*Permafrost, Phillips, Springman & Arenson (eds)*
*© 2003 Swets & Zeitlinger, Lisse, ISBN 90 5809 582 7*

# Quantitative analysis of rock glacier creep by means of digital photogrammetry using multi-temporal aerial photographs: two case studies in the Austrian Alps

V. Kaufmann & R. Ladstädter
*Institute of Geodesy, Graz University of Technology, Austria*

ABSTRACT: This paper presents a special method of measuring surface deformation and flow velocity of creeping rock glaciers based on digital photogrammetry. The underlying concept of automatic measurement of 3-D surface displacement vectors in time-series of multi-year digital aerial photographs is explained. In contrast to standard photogrammetric procedures, image matching is not carried out in the space of the original photos but in quasi-orthophotos derived from the use of rough and preliminary digital terrain models. A software package called ADVM (Automatic Displacement Vector Measurement), written in Visual C++ for running on a Windows-based PC, has been developed. The software has been tested within the framework of two case studies which comprise the spatio-temporal analysis of the kinematic behavior of three active rock glaciers in the Austrian Alps. The adjacent Inneres and Aeusseres Hochebenkar rock glaciers in the Oetztal Alps and the Hinteres Langtalkar rock glacier located in the Schober group, Hohe Tauern range, are investigated. Selected results of the photogrammetric evaluation are presented numerically and graphically.

## 1 INTRODUCTION

### 1.1 *Rock glacier creep*

Rock glaciers, perennially frozen ice/rock mixtures under periglacial conditions, are of great interest to permafrost researchers (Haeberli 2000). Active rock glaciers creep downslope by force of gravity with annual flow velocities ranging from centimetres to metres. Due to predominantly steady-state flow/creep over long time periods rock glaciers display a lava flow-like landform with furrows and ridges often alternating with each other at the surface. This reflects the internal deformation process of the permafrost body. Firstly, purely descriptive information about the current kinematical state of a rock glacier is of importance. Is the rock glacier active or not, and if it is active, what does the spatial distribution of its surface velocity field look like? In order to support more detailed studies, such as system analysis through complex modelling (cp. Kaeaeb et al. 2003), long-term monitoring programs have to be considered. These should comprise precise information about the geometric behaviour of the rock glacier surface. Future global warming is predicted to have an particular impact on rock glaciers, by indirectly influencing the overall kinematic state of rock glaciers by changing the surface flow velocity and surface height. Steady-state creep may be disrupted by other factors however, e.g. landslides.

### 1.2 *Measurement methods of rock glacier creep*

Quantitative information about the kinematic behavior of rock glaciers can be obtained either by field survey or through the application of airborne or spaceborne remote sensing techniques. The former method requires rock glacier field data to be physically entered by a person either with GPS instrumentation, or with a reflector when undertaking a classical geodetic survey with a total station. Exceptions are two other terrestrial remote sensing methods, terrestrial laser scanning and terrestrial photogrammetry. The first method is still in the investigation stage (Bauer et al. 2003), whilst the latter is currently not utilised. Aerial photogrammetry is presently the most powerful technique for obtaining precise and reliable geometric information about the surface of a rock glacier. In addition, satellite-based differential SAR interferometry (DInSAR) offers new possibilities in monitoring rock glaciers (Kenyi & Kaufmann 2003). Kaeaeb & Vollmer (2000) provide concise information on the various aerial photogrammetric measuring techniques. Among these techniques digital photogrammetry is the latest and most promising development.

Borehole deformation measurements using slope indicators and magnetic rings are not considered in this context.

### 1.3 *Digital photogrammetry – a modern technology*

During the last decade digital photogrammetry has become a mature technology. The use of analytical plotters has diminished since digital photogrammetric workstations are more frequently utilised in modern photogrammetric production workflow. Such workstations are quite user-friendly and their handling is no longer restricted to specialists only. Digital photogrammetry benefits from a high degree of automation. Several photogrammetric tasks, such as the relative orientation of a stereomodel and the generation of digital terrain models (DTMs), can be fully automated. If we consider the mapping of the 3-D surface velocity field of a rock glacier, identical terrain features, such as large boulders have to be tracked within the multi-temporal aerial photographs. This can be best accomplished by means of digital image matching. Kaeaeb & Vollmer (2000) have developed a special photogrammetric software, CIAS, which measures a dense field of horizontal surface displacement vectors based on individual orthophotos.

