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Terrestrial laser scanning for rock glacier monitoring

A. Bauer & G. Paar
Institute of Digital Image Processing, Joanneum Research, Graz, Austria

V. Kaufmann
Institute of Geodesy, Graz University of Technology, Austria

ABSTRACT: The evaluation of glacier and rock glacier surface changes needs fast and cheap observation methods with an accuracy in the range of a few centimeters. Long-range laser scanners can achieve measuring distances up to a few kilometers of range. It is shown that a system using such a device is able to successfully perform an efficient long-term change survey. We report on the sensor and software setup, the logistics and the procedure for data evaluation to perform the proposed monitoring task. An experiment was carried out at the Hinteres Langtalkar rock glacier in the Hohe Tauern range of the Austrian Alps. The obtained results enable the access to high-resolution surface deformation data in all three dimensions. Relevant parameters and advantages of the systems as well as drawbacks and ideas for further improvements are pointed out. The operational system is available for further scientific exploitation.

1 INTRODUCTION

The automatic detection and evaluation of three-dimensional (3D) deformations, the generation of velocity fields and a full spatial high-resolution coverage of entire rock glaciers concerning these effects has only been made possible since imaging sensors in combination with computer-based data processing are available. Recent advances have been made both in the field of active remote sensing from space (Kenyi & Kaufmann 2003) and aircraft (Baltsavias 2001), aerial photogrammetry (Kaufmann & Ladstaedter 2003), and most recently with the availability of high-resolution optical remote sensing (Kääb 2002). Sharov & Gutjahr (2002) could show that change detection using SAR imagery is possible up to a height resolution of a few cm.

Most of these methods rely on sensing from nearly vertical viewing angles which means that steep slopes can only be covered with strong restrictions in measurement performance, if at all. Rock glaciers are creeping ice/rock mixtures and express themselves as highly complex in dynamics and shape. Active rock glaciers are characterized by steep fronts, causing most of the remote sensing based strategies to fail or degrade due to the above mentioned restriction. Moreover the front slopes rapidly change in shape, texture and object distribution due to debris fall, sliding and accumulations, causing standard change detection strategies to fail, since they rely on a high degree of similarity between data of different epochs.

We propose to use terrestrial laser scanning technology to overcome these problems. The necessary sensor setup is described and the various processing stages for data evaluation and visualization are pointed out. A digital elevation model (DEM) is generated for each measurement epoch and differences between DEMs are used to describe the 3D surface deformations. In addition, matching based on DEM structure provides horizontal motion vectors. The main focus of the paper is the application of the whole procedure to gain 3D high-resolution surface deformation data of the front slope of a highly active rock glacier in the Austrian Alps. The results obtained are shown numerically and graphically. The paper concludes with some discussions and recommendation for further technological improvements with respect to rock glacier investigation.

2 LASER SCANNING TECHNOLOGY

Scanning laser imaging has turned out to be an essential component of geotechnical disaster monitoring. The available laser devices have reached a technological fitness for this class of application just in the recent past (Paar & Bauer 2001). With a maximum range of more than 2 km to naturally reflecting targets, a wide field-of-view, and a ranging accuracy of better than 2 cm remote monitoring of events like the Schwaz rock slide, Austria, Summer 1999 (Scheikl et al. 2000; Paar et al. 2000) could be accomplished.

There are quite a few systems on the market with an operating range between near-range (up to 10 m) and 300 m (cyra 2002, mensi 2002). However, an integrated scanning device covering a range of more than 1 km for non-reflective targets is currently only offered by Riegl Laser Measurement Systems (Horn, Austria) (riegl 2002), namely the LPM-2 k (Figure 1, left). Its distance measurements are based on the time-of-flight principle, for each single measurement a burst of several hundred laser pulses are emitted. The reflected return pulses are analyzed by a digital signal processor (DSP) to compile a single distance measurement. Several measurement modes ("first pulse", "last pulse", "strongest pulse") can be selected for the method used by the DSP. The distance measurement unit is mounted on a pan and tilt orientation unit motorized by step engines, the exact pan and tilt angles are read out by encoders similarly to a motor theodolite. The device is controlled by an off-the-shelf PC via RS-232 interface which handles both the device control and the data transfer from the sensor to the PC. The control software on the scanning device allows the acquisition of an (almost) rectangular regular grid of measurements in sensor co-ordinate space, which is stored as one data file on the control PC. Each individual element within this grid consists of distance, reflectance value, the two angular measurements from the encoders of

