

# Remote Sensing Data for Monitoring Periglacial Processes in Permafrost Areas: Terrestrial Laser Scanning at the Hinteres Langtalkar Rock Glacier, Austria

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## Abstract

This article discusses long-range terrestrial laser scanning (TLS) as a monitoring technique focusing on recent geomorphic changes at the near-terminus zone of the Hinteres Langtalkar rock glacier (46°59'N, 12°47'E). This rock glacier is characterised by extraordinarily high movement rates at its lower part since the mid-1990s. The surface of this collapsing part of the rock glacier is characterised by a very disturbed topography, which causes problems for terrestrial as well as remote sensing monitoring methods. The lack of textural information makes approaches such as optical flow detection in grey-scale images non-applicable at this study area. Long-range TLS is completing the dataset with distance measurements leading to 3D point clouds, which are afterwards converted into accurate 3D models. Analysis of surface kinematics derived from five digital elevation models (DEM) obtained during TLS campaigns between 2001–2006 shows promising results covering this lack of data in unfavourable terrain.

**Keywords:** Austrian Alps; high-resolution DEM; LIDAR; rock glacier kinematics; terrestrial laser scanning.

## Introduction

Surface dynamics of rock glaciers are of increasing interest due to a high relationship to thermal conditions of permafrost areas. A few rock glaciers in the Alpine arc reacted to increasing air temperatures with extraordinarily high movement rates over several years (Roer et al. 2003). Most of them now show decreasing surface velocities (Delaloye et al. 2008). The Hinteres Langtalkar rock glacier changed its behavior most likely in 1994, moving over a prominent bedrock ridge into steeper terrain (Avian et al. 2005). Despite the remoteness of the location, a comprehensive monitoring network has been installed to get a better understanding of present processes, such as a geodetic survey (annually since 1998; Kienast & Kaufmann 2004), monitoring of the near-surface and surface thermal regime (since 2006 within the project ALPCHANGE), terrestrial laser scanning (2x2000, 2x2001, 2004, 2005, 2006, and 2007; cf. Bauer et al. 2003), and digital photogrammetry (1969, 1974, 1983, and 1997; cf. Kaufmann & Ladstädter 2004), providing data of different nature and in different resolutions in time and space. Long-range TLS ought to monitor the lowest part of the rock glacier to gather information about vertical surface changes and 3D movement rates.

## Geographical Setting

The cirque-system Hinteres Langtalkar (46°59'N, 12°47'E) is situated in the Schober Mountains within the Hohe Tauern Range (Central Alps, Austria) (Fig. 1). The cirque-system is a hanging valley at the orographic right side of the Gössnitz Valley. The cirque covers an altitudinal range between

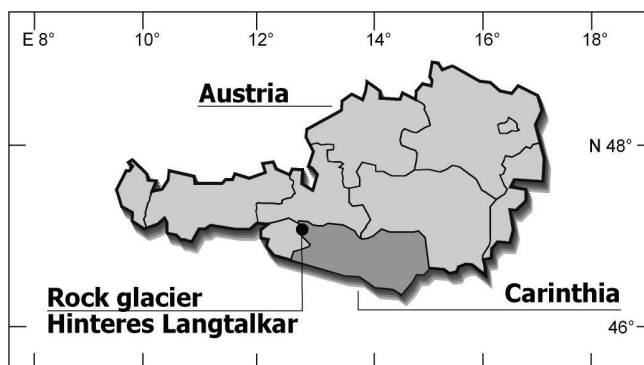


Figure 1. Location of Hinteres Langtalkar within Austria.