In the following section we are going to present a quite similar approach. Our solution however is more rigorous and as a consequence a higher degree of accuracy in the 3-D displacement/flow vectors can therefore be expected.

## 2 OUTLINE OF THE PROPOSED DIGITAL PHOTOGRAMMETRIC METHOD

### 2.1 *Analog-to-digital conversion of photographs*

Digital photogrammetry is based on the evaluation of digital images. This implies the digitisation of any given analogue aerial photographs (film transparencies). In order to achieve high geometric and radiometric quality, a high-precision photogrammetric scanner must be used (Gruber & Leberl 2001). We do not recommend the use of low-cost desktop image scanners since their geometric stability is not sufficient to obtain the anticipated photogrammetric accuracy. Even photogrammetric scanners may cause erroneous results, such as systematically wrong velocity fields in cases where the scanner is not well calibrated or is malfunctioning (Kaufmann & Ladstaedter 2002). If a photogrammetric scanner is not available, the necessary image scans can be provided through service companies. In the near future high-resolution digital cameras will make the classical film-based aerial camera obsolete.

### 2.2 *Automatic computation of 3-D displacement vectors*

#### 2.2.1 *The basic concept*

The basic concept of the automatic measurement of 3-D flow vectors in digital multi-temporal photographs for rock glacier studies was already formulated by Kaufmann and Ladstaedter in 2002. Precise 3-D measurements can be performed using digital orthophotos, as first described by Baltsavias (1996). For the sake of simplicity and clarity we consider two stereopairs of aerial photographs acquired at two different time periods t1 and t2 as shown in Figure 1. It is assumed that the appropriate photogrammetric orientation, (interior, relative and absolute orientation) is available and that the elements of exterior orientation

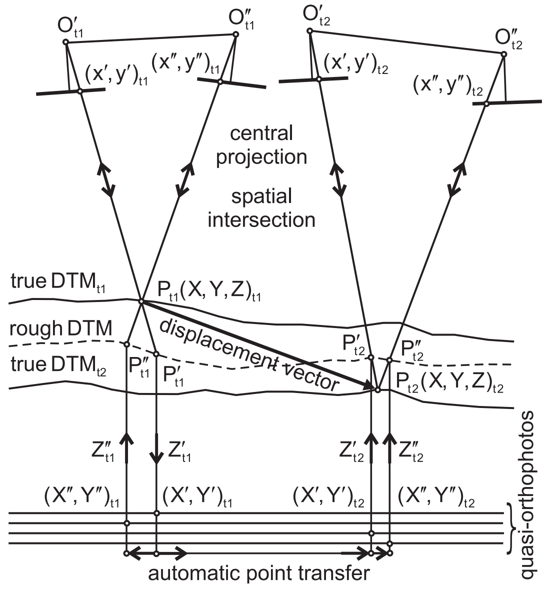


Figure 1. Computation of 3-D displacement/flow vectors using quasi-orthophotos.