Figure 1. Left: Laser scanner LPM-2k by Riegl Laser Measurement Systems. Right: Reflective reference target used for sensor orientation.

Table 1. Technical parameters of LPM-2 k by Riegl Laser Measurement Systems.

Scanner parameter	Value (range)
Measuring range for	
good diffusely reflective targets	up to 2500 m
bad diffusely reflective targets	$>$800 m
Minimum distance	10 m
Ranging accuracy	$\pm$25 mm
Positioning accuracy	$\pm$0.01 gon
Measuring time/point	0.25 s to 1 s
Measuring beam divergence	1.2 mrad
Laser wavelength	0.9 μm
Scanning range horizontal/vertical	400 gon/180 gon
Laser safety class	3B, EN 60825-1
Power supply	11–18 VDC, 10 VA
Operation temperature range	-10 to $+50$°C

the mounting unit, and an estimated RMSE of the distance measurement for reliability check. The relevant technical specification is shown in Table 1.

3 MEASUREMENT AND DATA PROCESSING

3.1 *Data acquisition*

Once a region of interest (ROI) for data acquisition has been defined, the control software causes the scanner to acquire the selected rectangular region in spherical coordinates. A data logging scheme allows the establishment of a data base making sure that all relevant original data and their relations remain complete, unique and unchanged.

3.2 *Sensor orientation*

Sensor orientation is done using reflective reference targets (Figure 1, right). An area around such a target is scanned with small grid width. A centroid localization algorithm on the resulting image gains the angular components of the target coordinates in the scanner spherical coordinate system. The distance is calculated as weighted average of all individual distance measurements covering the target.

Since the current version of LPM-2 k does not contain an electronic leveling sensor like standard theodolites it is necessary to determine all unknown position and orientation parameters using the reference targets. Current research aims at using natural such as (non-moving) distinct landmarks provided by the alpine environment (rock formations) for sensor orientation.

In addition to the determination of sensor orientation and location the reference targets can be used to determine compensation values for atmospheric effects on the distance measurements. The combination of the compensation values (multiplication factor as simplest approach) together with current transformation vector and rotation matrix is called *sensor state*, which is stored together with each measurement.

3.3 *Generation of the DEM*

A DEM is a regularly spaced grid in desired resolution on a horizontal plane. It is used to store the elevation as a vertical distance at the grid points.

This data structure best complies with the practical requirements such as difference measuring, volume change evaluation, and visualization thereof. Operating on DEMs allows quick access to the surface heights in a well-defined geometry.

As a first step during DEM generation each individual measurement (given in the spherical co-ordinate system of the laser scanner) is transformed into a georeferenced co-ordinate system by means of the sensor state (see Section 3.2) stored with the measurement.

Direct mapping from the sensor spherical system to the DEM Cartesian co-ordinate space would result in a sparse and non-uniform elevation map, especially at large distances and flat angles to the surface.

We use the Laser Locus Method instead (Kweon & Kanade 1992). It completely works in sensor space to compute the surface heights. For each grid point on the reference plane a hypothetical vertical line is inspected. Its intersection with the observed terrain is determined completely in spherical image space utilizing regularly spaced sensor measurements. This yields a dense DEM with predefined resolution and elevation measurement uncertainty.

3.4 *DEM comparison*

The resulting DEM from each measurement campaign represents a dated state of the region covered by the sensor measurements. Since the data is georeferenced, simple differences between the DEMs reflect the changes in elevation between the campaign dates.