2300–3019 m a.s.l. The northwest facing tongue-shaped rock glacier itself covers the entire upper cirque floor with a lower margin at 2455 m a.s.l., root zones beginning in appr. 2700 m a.s.l. and a geometry of 600x300 m (Fig. 2). In general, rock glaciers are numerous in the Schober Mountains due to favorable geological conditions, leading to a total number of 77 intact rock glaciers (cf. Lieb 1998). Furthermore, the main range of the Central Alps (10 km to the N) causes pronounced continental climatic characteristics with a mean annual air temperature (MAAT) of 0°C at 2200 m a.s.l. and precipitation of ~1500 mm at 2000 m a.s.l. Glaciation in the Schober Mountains is developed only in some cirques and decreased rapidly during the last decades due to atmospheric warming (Kellerer-Pirklbauer & Kaufmann 2007). Auer et al. (2002) report a rising of the MAAT of 1.6°C since 1886 at the Hoher Sonnblick Meteorological Station (3106 m a.s.l., 15 km E of Hinteres Langtalkar) which is above the global average of 0.74°C (cf. IPCC 2007).

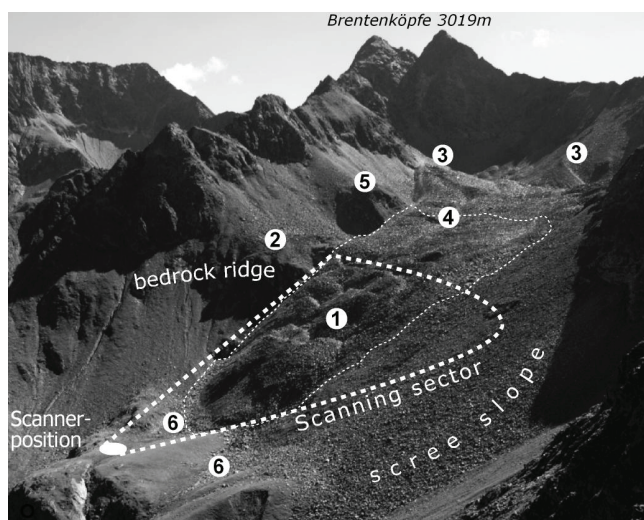


Figure 2. The cirque-system Hinteres Langtalar including the monitoring configuration. Codes in photograph: (1) Area of intensive rock glacier movement and disintegration, (2) prominent bedrock ridge partly covered by periglacially weathered debris, (3) latero-terminal moraine ridges dating from the Little Ice Age (~1850 AD), (4) crevasses on rock glacier indicating high strain rates, (5) meteorological station and (6) fresh boulders spreading over alpine meadows adjacent to the rock glacier front. The thin dashed line comprises the recently fast-moving part of the rock glacier. Scanner position is in a distance of ~90 m to the rock glacier front (Photograph by Viktor Kaufmann 24.08.2003).

## Methods

Laser scanning or LiDAR (Light detection and ranging) data have been used intensively for high mountain applications during the last decade. Examples are monitoring of glacier surface elevation changes by Airborne Laser Scanning/ALS (e.g., Baltasvias et al. 2001, Würlländer et al. 2004) or TLS (e.g., Avian et al. 2007), monitoring of periglacial processes using TLS (e.g., Bodin et al. 2008), hazard monitoring by TLS (e.g., Conforti et al. 2005, Rabatel et al. 2007) or snow cover monitoring using TLS (Prokop 2007). Primary resulting digital elevation models (DEM) are used to consider surface elevation variations to quantify, for instance, glacier dynamics. Determination of horizontal flow fields with high-resolution DEMs was presented by e.g., Bucher et al. (2006) with the aid of the software IMCORR, using concepts from aerial image matching (cross correlation in grey-scale images).

The ability of TLS to acquire high-resolution 3D data of surface structures makes this technique an interesting instrument for measuring high mountain environments. The integrated measurement system is capable of describing 3D motion and deformation of rock glacier surface within a few hours measurement. It is a time-of-flight system that measures the elapsed time of the pulse emitted by a photo-diode until it returns to the receiver optics. Maximum range depends on the reflectivity of surface (which is favourable for snow and debris-covered terrain) and atmospheric visibility (best for clear visibility, bad for haze and fog). A measuring range of

Table 1. Scanner parameters and values of the used instrumentation Riegl LPM-2k Long-range Laser Scanner.