of each individual photograph are therefore known. If we want to determine the 3-D displacement vector shown we have to track point $P_{t1}$, defined as a prominent terrain feature on the rock glacier surface at time period t1, and then find its corresponding location $P_{t2}$ on the deformed surface at time t2. Since the respective DTMs, denoted as "true" DTMs, are not available at this processing stage, we consider a rough, preliminary DTM. In fact, two preliminary DTMs, each representing the surface of a time period, may be used. Four quasi-orthophotos can be computed using the rough DTM. As a result, each of the four quasi-orthophotos can be geometrically superimposed on top of the other. Since the rough DTM deviates from the true DTMs and point P has moved from its original position, the ground projections of the point location of P in the quasi-orthophotos do not coincide. The next step is the automatic point transfer, the detection of the corresponding/homologous points in the respective quasi-orthophotos. We propose a hierarchical multi-resolution approach using area-based grey level matching techniques (computation of the normalized cross-correlation coefficient and/or least-squares matching). We start with the point location $(X', Y')_{t1}$ and search for the three other positions as shown in Figure 1. After finding them we can back-project all four points into their respective photographs. With a spatial intersection of homologous rays the 3-D location of the monitored point can be determined for the two time periods. The vector pointing from $P_{t1}$ to $P_{t2}$ defines the 3-D displacement vector. The described solution is stringent. If the rough DTMs are identical to the true ones, no disparities, such as image parallaxes, will be detected between quasi-orthophotos belonging to the same time period. This means that the given orthophotos are already true, perfect orthophotos. Furthermore, this means that the remaining non-zero disparities between these kinds of orthophotos of different time periods are due to surface deformation. This, of course, is only valid if the elements of photogrammetric orientation are free of errors and the image scans are perfect.

#### 2.2.2 *An example*

A representative example of practical application of the above-mentioned basic concept of computation of 3-D displacement vectors is shown in Figure 2. The sample set has been taken from work described later in Section 3.

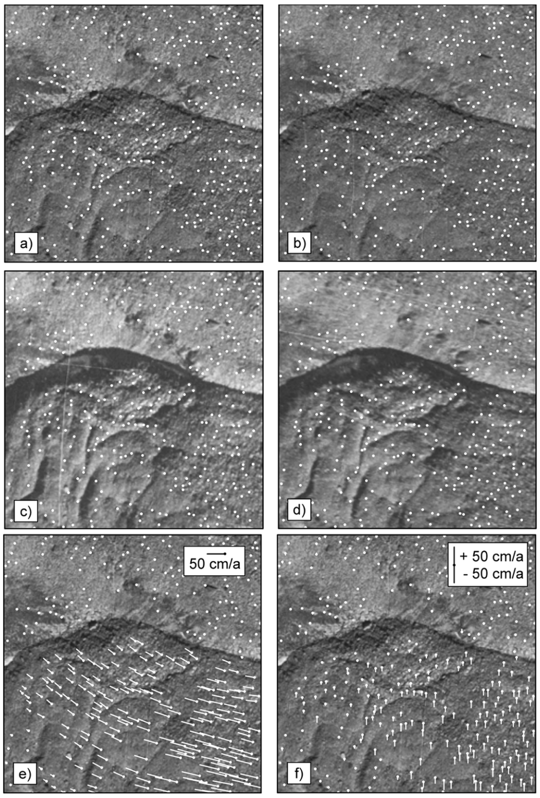


Figure 2. The above example refers to the geometric analysis of the Inneres Hochebenkar rock glacier for the time period 1953–1969 (see also Section 3). The location of the area of interest (150 m × 150 m) is outlined in Figure 4. Figures 2a and 2b (stereopair of 1953) and Figures 2c and 2d (stereopair of 1969) are the quasi-orthophotos (pixel size of 25 cm) which have been generated using the photogrammetrically derived DTM of 1953. Distinct points were automatically selected using the Foerstner interest operator in the quasi-orthophoto of Figure 2a. From the set of points obtained 334 points (white dots) were successfully transferred into the other three orthophotos. Point locations were predicted using the normalized cross-correlation coefficient, whereas high-precision image matching was carried out using the least-squares matching technique. The obtained mean annual 3-D movement of the points is presented graphically in Figures 2e (horizontal flow vectors) and 2f (vertical flow velocity). The upper third of the area, which is not part of the rock glacier itself, does not show significant movement since it is stable bedrock. Image source: 1953 (image scale 1:15,000, frame size 18 cm × 18 cm, flying height 5915 m); 1969 (image scale 1:29,100, frame size 23 cm × 23 cm, flying height 7080 m); aerial photographs: © BEV-2000, Vienna.

