was ± 1 cm (Sanjosé *et al.* 2007a, 2007b; Matías *et al.* 2009).
- For many years detailed mapping has been done using new techniques of automatic restitution (Gwinner *et al.* 2000, Kaufmann and Ladstädter 2008; Matías *et al.* 2009). Convergent photogrammetry with the application of the program 'Restitutor' and normal photogrammetry with the use of analytical and digital restitutors have been combined to obtain a detailed morphological map. Our computerized studies have led to the development of the software 'Restitutor', which allows 3D reconstructions to be made automatically and in great detail from the set of images collected (Matías *et al.* 2012).
- A scanner laser can be used for the precise monitoring of sectors of interest and topographic mapping of the rock glaciers (Bauer *et al.* 2003). The aim is to

know changes in vertical and horizontal with accuracy of around 1–3 cm. The placement conditions determine the use of long range instruments, or short range ones. The conventional scanner laser (C10 de Leica), used for small landforms, measures 50 000 points/second but its scope is limited to 200 m distance. The 'Image Station' Total Station enables scans from more than 1000 m with a positional accuracy of 2 cm, but the accuracy depends of the distance. At less than 150 m the points measured are 20 points $s^{-1}$, but when the distance is greater than 150 m, it measures 1 point $s^{-1}$. This technique can be applied to glaciers and rock glaciers. A scanned net is obtain to get a Triangular Irregular Net (TIN) and so to built a Digital Elevation Model (DEM) from which annual spatial variations of volume lost or gain, can be calculated.

## Dynamics in the Sierra Nevada (Corral del Veleta rock glacier)

The dynamics of this rock glacier are monitored from 2001, using different geomatic techniques (Sanjosé *et al.* 2007a). Since then, the results obtained have revealed different types of movement over time at the control points. The controls in place, most of which were measured annually and on the same dates (the last week in August) (Fig. 2a), allow us to conclude that this is a stabilized rock glacier owing to the fact that the frozen bodies housed in its interior tend to progressive degradation (Salvà-Catarineu *et al.* 2010; Salvador-Franch *et al.* 2011; Gómez-Ortiz *et al.* 2012).

### *General behaviour*

The behaviour and values of the vertical (sinking) and horizontal displacements or planimetrics of the rock glacier obtained using the total station throughout the period 2001-2009 has been described in elsewhere (Sanjosé *et al.* 2007a, 2007b; Gómez-Ortiz *et al.* 2008; Matías *et al.* 2009) (Table 1). The displacements detected show high variability, more at the root and front of the rock glacier than in the middle. The main reason lies in the topographic slope of each section that is being monitored.

The body of the rock glacier has compact and rigid behaviour during the cold and snowy season (winter) and is less rigid during the season of snow melting and/or no snow (summer). As a result, movements only take place from the middle of the summer, when the thermal wave of external radiation manages to melt the ground snow and penetrate through the active layer until it reaches the underlying frozen body, which then degrades (Table 2) (Gómez-Ortiz *et al.* 2008).

Table 2 shows the dynamics of the same control point as in Table 1, with data obtained in mid-July and the end of August (periodic observations). In Table 2, we can see that for full years (August–August) two pieces of data are available: August-July (10 months and 15 days) and July–August (45 days), and for each period the results are similar. However, rock glacier dynamics may also be affected by the moment of the first winter snowfall (October or November), i.e. when the rock glacier becomes covered with snow and when it is completely free of it (mid-July), the dynamic absence during winter could be confirmed. Between November 2009 and August 2012, the entire body of the rock glacier remained covered by 2 m depth snow cover, paralyzing possible movement (Fig. 2b).

### *Monitoring of the outline and profiles*

The evolution of the outline and five profiles in different stretches of the rock glacier has been determined using a total station in some years and with GPS-RTK in others (Fig. 7). This has been done from the follow-up and monitoring of control points. These controls were also annual with 68 control points for the perimeter and 88 along the profiles.