Scanner parameter	Value (range)
Measuring range for:	
- good diffusely reflective targets	up to 2500m
- bad diffusely reflective targets	>800m
Ranging accuracy	+50mm
Positing accuracy	+0.01gon
Measuring time / point	0.25s to 1s
Measuring beam divergence	1.2mrad
Laser wavelength	900nm
Scanning range	
- horizontal	400gon
- vertical	180gon
Laser safety class	3B, EN 60825-1
Power supply	11-18V DC, 10VA
Operation temperature range	-10 to +50°C

up to 2000 m allows hazardous sites to be easily measured from a safe distance. Since each single measurement consists of a multitude of laser-pulses, different measurement modes ("first pulse," "last pulse," "strongest pulse") give proper results even during bad weather conditions and on poor surfaces like vegetated, moist, or roughly structured terrain that might otherwise lead to ambiguous measurements. Table 1 gives an overview of technical information concerning the long-range TLS Riegl LPM-2k.

### The measurement

Information at each individual measurement point includes the distance to the surface, the exact angular positions, the reflectance, and an estimated root mean square error (RMSE) of the distance measurement for reliability check. Measurements with an accuracy of distance better than 5 cm are automatically combined to a measurement grid. In general, several methodological, technical, and logistical problems are to be encountered when establishing an integrated monitoring system in this high alpine environment. These include among others the stability of device control software, the automatic sensor orientation, the high number of measurements, the compensation of weather influences, and the selection of reliable measurements. In addition, it is of particular importance to consider the highly heterogeneous surface in terms of material (rock, vegetation, and humidity in general) and structure. Many years of experience in the field of TLS (beginning in 2000) result in the development of a well-engineered, stable acquisition and analysis system, which in combination with expert field work, copes with all the conditions.

### Data processing

The TLS dataset is converted to a DEM, which is a digital raster representation of surface topography. In general, a horizontal reference surface is used. However, topology is often highly varying in terms of inclination; for example,

most of the potentially insecure surfaces are characterized by comparable steep fronts. In order to represent the surface data in best resolution, we generalize the DEM to an analytical reference model that best describes the global shape of the observed surface. To raster, a regularly spaced grid is defined on the reference model, and the “height” on every pixel is processed as normal distance to the reference surface. This data structure complies well with practical requirements such as difference measuring, volume change evaluation, and various visualization tasks. Neighbourhood relations of measured data points are directly described in the DEM structure; therefore, operating on DEMs allows quick access to the surface heights in a well-defined geometry. Direct mapping from the sensor spherical system to the DEM cartesian coordinate space would result in a sparse and non-uniform elevation map, especially at great distances. To avoid interpolation artefacts, the Laser Locust Method (Kweon et al. 1992) for DEM (Bauer et al. 1999) generation proves to be a robust tool for data acquisition from flat angles and supports error detection and utilization of additional confidence values provided by the range sensor. Since the DEMs of (temporally) different surface measurements are geo-referenced, simple differences between the DEMs reflect the changes in elevation. In consequence we can derive a full description of change in volume, spatial distribution of shape, or arbitrary profiles on the surface.

Single time-of-flight measurements are automatically combined to a measurement grid that enables the generation of a dense, enhanced DEM of the rock glacier surface. Repeatable sensor orientation is performed using reflective targets fixed on stable surfaces somewhere in the spherical field of view of the sensor. TLS measures the position of a theoretical, stable point on the surface within a given reference system.

#### *Surface motion analysis*

The DEM differences primarily only describe the vertical distance of the surface change. In order to understand the complex kinematics of rock glacier deformation – like the highly dynamic lowest part of the Hinteres Langtalar rock glacier – further knowledge about the 3D surface motion patterns is required. Among others, Käab et al. (2003) and Kaufmann & Ladstädter (2004) provide solutions to calculate the 3D motion by means of optical flow detection on the grey level images using correlation-based matching. This method is not applicable to the current laser scanning configuration, since similar reflectance conditions cannot be assured (basic requirement for robust matching). Tracking of objects on the surface can still be performed by the high-resolution surficial morphology provided by the DEM (despite the lack of textural information). Only on surfaces, where the structural surface changes are relatively small, state-of-art matching methods (cf. Paar & Almer 1993) obtain dense tracking vectors. In combination with the primarily obtained DEM differences mentioned above, this results in a three-dimensional vector field that describes the kinematic state of the rock glacier surface within the given periods.