### 2.3 *ADVM software*

A special Windows-based software package called ADVM (Automatic Displacement Vector Measurement) has been developed at the Institute of Geodesy, Graz University of Technology (Ladstaedter 2001). This software is written in Visual C++. A graphical user interface facilitates the definition of the various configuration files. All time-consuming processing is done in batch mode. The core of the software consists of four main modules, 1) computing of interest points, 2) prediction of corresponding points, 3) point transfer by means of least-squares matching, and 4) spatial intersection. Additionally, some 25 utility modules are available for pre- and post-processing.

Furthermore, quick visualizations of the results are obtained using SURFER (Golden Software, Inc., USA). Standard photogrammetric tasks are carried out using an analytical plotter (DSR-1 of Kern) and/or a digital photogrammetric workstation (ImageStation of Z/I Imaging).

## 3 TWO CASE STUDIES

The applicability of the proposed digital photogrammetric method for detecting, mapping and quantifying, rock glacier creep has been tested and assessed within two case studies. Three rock glaciers located in two different study areas in Austria have been investigated (Fig. 3).

### 3.1 *Hochebenkar rock glaciers*

In the first case study we have analysed two rock glaciers, Aeusseres and Inneres Hochebenkar, located in adjacent cirques in the Oetztal Alps (Fig. 4). Detailed permafrost mapping in the region of the Hochebenkar rock glaciers has previously been undertaken (Haeberli & Patzelt 1982). The Aeusseres Hochebenkar rock glacier is well-known because of its long record of velocity measurements (Pillewizer 1957, Vietoris 1972, Schneider & Schneider 2001). Nagler et al. (2001) have carried out a motion analysis of both rock glaciers using satellite-based differential SAR

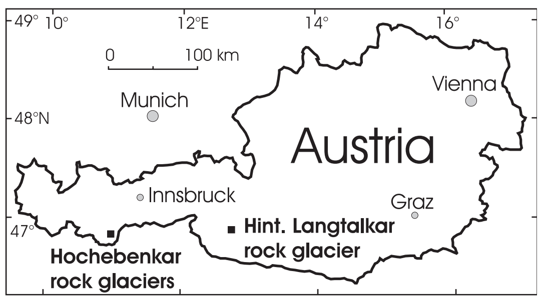


Figure 3. Location map of both study areas.

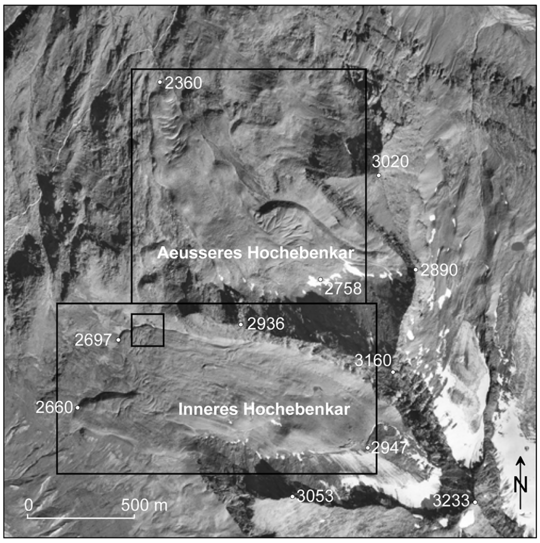


Figure 4. Orthophoto (September 11, 1997) of the study area showing both Hochebenkar rock glaciers. The boxes delineate the areas shows in Figures 2, 5 and 6, Aerial photograph: ©BEV-2000, Vienna.