The results reveal very little variation in the outline or surface shape but continuous deformation in the profiles. For 2002–2009, vertical sinking movements gave a mean value per year of –34.4 cm. Profile 4, which is perpendicular to the rock glacier displacement (Fig. 3a), behaves similarly to the rest of the transversal profiles (profiles 1, 2, 3) (Fig. 7). Moreover, the behaviour of profile 5 is described (Fig. 3b), which is longitudinal to the rock glacier. This profile shows the recession of the glacier, as described below.

### *Frontal monitoring*

With the IS (Imaging Station) total station and TLS, monitoring of the front of the rock glacier was carried out from the data collection of a point cloud, without the need of the total station reflector. This instrumental technique has the advantage of identifying and monitoring the movement of control points at the same time that a general photograph of the point observed is obtained (Fig. 4).

Using this technique it has been observed that the dynamics of the front of the glacier is not homogeneous. There is a greater movement in the upper part, to a lesser extent in the central area and little or none at all in the lower part (Fig. 5). The movement of the upper and central parts lies in the instability of the blocks of rocks on the ground, so they are dependent on the sharp slope of the rock glacier front.

The follow-up of the reference points from 2005 to 2009 shows that cumulative values of sinking greatly surpass their horizontal equivalents and the rock glacier is actively sinking. The recession of the front of the rock glacier can be checked with the points measured in the lower area, in which there was hardly any displacement in 2009 (horizontal: 3 cm; vertical: 0 cm) (Fig. 5).

### *Detailed mapping*

For many years detailed mapping has been done using new techniques of automatic restitution. ‘Restitutor’ is a computer program, which calculates a first 3D surface using a feature based solution (Matías *et al.* 2009, 2012). Next, it completes this first approximation using a 3D multi-view reconstruction algorithm (Goesele *et al.* 2006). In the end, a dense 3D reconstruction is obtained (millions of 3D points).

Also, the progress made in the image matching methods and the use of techniques from computer vision are leading to improvements in ‘Restitutor’. Figure 6 shows an example DEM obtained using this software.

### *Laser scanner surveying*

In August 2010 and 2011 the rock glacier was buried under snow (Fig. 2b). Measurements using other techniques were not viable and in the 2011 survey it was decided that laser scanning be used to compare the topographic profiles of 2009 with those obtained using the laser scanner.

The laser scanner is being used to map the area of the rock glacier which, given its length and orientation, involves different positionings of the laser scanner and them joined together using the ‘target resection’ technique (Fig. 7).

From this laser scan it was observed that at the end of August 2011 the mean thickness of the winter snow was 4 m on the rocky surface of the rock glacier. At the front of the rock glacier, the thickness of the snow was 10 m in some places. Similarly, the data from 2009 showed the position of the tube installed in the heart of the active layer of the rock glacier, that housed the chain of sensors that continually record the internal temperature of the ground, and also that its displacement was 3 cm. We attribute this displacement to the period between the measurement at the end of August 2009 and the arrival of the first snowfalls the following winter.

## Rock glacier dynamics in the Pyrenees

The aim of this research is the comparative analysis of the best known rock glaciers in the Pyrenees in order to observe their morphological, dynamic and structural similarities and differences, particularly of their internal structure and surface dynamics. Common aspects must be established for their description and use as environmental indicators, as set against their different locations. Similarly, the structures and dynamics deriving from the deformation of rock glaciers will be differentiated from those attributable to thermal processes, which will lead to the definition of states of balance or instability.

### *Argualas rock glacier*

In the Argualas rock glacier, six campaigns were made with a total station between 1991 and 2000. This is the first rock glacier studied in Spain using modern geomatic techniques, and a mean annual movement of 20-40 cm was measured (Serrano *et al.* 2006). The technique used (Total Station) the achieved precisions on planimetry and altimetry of ± 3 cm. Moreover, in 2000 the photogrammetric technique of ‘close-range and convergent’ was used to map a small area of the rock glacier. An attempt was made to use GPS techniques but the results were unacceptable, which was possibly caused by the proximity of high surrounding rock walls, leading to the interruption of satellite signals (Sanjosé 2003).