3.5 *Motion field analysis*

The DEM differences describe only the vertical component of the surface change. In order to understand the complex kinematics of rock glacier deformation furthermore the knowledge on surface motion in all three dimensions is required.

Kääb et al. (2002) and Kaufmann & Ladstaedter (2000) provide solutions to calculate the 3D motion by means of optical flow detection on the gray level images using correlation-based matching. This method is not applicable to the current laser scanning setup, since it cannot be assured to have similar reflectance conditions, which is a prerequisite for robust matching.

Despite this lack of textural information the tracking of objects on the surface can still be performed by the high-resolution structural data provided by the DEM. State-of-art matching methods (Paar & Almer 1993) obtain dense tracking vectors only on regions where the structural surface changes are relatively small. In combination with the DEM differences mentioned above, this results in a three dimensional vector field that describes the kinematics state of the rock glacier surface between the given epochs.

3.6 *Postprocessing and visualization*

Since the DEM is given in a georeferenced co-ordinate system the visualization is mainly application driven and can be performed by standard commercial systems.

Current modes of visualization include color-coded overlay of motion vector components on ortho images, animated 3D views, arbitrary profiles and simple numerical values plotted within a predefined grid. Moreover volume calculations and various statistical protocols can provide an efficient and helpful tool for geoscientists.

4 EXPERIMENT AND RESULTS

4.1 *Experimental setup*

In the last years beginning with 2000 a set of experiments was started using this new technology for monitoring both glaciers and rock glaciers in the Austrian Alps. The test sites include the Pasterze glacier as well as a debris covered glacier and the Hinteres Langtalkar rock glacier, all located in the Hohe Tauern National Park. In this paper we focus on the Hinteres Langtalkar rock glacier which was measured in July and August 2000 and 2001, respectively (Table 2). The ongoing sliding process and the steepness of the rock glacier front slope prevent standard geodetic measurements as well as surface motion analysis by photogrammetric methods. A detailed description of the situation including maps can be found in Kaufmann & Ladstaedter (2003).

For sensor orientation a geodetic network of 5 reference points was provided by the Institute of Geodesy. For each of the 4 individual measurements the sensor orientation was obtained independently. The sensor location was selected at a distance of about 100 m to the foot of the rock glacier front slope (Figure 2). The resolution of the measurements was mainly limited by the acquisition time. A grid width of 0.5 m could be established at the center of the front slope, corresponding to 140×200 single measurements.

4.2 *Results*

Figure 3 shows the original laser measurement data. Figure 4 shows the resulting DEM. Figure 5 shows the difference DEM within a period of one year. The elevation change varies from -2.0 m to $+1.5$ m. The bright areas indicate areas with large elevation change of the surface. Stable areas outside the rock glacier

Table 2. Measurement campaigns at the Hinteres Langtalkar rock glacier.

	12.7. 2000	21.8. 2000	28.7. 2001	24.8. 2001
Measuring expenditure	9 h	5 h	6 h	5 h
Orientation accuracy [m]	0.07	0.06	0.02	0.02
Valid measuring points	26517	26437	26274	26312

show an RMSE of 11 cm and a systematic difference of 3 cm in height.

On Figure 6 a debris flow event is documented. The spatial distribution of the observed mass movement can be identified and numerically evaluated. The flow has been caused by subsurface drainage after heavy rainfall. The first indications of this event can already be recognized at the diagonal vertical structure on the center of Figure 2.