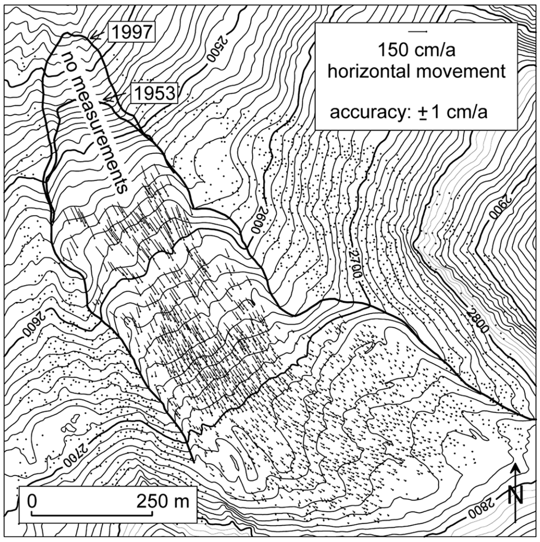


Figure 5. Flow vector field at Aeusseres Hochebenkar rock glacier for the time period 1953–1997. Corresponding terrian features could not be detected in the sliding zone at the lower end of the rock glacier. Max. mean flow velocity: 131 cm/a.

interferometry. A synoptic view of the rock glacier creep with respect to good spatial and temporal resolution however could only be achieved by means of aerial photogrammetry. Aerial photographs (8 different surveys between 1953 and 1997) have been acquired from the aerial photograph archive of the Austrian Federal Office of Metrology and Surveying (BEV), Vienna. Details on the various processing steps of the digital photogrammetric workflow are given in Kaufmann & Ladstaedter (2002). They also summarize the main findings of the spatio-temporal analysis of the kinematic behavior of both rock glaciers. In this paper we present the graphical representations of the spatial distribution of the mean annual horizontal movement (flow velocity) of both rock glacier surfaces for the time period 1953– 1997 (Figs 5 and 6).

Virtual flyovers and a computer animation (video film) showing the results obtained can be downloaded from http://www.cis.TUGraz.at/photo/viktor.kaufmann/animations.html or http://video.tu-graz.ac.at/tugbroadcast/.

### 3.2 *Hinteres Langtalkar rock glacier*

The Hinteres Langtalkar (HLK) rock glacier (Fig. 7) is located in the Schober group, Hohe Tauern range. Part of the Hohe Tauern National Park, the Schober group contains many rock glaciers (Buchenauer 1990, Lieb 1996). In 1997 an aerial survey was flown taking photographs of a nearby glacier. In these photos a peculiar landslide which had affected the snout of the HLK rock glacier could be identified (cp. Figs 8 and 10). Since then scientific investigations have analysed this remote, inaccessible rock glacier. Geological, as well as hydrological studies have already been carried out by Krainer & Mostler (2001). In order to study the rock glacier morphodynamics (past, present, future) in greater detail four different observation methods, geodetic surveying, photogrammetry, terrestrial laser scanning and DInSAR, were applied. A geodetic network consisting of 38 observation points was set up in 1998/1999. Figure 8 shows the horizontal displacement vectors obtained for the time period 1999–2000. Aerial photographs from 9 different years between 1954 and 1999 were made available through the aforementioned archive of aerial photographs. Based on this information, the landslide must have occurred between 1992 and 1997. The topographic situation of HLK rock glacier is quite similar to that of the Aeusseres Hochebenkar rock glacier (cp. Fig. 9 with Fig. 5). The snouts of both rock glaciers have moved into steeper terrain, evidently triggering the sliding process. The zone of very active movement at HLK rock glacier can only be investigated remotely (Bauer et al. 2003). Due to extending flow/creep of the main permafrost body some prominent transversal crevasses have developed, reflecting high longitudinal strain rates ($4.5-17.0 \times 10^{-3}\,a^{-1}$). The largest crevasse (2664 m) was already present in 1954. The geodetic and photogrammetric measurements confirm that the creeping process of the upper, intact part of the rock glacier has been constant over many years. The speed however may be increasing, with rates of $130\,cm\,a^{-1}$ measured for 1969–1974 compared to $280\,cm\,a^{-1}$ for 1997–1998. Figure 9 shows the photogrammetrically derived mean annual horizontal flow velocity (isotachs) for the time period 1997–1998. In order to compare these values with the geodetic measurements of 1999–2000,