### *Posets rock glacier*

The Posets rock glacier is in the same massif as the La Paul glacier. Both are analysed annually with different techniques due to their different characteristics (Fig. 8).

Measurements began on the Posets rock glacier in 2001, and two fixed stations were set up at stable sites and ten control points on the rock glacier. The GPS-RTK technique was chosen, since the rock glacier is some distance from the surrounding walls and therefore there are no obstacles that might interrupt the satellite signal or rebounds of the ‘multipath’ signal (Serrano *et al.* 2010). In this way, the coordinates of the points are obtained and measured at the same time, and are analysed with those of the previous year. If the coordinates are similar, the measurement is good and the difference shown is due to the displacement. But if the values of the annual measurements are exaggerated (> 1 m), the measurement is repeated in anticipation of the satellite configuration having changed.

Table 3 shows the result of a control point measured in the Posets rock glacier. As observed elsewhere, the dynamic (horizontal or vertical) movement is not uniform throughout the years. There are periods of greater displacement than others depending on climate variability during the study period. In general, the horizontal displacement is greater than vertical displacement, though for a certain control point (Table 3) there is an exception for the period 2005–2006 and for the bi-annual period 2009–2011.

The averaged results of the Posets rock glacier annual movement coincide with the values of other rock glaciers measured in the Pyrenees (Argualas and Maladeta). The mean horizontal displacement is 1.5 times the value of vertical displacement. This proportion applied to other European rock glaciers varies as in, for example, the Doesen rock glacier (Austrian Alps), in which the relationship is 3:1 and in the Corral del Veleta rock glacier, where it is 1:6 (Fig. 9). Therefore, there may be a relationship between the geographical latitude of European rock glaciers and their movement (planimetric/altimetric) deriving from their marginality in environments with permafrost (Sanjosé *et al.* 2010). In marginal environments where topoclimatic conditions are particularly important, a decrease is seen in the horizontal displacement of rock glaciers and an increase in thinning (vertical displacement) due to stretching and loss of frozen mass, in a transition towards instability (Fig. 9).

### *Maladeta Rock Glacier*

The Maladeta rock glacier is found in the Maladeta mountain massif, in the Alba cirque (Fig. 1). It has a tongue 45 m in width and 210 m in length with an abrupt and unstable front 15 m high.

From 2008 to 2012 geomorphological, thermal and geomatic studies have been continuously underway. The geomatic analyses consist of data collection using GPS-RTK over 15 control points. The precision of measurements is ± 3 cm and mean annual horizontal displacement of 6-8 cm has been determined (González-García *et al.* 2011).

The results of the data analysed reveal considerable differences in the velocity of horizontal displacement across the rock glacier. The area with the greatest movement is the front, with mean annual values of 8 cm, followed by the central area with values of 6 cm. With respect to vertical displacement, which is indicative of mass accumulation or loss, most of the points analysed register a loss of thickness at the rock glacier surface (Fig. 10).

This pattern of change corresponds to a low activity rock glacier in evident thermal disequilibrium with interannual variations in climate. Its location in a marginal periglacial area of a temperate high mountain environment yields behaviour that is similar to that recorded in the Argualas (Serrano *et al.* 2006) and Posets rock glaciers (Serrano *et al.* 2010). The study period is still short, but knowledge of its dynamics over time makes it an efficient morphoclimatic geoindicator (Serrano *et al.* 2010).

### *La Paul glacier*

The glacier does not permit the installation of control points (rods) and so the glacier is analysed using the generation of DEMs. In each survey a DEM is generated and compared with the DEMs of previous years.

In order to generate these DEMs, a great number of points must be measured in 3D, and for this reason we used the total station IS, which stores 20 points per second in its memory up to a distance of 150 m, and for greater distances, it saves approximately one point per second. Each point observed has a precision of 1 cm and over 10,000 points were measured in each survey, with a mean mesh point interval of 4 m.

Profiles are made with each DEM and are compared for the different areas of the glacier (Fig. 11a). Values of losses and gains in volume and thickness are obtained. Care must be taken to ensure that measurements are not taken when there is seasonal snow, as this would create uncertainty in the measurements. For this reason, laser scanner must be used on glacial ice.