The result of the DEM structure based motion field analysis is shown on Figure 7, combined with the vertical change obtained from the DEM differences. A horizontal motion up to $1.5\,\mathrm{m\,a^{-1}}$ and a vertical surface deformation up to $1.2\,\mathrm{m\,a^{-1}}$ could be detected. Within stable areas (e.g. upper right) no statistically significant change in all three components can be observed. The distribution of the detected motion directions is consistent with the assumption that the

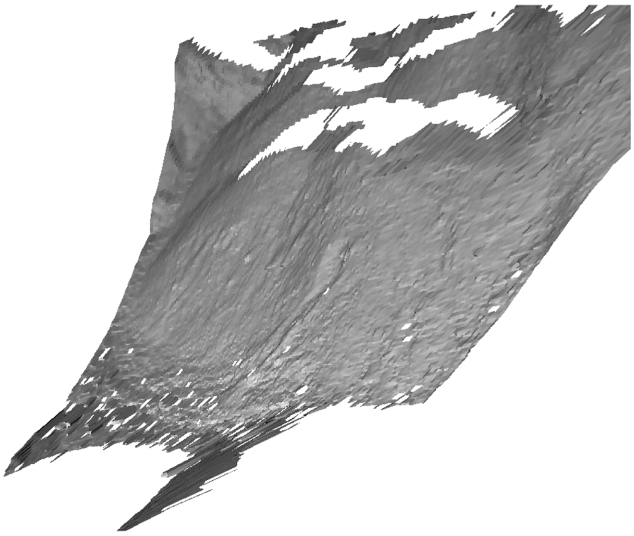

Figure 4. Digital elevation model (rendered) after geocoding. White areas within the DEM could not be measured due to occlusions.

Figure 2. Measurement campaign of July 2000 at the Hinteres Langtalkar rock glacier in the Austrian National Park Hohe Tauern.

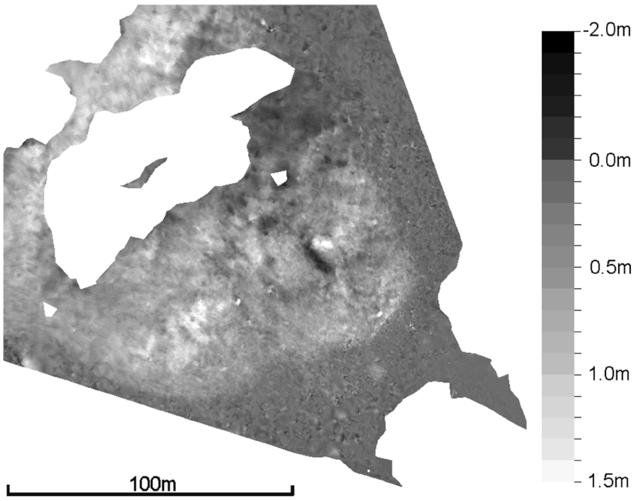

Figure 5. Difference DEM from August 2001 to August 2000 (greycoded).

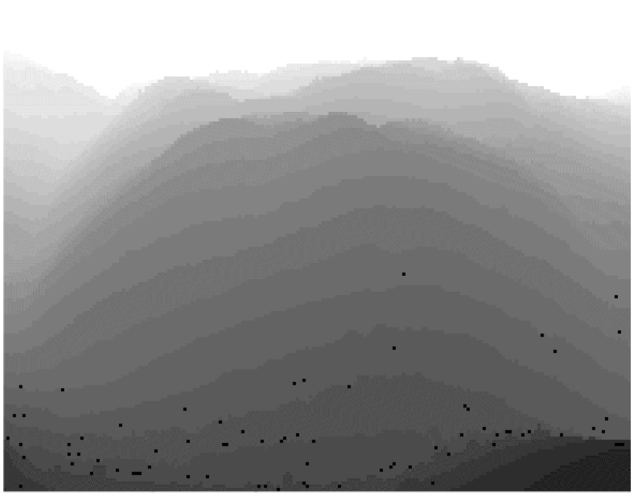

Figure 3. Laser scanner distance measurement of July 12, 2000 (greycoded: black = near, white = far).