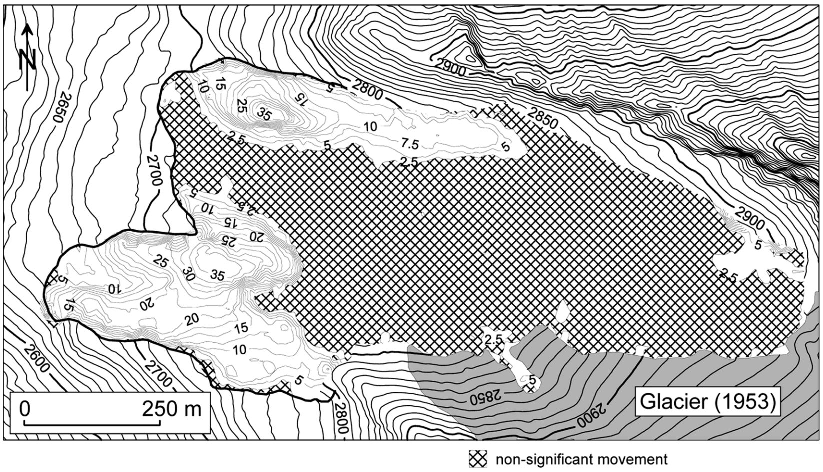


Figure 6. Mean annual horizontal flow velocity (cm $a^{-1}$) at Inneres Hochebenkar rock glacier for the time period 1953–1997 (44 years). Two active zones of surface movement can be recognized. The result shown is comparable with the findings of Haeberli & Patzelt (1982). The southern zone is composed of two independent flow units, which merge to form the visible tongue. The northern flow unit which is characterized by extreme surface lowering ($-8.9$ m) and a cluster of bended ridges and furrows can be seen. During the Little Ice Age this rock glacier was partly covered by a glacier (Hochebenferner). Now this glacier has retreated (1997: size 15.8 ha, cp. Figure 4).

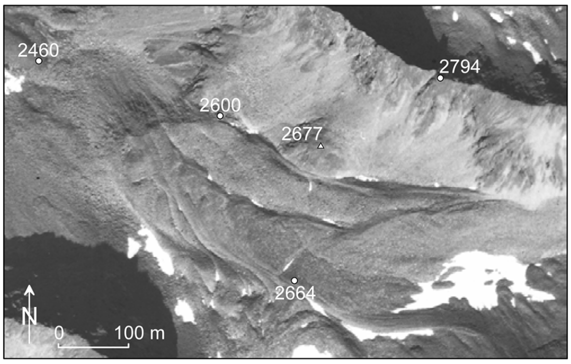


Figure 7. Orthophoto (September 4, 1991) of the study area showing the Hinteres Langtalker rock glacier. Photo: ©BEV.

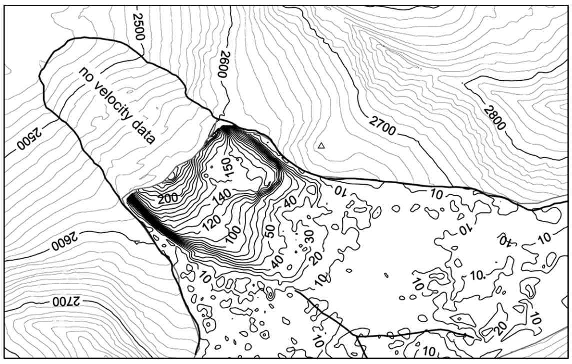


Figure 9. Mean annual horizontal flow velocity (cm $a^{-1}$) at Hint. Langtalkar rock glacier for the time period 1997–1998.