Results from the comparison between the scan data between 2010 and 2011 are dramatic. The limited presence of snow in both summers enabled us to compare the surface of the glacier. The comparison of the longitudinal profile between 2010 and 2011 surfaces shows a loss of 1.5 m (Fig. 11b). The loss of volume of the glacier accelerated in 2011 and 2012, thinning by 2.5 m.

## **Dynamics in Picos de Europa**

### *The Jou Negro ice patch*

The Jou Negro ice patch is located in a glaciokarstic cirque in the northwest of the Central Massif of the Picos de Europa, on the northern face of Torre Cerredo peak. The

Jou Negro cirque was occupied during the LIA by a glacier covering 52 hectares (González-Trueba, 2006). This glacier has now been reduced to a remnant of glacial ice or ice patch, partially covered in clasts and without movement by deformation of its mass. This ice patch is still in retreat after having lost around 65% of the glacial surface it had in the LIA, and its volume has decreased considerably.

Geomorphological and thermal studies have been underway since 2005 on the Jou Negro ice patch. In 2007, the use of geomatic (topography, geodesy, photogrammetry) and geophysics applications began. The topography of the profiles and the outline was performed in 2008 (Serrano *et al.* 2011b). In 2009 and 2010 measurements were not taken as the ice patch was covered in seasonal snow, and in 2011 and 2012 the scanning technique was used with the IS total station.

Using the photogrammetric technique (11 converging photographs from the frontal moraine of the ice patch) and the 'Restitutor' program, a map of the ice patch in 2007 and 2008 was obtained (Fig. 12). On this map measurements have been made of the longitudinal profiles and losses and gains in ice volume. These results have been compared with those obtained directly in the field, giving results with a vertical precision of 30 cm (Matías *et al.* 2012).

## Discussion and conclusions

There is a wide variety of geomatic techniques that can be used for the study of mountain geomorphology. They all seek maximum precision in the monitoring of 3D displacements (horizontal and vertical). The technique applied must be adapted to dynamic conditions of placement and accessibility of tools and landscape topography, and so there is no ideal general technique.

In the different processes studied, greater or lesser precision is achieved depending on the field of distance and on the technique used. Laser scanning techniques with IS permit millimetre precisions in close measurements (lobes and ploughing blocks) although they are not dealt with in this paper. For more distant measurements, between 150 and 1000 m, on glaciers and rock glaciers, the precision obtained has maximum values of ± 4 cm, which are suitable for this kind of landform behaviour. Through the use of GPS-RTK, the precisions obtained are of ± 3 cm, ideal for monitoring creeping flows, and at the same time it is a fast, cheap and efficient method. Nevertheless, its application in mountain has some difficulties, such as in the presence of vertical walls that interrupt the satellite signal, and rebounds causing the multipath effect, such that its use in the Argualas rock glacier, the Jou Negro ice-patch or the La Paul glacier is impossible. In these cases other techniques must be applied, such as the total station or the TLS. From emplacement conditions, the rheology of the process and monitoring needs, the most appropriate geomatic technique must be chosen, though they have all given good results in measuring and monitoring geomorphological processes.

The rock glaciers analysed show a complex and varied pattern of movement, both spatial and temporal. Moderate horizontal displacements dominate except in Argualas, which has a greater velocity but which is in line with the velocities recorded in many alpine rock glaciers and in that of Corral del Veleta, which reflects a more significant thinning. Horizontal displacement reveals distinct dynamics, some landforms increase their displacement velocity towards the front and others that decrease moderately from the source towards the front. All show a thinning tendency, with rheological stretching and thermal diffusion processes, and sharp annual variations in flow velocity. From the horizontal and vertical velocities, two behavioural models can be established. The pulsating rock glaciers are the most dynamic with higher horizontal flow velocities and greater capacity to transfer debris from the wall. The second one are rock glaciers with small horizontal displacements and the predominance of thinning, a attenuated dynamics in response to thermal diffusion of the internal frozen bodies, as in the case of the Corral del Veleta rock glacier.