Table 2: Periods of data acquisition and quality parameters. Data used for analysis discussed in this study are indicated in bold.

Period	total pts	used pts	PR <sup>(1)</sup>	OA <sup>(2)</sup>
07/2000	27048	26381	0.98	0.07
<b>08/2000</b>	<b>27048</b>	<b>26437</b>	<b>0.98</b>	<b>0.06</b>
07/2001	27048	26274	0.97	0.02
<b>08/2001</b>	<b>26910</b>	<b>26312</b>	<b>0.98</b>	<b>0.02</b>
<b>08/2004</b>	<b>20424</b>	<b>19818</b>	<b>0.97</b>	<b>0.02</b>
<b>08/2005</b>	<b>27048</b>	<b>17843</b>	<b>0.65</b>	<b>0.02</b>
<b>09/2006</b>	<b>7836</b>	<b>6048</b>	<b>0.77</b>	<b>0.02</b>
07/2007	6384	5739	0.90	0.02

(1) PR: point ratio = numbers of points used/total number of points measured. (2) OA: orientation accuracy [m].

#### *Cross check with auxiliary data*

To control the significance of the image matching data, cross checking with displacement rates from adjacent parts of the rock glacier were considered. Geodetic survey has been carried out in the middle part of the rock glacier (data kindly provided by V. Kaufmann) with its lower measurement boundary at the disintegrated lower part of the rock glacier. These campaigns provide verification data for the displacement vectors derived from image matching (Tab. 2). Some limitations in interpretation have to be considered due to distances of up to 60 m between scanning area and respective control points.

## Results

#### *Quality of data from image matching*

To get more information about interpretability, a review of data quality is essential. In 2000–2005 the total number of acquired points is high with 20,000 to 30,000 per campaign. The surface topography of a rock glacier consists of boulders with sizes between a few decimeters up to some metres. This is of crucial importance in the face of a true reproduction of the real surface and subsequently in receiving reasonable results in terms of surface motion patterns. Due to problems with energy supply in 2006 and 2007, the scanning increment had to be reduced during these campaigns, leading to total point numbers below 10,000. This low number is unfavourable for interpolation and obtaining a DEM for an area-wide precise motion analysis. Orientation accuracy is satisfying for all periods with 0.02–0.07 m (Table 2).

#### *Annual displacements from image matching*

Results of the rock glacier motion analysis are given in mean annual horizontal displacement rates.

2000–2001: The stepped lowest part differentiates clearly in velocity patterns. The ridges show mean annual displacement rates of 0.78 ma<sup>-1</sup> (max. 1.38 ma<sup>-1</sup>) (Fig. 3A; zone 1), 0.95 ma<sup>-1</sup> (max. 1.73 ma<sup>-1</sup>) (Fig. 3A; zone 2), 1.38 ma<sup>-1</sup> (max. 1.64 ma<sup>-1</sup>) (Fig. 3A; zone 3), and 1.35 ma<sup>-1</sup> (max. 1.75 ma<sup>-1</sup>) (Fig. 3A; zone 4). The adjacent scree slope at the orographic left side of the rock glacier shows constant movement rates of 0.02–0.06 ma<sup>-1</sup> over the entire scanning area.