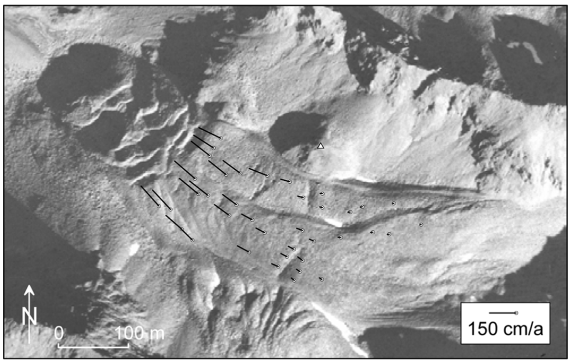


Figure 8. Horizontal displacement vectors (1999–2000) derived from geod. measurements. Orthophoto: September 12, 1999.

equivalent flow vectors were interpolated at the 38 observation points (Fig. 10). Flow directions are identical, the velocities obtained exceeding the geodetically derived values (rate of 25% for the lowermost points). A zone of large extending flow, which refers to the highest strain rate given above, can be seen in the orographic right side of the rock glacier. The volume of the landslide is estimated photogrammetrically at 170,000 $m^3$. The mass balance of the whole permafrost body for the time period 1974–1998 is significantly negative, with decay estimated to be greater than 45,000 $m^3$.

## 4 CONCLUSIONS AND OUTLOOK

We have introduced a digital photogrammetric concept for monitoring rock glacier surface deformation using digitized multi-temporal aerial photographs. A special software package, ADVM, has been developed and successfully tested in the framework of two case studies from the Austrian Alps.

The present concept incorporates state-of-the-art digital photogrammetric methods. Moreover, it follows an open system concept. This means that the determination of the elements of the exterior orientation of aerial photographs, the generation of digital terrain models, and finally the digital rectification process for generation of the (quasi-)orthophotos can be done with any commercially available digital photogrammetric systems. This approach offers great flexibility in the workflow since the modular structure allows for appropriate solutions according to available resources (software, hardware and financial budget) and the anticipated accuracy of the result. Change detection between multi-temporal quasi-orthophotos is the task of the ADVM software. Quasi-orthophotos offer at least two advantages, that aerial photographs of any scale and orientation can be considered in the monitoring task and disk space can be kept comparatively low. A demo

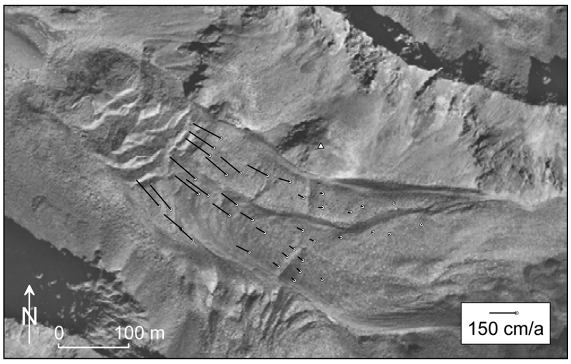


Figure 10. Horizontal displacement vectors interpolated from the data shown in Figure 9. Orthophoto: August 26, 1998.

version of the ADVM software can be downloaded from http://www.cis.tugraz.at/photo/richard.ladstaedter.

The computation of 3-D displacement vectors is done automatically, but we still refer to the current version as "semi-automatic", since optimum processing parameters, such as window size for image matching, have until now only been found iteratively with user interaction. Moreover, erroneous results and systematic offsets have to be detected and eliminated by an experienced user who is familiar with the specific monitoring task. This work can be quite time-consuming.

We are therefore planning to upgrade the ADVM software with additional features, such as multi-photo, geometrically constrained matching, which will also include a simplified rock glacier flow model.

We have learned from the case studies that the success of high-precision image matching depends very much on the quality of the photo textures involved. Furthermore, shadows and snow patches cause problems, and erroneous results in image matching can be expected.

## ACKNOWLEDGMENTS

The authors wish to thank M. Gruber from Vexcel Imaging Austria for scanning the aerial photographs free of charge. G. Kienast was responsible for the geodetic measurements. His work is greatly appreciated.

## REFERENCES

Bauer, A., Paar, G., Kaufmann, V. 2003. Terrestrial laser scanning for rock glacier monitoring. In *Proceedings of the 8th Int. Permafrost Conf. Zurich, Switzerland* (this volume).

