CHANGE DETECTION OF A MOUNTAIN SLOPE BY MEANS OF GROUND-BASED PHOTOGRAMMETRY: A CASE STUDY IN THE AUSTRIAN ALPS

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ABSTRACT

The surface topography of mountainous areas is often subject to continuous spatio-temporal changes due to gravitational and climatic forces. In this paper we focus on periglacial phenomena, e.g., permafrost creep and other gravitational mass movements (solifluction, etc.) Various in-situ and other non-contact (remote sensing) measurement techniques can be applied in order to derive metric information of surface deformation and flow velocity. In the present work we have investigated the potential of ground-based (terrestrial) photogrammetry for monitoring mountain slopes of local extent (typically 10^2 - 10^3 m) using a low-cost digital camera and applying a digital photogrammetric workflow. A case study has been carried out in the Ötztal Alps, Austria. We selected the Outer Hochebenkar rock glacier since it has been subject to intensive research for many decades. Ground-based photogrammetry is feasible, because photogrammetric baselines can be easily established on the opposite slope, thus allowing multiple stereoscopic coverage of the area of interest. The main task of the case study was to derive 3D displacement vectors of the surface. The paper describes the various pre-processing steps involved, i.e. camera calibration, scanning of the analog photographs and digital resampling for obtaining geometrically refined images. Control points needed for exterior orientation were taken from existing aerial photographs. The measurement of dense fields of displacement vectors is carried out using the in-house developed *ADVM* (Automatic Displacement Vector Measurement) software, which was originally developed for the monitoring of rock glaciers using aerial photographs. The results of comparative analysis are presented numerically and graphically. The paper finally summarizes the main findings and specifically addresses the pros and cons of applying low-cost digital consumer cameras in ground-based monitoring tasks in mountainous areas.

1 INTRODUCTION

The Outer (German: Äusseres) Hochebenkar rock glacier (46°50'N, 11°01'E) is located in the Ötztal Alps, Austria close to the village of Obergurgl (see Fig. 1). It is a tongue-shaped rock glacier, about 1 km in length and 42 ha in size. The rooting zone is located at about 2800 m a.s.l. and its snout reaches down to about 2360 m a.s.l. This rock glacier is characterized by a comparatively high flow velocity of several m/yr and periodically changing flow rates. Below 2580 m, which marks the end of the steady-state creeping zone, the snout has moved into very steep terrain. In this area landslides have occurred due to the specific topographic situation. Detailed permafrost mapping of this region has been carried out by Haeberli & Patzelt, 1982.

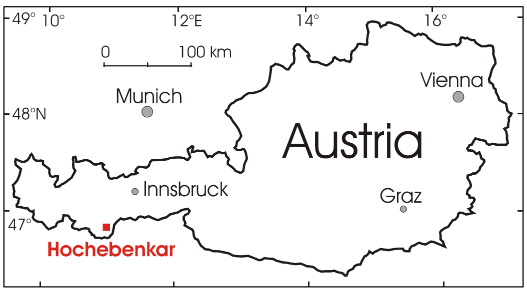


Figure 1. Geographical location of the Outer Hochebenkar rock glacier.

The Outer Hochebenkar rock glacier is well known for its long record of velocity measurements. Early ground based photogrammetric surveys were performed by W. Pillewizer in 1938, 1953 and 1955, using photographs oriented orthogonal to the main flow direction (Pillewizer, 1957). Geodetic measurements were started in 1951 by L. Vietoris (Vietoris, 1972) and have been continued from 1972 until the present by H. Schneider. A review of this long record of measurements is given in (Schneider & Schneider, 2001). Morphodynamics have also been studied using differential

SAR interferometry (Nagler et al., 2001) for a 35 day period in 1995. Furthermore, aerial photogrammetry has been used to study the Outer as well as the adjacent Inner Hochebenkar rock glacier using eight epochs of aerial survey in the time period between 1953 and 1997 (Kaufmann & Ladstädter, 2002a).

In this paper, however, photographs from terrestrial surveys organized by members of the Institute of Remote Sensing & Photogrammetry (Graz University of Technology) have been used. The first survey was carried out in 1986 on September 23rd , a second one in 1999 (Sept. 9th) and a last one in 2003 (Sept. 19th). A photogrammetric evaluation of these photographs has not been performed prior to this study. This paper will present preliminary, yet unpublished results obtained by automated digital processing of the images.

2 TERRESTRIAL PHOTOGRAMMETRIC SURVEY

2.1 Camera equipment

Four different camera systems were used in the surveys of 1986, 1999 and 2003:

(a) Phototheodolite Zeiss Photheo 19/1318 with 190 mm lens, 13 cm x18 cm glass plates,
(b) Linhof Metrika with 150 mm lens, 9 cm x 12 cm black-and-white negative film (vacuum magazine), réseau glass plate (99 crosses),
(c) Rolleiflex 6006 with 150 mm lens, semi-metric camera, 6 cm x 6cm color reversal film, réseau plate (121 crosses),
(d) Nikon D100 with 50 mm lens, digital still camera, 6 MegaPixel CCD array, IBM 1 GByte Microdrive.