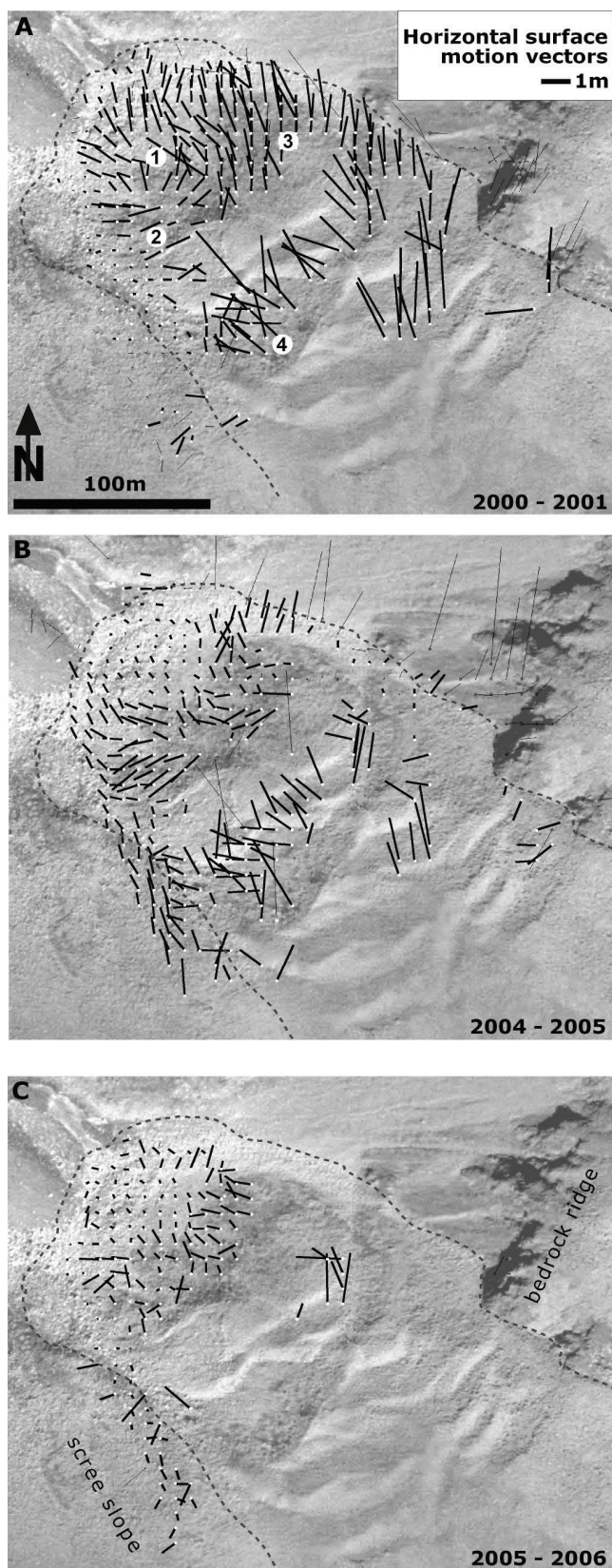


Figure 3. Horizontal displacement rates [ $\text{ma}^{-1}$ ] for three annual periods: (A) 2000/01, (B) 2004/05 and (C) 2005/06. Motion vectors are obtained from DEM differences, DEMs were derived from TLS data. Numbers (1-4) indicate zones of different behaviour in terms of surface velocity; for details refer to text (Orthophotograph ©Nationalpark Hohe Tauern, 1998).

2004–2005: Quality of velocity data from this period tends to be unsatisfying in some areas. Distinct differentiation between obviously moving and akinetic areas at the margin of the rock glacier is not possible. Velocity patterns do not indicate a distinct border between the scree slope and the rock glacier body. Furthermore, displacement rates of  $0.35\text{--}0.40\text{ ma}^{-1}$  seem to be unreasonable for this particular area. Surface topography on the rock glacier itself can be deduced from flow fields properly, as they show similar patterns as in the other periods.

2005–2006: Flow velocities and patterns are more difficult to interpret, although the ridges are detectable due to higher displacement rates ( $0.75\text{ ma}^{-1}$ ). The main front shows rates around  $0.15\text{ ma}^{-1}$ , the left margin is distinguishable towards the non-moving scree slope. Coarse point resolution leading to small spots of areal data does not allow reasonable interpretation of the upper part of the rock glacier tongue (cf. uppermost scanning area in Fig.2).

#### *Direction of annual displacement vectors*

Direction of movement at the terminus zone of the rock glacier shows outward movement of displacement vectors as expected. The ongoing development of the imbrication and the distinct shifting of detritus is visible in abrupt changes of the magnitude and direction of velocity vectors (Fig. 3, A-C, 1-4).