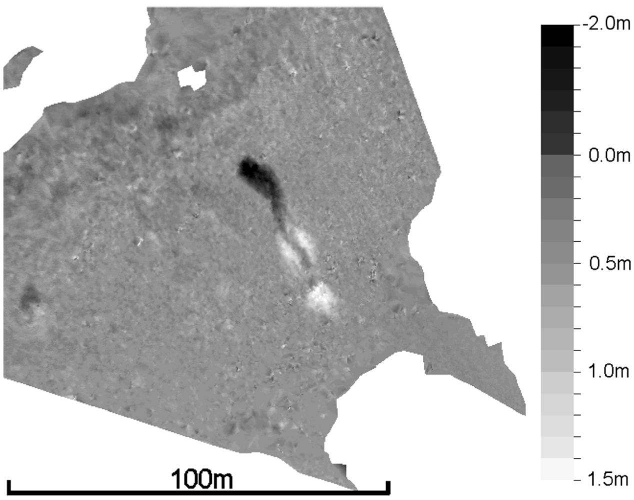

Figure 6. Part of difference DEM from August 21, 2000 to the first campaign of July 12, 2000 (greycoded).

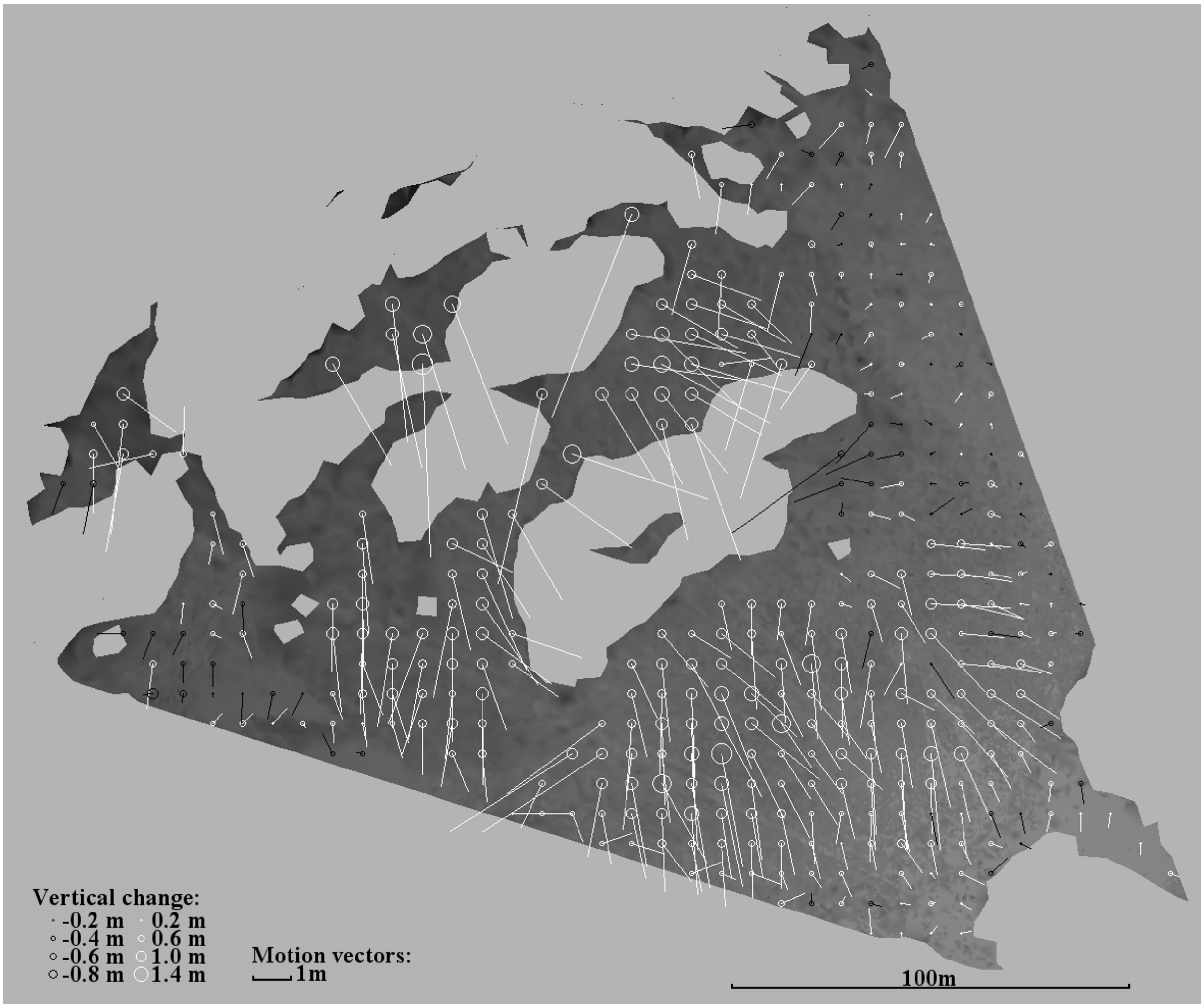

Figure 7. Results of surface structure matching: Change between August 2000 and August 2001. Circles describe vertical changes, the vector field displays the horizontal movement.

overall motion is mainly induced by gravity action, although local irregularities may be caused either by local sliding events or errors of the matching process.

4.3 *Discussion*

The full end-to-end chain of rock glacier monitoring using a long-range terrestrial laser scanner is demonstrated in the experiment. Small debris falls as well as accumulation of debris and scree can be detected, the local mass movements can be evaluated down to single cubic meters. Dangerous geodetic field work in areas of difficult direct access can be completely avoided.

The experiments, however, showed also some potential for improvements as well as basic deficiencies.

– A major tradeoff is currently found between measurement time and resolution, but further developments in terms of scanner hardware will reduce the necessary measurement time significantly. In the case of the described experiment, the available sensor range (up to 2000 m) was by far enough for the given requirements (maximum distance 300 m).
– Another disadvantage of the method is the necessity to have reference targets for sensor orientation. Current research tends to solve this problem with natural targets, a test data set has already been acquired during the described campaigns.
– Each data acquisition site typically requires at least one day of field work, currently two persons are needed to carry the equipment, which is mainly caused by heavy power supply units. For areas of high interest (e.g. in case of georisk areas) the system can be established in a stationary mode to continuously monitor all seasons. In this case the costs of the system in the range of several ten-thousands of Euros have to be taken into account.

5 TECHNICAL REALIZATION

The framework described in this paper has been technically realized in an operational system that is available for scientific and commercial use. The DIBIT Geoscanner (dibit 2002) consists of all necessary modules, namely