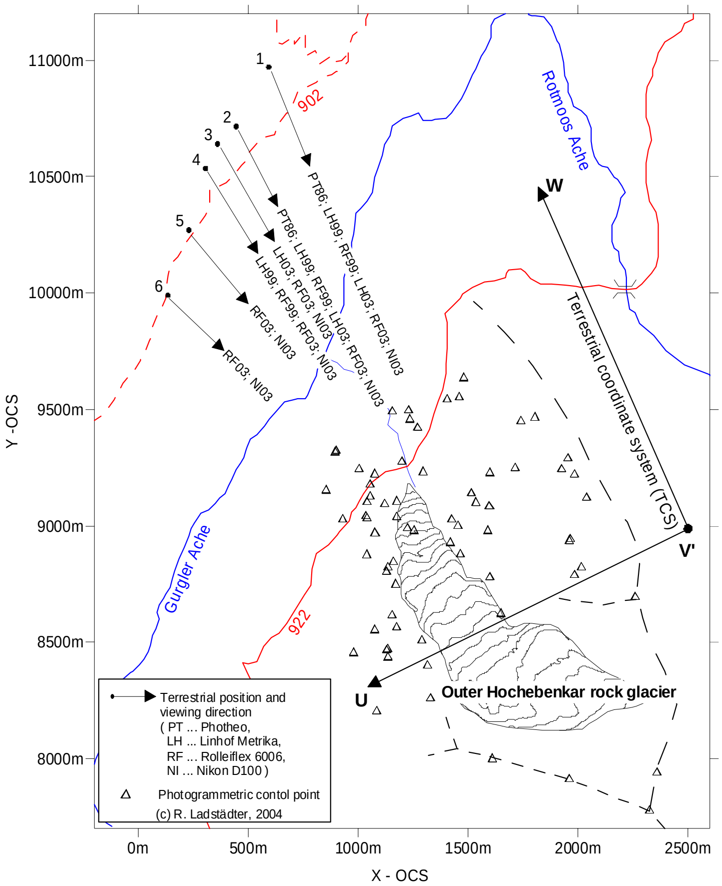
(a) *(b)* *(c)* *(d)*

Figure 2. Camera equipement used for terrestrial photogrammetric survey.

Remarks: The Photheo 19/1318, which was built in 1961, can no longer be used because photographic glass plates are no longer available. In addition, roll film for the Linhof Metrika large format camera is becoming more and more expensive because this type of photographic material can only be ordered in large quantities.

2.2 Terrestrial photogrammetric setup

Six camera positions were used during the three observation epochs. They are all located on the opposite slope at about the same height (2450-2600 m a.s.l.) as the lower part of the Outer Hochebenkar rock glacier. They can easily be reached taking hiking trail 902, which leads from the village of Obergurgl to the Ramol hut (3005 m a.s.l.) on the western side of the Gurgl Valley (see Fig. 3).



Both points 1 and 2 were installed during the 1986 survey, forming a 294 m long baseline. It is assumed by the authors that this is a similar configuration to that used by W. Pillewizer in 1953 and 1955 (Pillewizer, 1957). A stereo pair was taken using the Zeiss Photheo 19/1318 and parallel viewing directions.

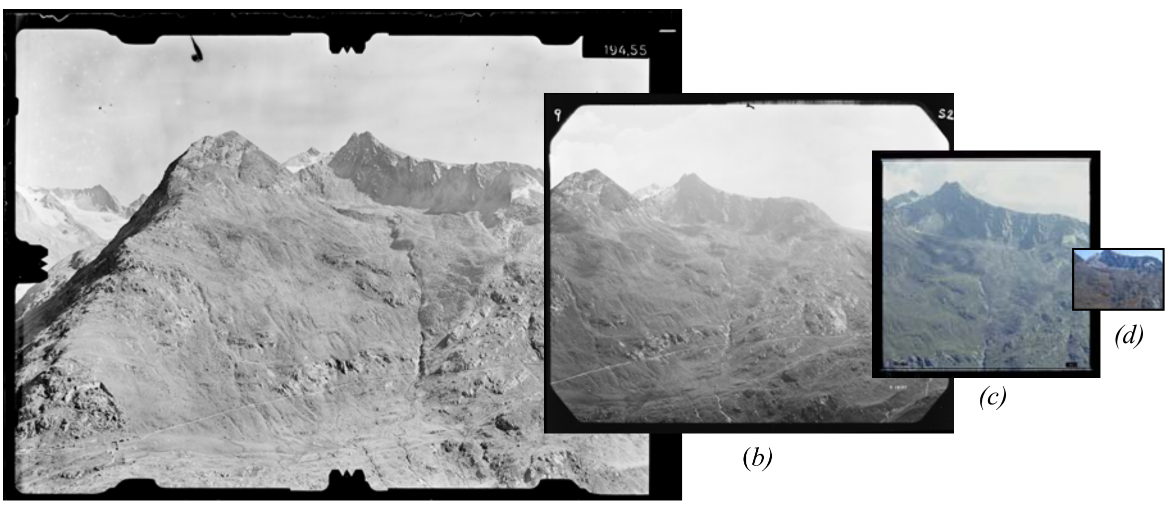
The baseline was extended to the south by a third point (number 4) in the survey of 1999, forming a second baseline of 225 m length. Photographs were taken using a Linhof Metrika and a Rolleiflex 6006 semi-metric camera.