The study of the dynamics of glaciers and rock glaciers is a good indicator of the local repercussion of climate change, although such a small available data series prevents any conclusions from being reached. Therefore, we must continue monitoring in order to make comparisons with events in the future.

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**Figure captions:**

Fig. 1. Location of the study areas. Pyrenees: 1, Argualas; 2, Posets; 3, Maladeta. Cantabrian Range, Picos de Europa: 4, Central massif-Jou Negro. The Sierra Nevada: 5, Corral del Veleta.

Fig. 2. State of the Corral del Veleta rock glacier: (a) Photograph in August 2009; (b) Photograph in August 2010.

Fig. 3. Corral del Veleta rock glacier, evolution of the profiles during 2002–2009: (a) Transversal (profile 4); (b) Frontal (profile 5). The position of the profiles is shown in Figure 7.

Fig. 4. Upper photograph: General image of the front of the Corral del Veleta rock glacier taken by IS station. Lower photographs: Details of the same point during 2006, 2007 and 2008 (left to right).

Fig. 5. Net displacement (left to right) throughout the slope and horizontal advance of three points in the upper, central and lower parts of the front of the Corral del Veleta rock glacier.

Fig. 6. Triangulation network obtained with ‘Restitutor’ in the Corral del Veleta rock glacier. The red line indicates the outline of the rock glacier.

Fig. 7. Result of the scan with the position of the profiles in the Corral del Veleta rock glacier.

Fig. 8. Position of the Posets rock glacier (red) and the La Paul glacier (green). The photograph was taken from www.komandokroketa.org.

Fig. 9. Comparison between mean horizontal/vertical displacement among four European rock glaciers: Doesen (Alps), Posets (Pyrenees), Maladeta (Pyrenees) and Corral de la Veleta (the Sierra Nevada).

Fig. 10. Net dynamics of the Maladeta rock glacier (2008–2011).

Fig. 11. Evolution of the La Paul glacier using the comparison of profiles/year: (a) Representation of the longitudinal profile (465 m); (b) Profile evolution between 2009 and 2012.

Fig. 12. DEM obtained by photogrammetry ‘Restitutor’ (2008) and profiles represented in red. The small photograph shows a panoramic view of the Jou Negro ice patch.

Table 1. Dynamic evolution of a ‘control point’ of the Corral del Veleta rock glacier during the period 2001–2009 (end of August).

| Annual Period | Horizontal Movement (m) | Vertical Movement (m) |
|---|---|---|
| 2001–2002 | 0.13 | –0.15 |
| 2002–2003 | 0.20 | –0.38 |
| 2003–2004 | 0.05 | –0.15 |
| 2004–2005 | 0.32 | –0.75 |
| 2005–2006 | 0.27 | –0.58 |
| 2006–2007 | 0.23 | –0.58 |
| 2007–2008 | 0.14 | –0.52 |
| 2008–2009 | 0.07 | –0.35 |

Table 2. Dynamic evolution of a “control point” of the Corral del Veleta rock glacier during 2005-2008 with (July-August) and (August-July).

| Annual Period | Horizontal Movement (m) | Vertical Movement (m) |
|---|---|---|
| August 2005–July 2006 | 0.14 | –0.29 |
| July 2006–August 2006 | 0.13 | –0.29 |
| August 2006–July 2007 | 0.12 | –0.29 |
| July 2007–August 2007 | 0.10 | –0.28 |
| August 2007–July 2008 | 0.09 | –0.27 |
| July 2008–August 2008 | 0.06 | –0.24 |

Table 3. Dynamic evolution of ‘control point’ number 6 in the Posets rock glacier between 2001–2011.

| Annual Period | Horizontal Movement (m) | Vertical Movement (m) |
|---|---|---|
| 2001–2005 (4 years) | 0.45 | –0.13 |
| 2005–2006 | 0.08 | –0.09 |
| 2006–2007 | 0.10 | –0.09 |
| 2007–2008 | 0.07 | –0.03 |
| 2008–2009 | 0.07 | –0.05 |
| 2009–2011 (2 years) | 0.17 | –0.23 |