1 Data acquisition unit for stationary and mobile automatic scanner control and data storage.
2 Orientation unit to identify the sensor orientation within a geodetic network.
3 Visualization unit to visualize the changes obtained by the system and to integrate them into formats well known by the user community.

All the results are immediately available, which makes the laser scanner monitoring a valuable tool for hazard prediction, risk evaluation and scientific fieldwork. Such a system can be either operated non-stationary, or installed within less than two days at any location having access to power supply and mobile telephone connection. All relevant data processing and visualization can be done on-site which makes the system extremely useful for efficient research in the field.

The system is scalable to scientific requirements. Forthcoming discussions with geoscientists will influence further developments.

6 CONCLUSION

A terrestrial laser scanning system was presented that is capable of acquiring high resolution 3D data of surface structures. It is shown that the system is capable of describing 3D motion and deformations of rock glacier fronts within a single day's measurement campaign, including logistics and evaluation. Only one person is necessary to operate the system. The results gathered through the last 2 years of monitoring have been presented and analyzed.

The major advances of the terrestrial laser scanning of rock glaciers therefore lie in the accessibility of steep slope areas, together with the ability to identify and evaluate both global (velocity field distribution) and local (debris flow, avalanches) permafrost effects.

We could show an operational end-to-end solution for terrestrial laser scanning data acquisition, evaluation and visualization. The system is ready to be incorporated into creeping mountain permafrost monitoring frameworks, optionally as stationary or mobile unit. The proposed terrestrial laser scanning method can extend, complement and verify state-of-the-art remote sensing strategies for rock glacier monitoring.

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