Baltsavias, E.P. 1996. Digital ortho-images – a powerful tool for the extraction of spatial- and geo-information. *ISPRS Journal of Photogrammetry and Remote Sensing* 51: 63–67.

Buchenauer, H.W. 1990. Gletscher- und Blockgletschergeschichte der westlichen Schobergruppe (Osttirol). In *Marburger Geographische Schriften* 117: 276 p.

Gruber, M. & Leberl, F. 2001. Description and evaluation of the high quality photogrammetric scanner UltraScan 5000. *ISPRS Journal of Photogrammetry and Remote Sensing* 55: 313–329.

Haeberli, W. 2000. Modern research perspectives relating to permafrost creep and rock glaciers: A discussion. *Permafrost and Periglacial Processes* 11(4): 290–293.

Haeberli, W. & Patzelt, G. 1982. Permafrostkartierung im Gebiet der Hochebenkar-Blockgletscher, Obergurgl, Ötztaler Alpen. *Zeitschrift für Gletscherkunde und Glazialgeologie* 18(2): 127–150.

Kaeaeb, A. & Vollmer, M. 2000. Surface geometry, thickness changes and flow fields on creeping mountain permafrost: Automatic extraction by digital image analysis. *Permafrost and Periglacial Processes* 11(4): 315–326.

Kaeaeb, A., Kaufmann, V., Ladstaedter, R., Eiken, T. 2003. Rock glacier dynamics: Implications from high resolution measurements of surface velocity fields. In *Proceedings of the 8th International Permafrost Conference, Zurich, Switzerland* (this volume).

Kaufmann, V. & Ladstaedter, R. 2002. Spatio-temporal analysis of the dynamic behaviour of the Hochebenkar rock glaciers (Oetztal Alps, Austria) by means of digital photogrammetric methods. In *Grazer Schriften der Geographie und Raumforschung* 37: 119–140.

Kenyi, L.W. & Kaufmann, V. 2003. Measuring rock glacier surface deformation using SAR interferometry. In *Proceedings of the 8th Int. Permafrost Conf. Zurich, Switzerland* (this volume).

Krainer, K. & Mostler, W. 2001. Der aktive Blockgletscher im Hinteren Langtal Kar, Gößnitztal (Schobergruppe, Nationalpark Hohe Tauern, Österreich. In *Wissenschaftliche Mitteilungen aus dem Nationalpark Hohe Tauern* 6: 139–168.

Ladstaedter, R. 2001. Blockgletscher-Monitoring mittels Digitalphotogrammetrie. *Publikationen der Deutschen Gesellschaft für Photogr. und Fernerkundung* 10: 459–466.

Lieb, G. 1996. Permafrost und Blockgletscher in den östlichen österreichischen Alpen. In Leitner, W. (ed.), *Beiträge zur Permafrostforschung in Österreich; Arbeiten aus dem Institut für Geogr. der Karl-Franzens-Univ. Graz* 33: 9–125.

Nagler, T., Mayer, Ch., Rott, H. 2001. Feasibility of DINSAR for mapping complex motion fields of Alpine ice- and rock-glaciers. In *Proc. 3rd Int. Symp. on Retrieval of Bio- and Geophysical Parameters from SAR Data for Land Applications, Sheffield, UK, 11–14 September 2001*.

Pillewizer, W. 1957. Untersuchungen an Blockströmen der Ötztaler Alpen. In Geomorphologische Abhandlungen. *Abhandlungen des Geographischen Instituts der freien Universität Berlin* 5: 37–50.

Schneider, B. & Schneider, H. 2001. Zur 60jährigen Messreihe der kurzfristigen Geschwindigkeitsschwankungen am Blockgletscher im Äusseren Hochebenkar, Ötztaler Alpen, Tirol. *Zeitschrift für Gletscherk. u. Glazialg.* 37(1): 1–33.

Vietoris, L. 1972. Über den Blockgletscher des Äußeren Hochebenkars. *Zeitschrift für Gletscherkunde und Glazialgeologie* 8(1–2): 169–188.