#### *Cross checking with results from geodetic survey*

Surface displacements derived from geodetic surveys in both periods at least coincide with displacement ranges obtained from TLS image matching (Tab. 3). However, substantial controlling is not possible due to poor data overlap. The main problems are hazardous working conditions for terrestrial monitoring, making geodetic or GPS surveys hardly feasible in the fast-moving sections of this rock glacier (up to  $2.38\text{ ma}^{-1}$  in 2003–2004). The steep rock glacier's front surface changes rapidly in shape, texture, and object distribution. This results in unfavorable conditions for analysis of optical data; viewing angles nearly vertical or area-wide changes in surface cause problems in automatic detection).

High values at some areas of the right margin of the rock glacier, the bedrock, and vegetated areas are results due to unfavorable scanning geometry and therefore are not taken into account as the exact rock glacier extent is known from fieldwork.

## **Discussion and Conclusions**

High-resolution DEMs derived from long-range terrestrial laser scanning are a good data basis for monitoring permafrost processes related to geo-hazards. Derivates like surface elevation changes and displacement vectors (in case of the availability of multi-temporal high-resolution DEMs) provide useful information about 3D surface dynamics. However, the quality of dataset s and concepts for calculating morphometric parameters have

to be assessed critically. Point density is a crucial factor (cf. Bodin et al. 2008) as is the quality of the measurement itself (high point ratio and total point number). Remoteness (sufficient energy supply) and atmospheric conditions (e.g., air humidity) are crucial limiting factors. The exemplary study of the Hinteres Langtalkar rock glacier demonstrates the importance of independent control data for evaluation, and the problems in acquisition of the latter. High landscape dynamics – frequent shifting of material, block falls – inhibit terrestrial surveys. Methodological problems in automatic data interpretation (e.g., inadequate texture for photogrammetry) complicate remote sensing approaches. The current monitoring configuration lacks additional control targets in the vicinity of the upper rock glacier tongue on the bedrock. Large differences in velocity values of different periods do not allow the interpretation of recent processes precisely at present.

In terms of velocity patterns, topography, and surface modification, some considerations are appropriate. In the lowest section of the rock glacier front, the surface velocity is decreasing to the margin as expected. Flow patterns are detectable in step-like relief which geomorphodynamically results in a distinct surface topography (Figs. 2, 3). High velocities within ridges and sharp limits at the ridge fronts to slower areas support this assumption. The formation of the micro-relief within ridges is also visible in the displacement patterns. Surface velocity patterns also exhibit distinct differences between the main rock glacier body and adjacent permafrost areas at the orographically left side. At the beginning of the steeper part of the lower rock glacier tongue, varying directed vectors in both periods indicate non-laminar movement of that particular part and are therefore interpreted as intense modification and frequent shifting of the disturbed surface.

As this particular rock glacier shows extraordinary surface velocity rates (cf. Avian et al 2005, Roer et al. 2005), upcoming TLS campaigns on the middle and upper section of the rock glacier would enhance knowledge about methodological problems due to the availability of independent data derived from geodetic measurements.

### Acknowledgments

These activities were carried out within the framework of the project ALPCHANGE (www.alpchange.at) funded by the Austrian Science Fund (FWF) through project no. FWF P18304-N10. We kindly acknowledge the help of Viktor Kaufmann (Institute of Remote Sensing and Photogrammetry, Graz University of Technology) for providing data from geodetic surveys. We also thank students of the Institute of Geography and Regional Science, University of Graz and the Institute of Remote Sensing, Graz University of Technology, Austria as well as several volunteers of the Nationalpark Hohe Tauern for their support during field campaigns.

Table 3. Annual horizontal displacement rates from geodetic measurements (based on unpublished data by V. Kaufmann) and image matching of adjacent areas.

Image matching displacement range [ma <sup>-1</sup> ]	Geodetic survey	
	Points	displacement [ma <sup>-1</sup> ]
2000/2001		
0.99 – 2.04	24	1.504
0.92 – 1.88	25	1.468
1.26 – 1.93	27	1.720
1.56 – 2.29	28	1.683
2004/2005		
1.05 - 1.98	24	2.017
0.97 – 1.89	25	1.734
no data	27	1.967
1.23 – 2.32	28	1.947

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