Finally, in the 2003 survey, point no. 3 was added (in between points no. 2 and 4). Photographs were taken from points 1, 2 and 3 using our last film roll available for the Linhof Metrika. Photographs were also taken from points 1-4 and two additional but more distant points (5 and 6) using the Rolleiflex 6006 and Nikon D100 cameras. The total distance between points 1 and 6 is quite large, i.e. 830 m. The viewing directions from this camera positions therefore become largely convergent ($\Delta\varphi\approx26°$).

Figure 3. Map of the terrestrial survey of the Outer Hochebenkar rock glacier.

2.3 Image format, scale and geometric resolution

All analog images were digitized using the UltraScan 5000 photogrammetric scanner of Vexcel Imaging Austria in order to combine analog and digital image data in a single, digital photogrammetric workflow. A scan resolution of 10 µm was used for all images. The geometric accuracy is assumed to be better than ±3 µm (Gruber & Leberl, 2001).



(d)

(c)

(b)

(a)

Figure 4. Comparison of the image formats of the cameras (a)-(d) used.

The size of the resulting image scans and the digital image data obtained from the Nikon D100 camera is given in Table 1. Image scale, given for a mean object distance of 1800m, varies for each camera system according to the focal length.

Camera	*Mean scale*	*Image size [pixel]*	*Resolution_v (vertical plane)*	*Resolution_h (ground plane)*
Photheo 19/1318	1 : 9500	18000 x 13000	9.5 cm	19 cm
Linhof Metrika	1 : 12000	12000 x 9000	12 cm	24 cm
Rolleiflex 6006	1 : 12000	6000 x 6000	12 cm	24 cm
Nikon D100	1 : 36000	3008 x 2000	28 cm	56 cm

Table 1. Image scale, size and geometric resolution.

Geometric resolution in object space is computed by multiplying the pixel size with the mean image scale. This gives a theoretical value (denoted as "*Resolution_v*"), which only holds for a vertical plane normal to the viewing direction located in the mean object distance. Note also that the size of the Nikon D100 CCD sensor element is 7.8 µm. Compared with the Rolleiflex 6006 scan, the image scale is thus smaller by a factor of three but the image resolution is only about 2.4 times lower.

In order to directly compare this resolution with the ground sampling distance (GSD) of an aerial photogrammetric survey, a small part *s* of the rock glacier surface is considered (see Figure 5). The mean inclination angle α of the lower part of the rock glacier is about 26°. Assuming a horizontal viewing direction, the size of the projected surface part *s″* can be calculated by multiplying *s* by the scale factor *sin(α)*. The scale factor for a projection into the ground plane (yielding *s′*) on the other hand is *cos(α)*. The projected surface part *s″* therefore corresponds to the element *s′* in the ground plane, which can be derived by the following formula: $s' = s'' \cdot \cot(\alpha) \approx s'' \cdot 2.0$. This value is given in the last column of Table 1 ("*Resolution_h*").

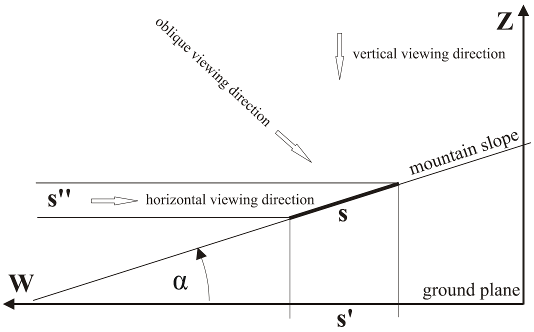


Figure 5. Geometric resolution depending on the viewing direction.

2.4 Image quality

The image quality of the scanned glass plates (Photheo) is reduced by a relatively high contrast. The Linhof Metrika scans on the other hand are of excellent quality, which allows to easily identify blocks of medium scale (~1 m in diameter) on the rock glacier surface. The Rolleiflex scans, being of the same scale, are of slightly reduced sharpness, but image resolution is still considered to be sufficiently high. Visual inspection is disturbed, however, by the many réseau crosses which are necessary for geometric correction of the images. The image data of the Nikon D100 camera is stored in 24bit (RGB) TIFF format. The surface of the rock glacier cannot be resolved in detail (only some of the biggest rocks can be identified) because of the low geometric resolution, which is made even worse by the internal color interpolation process.

3 IMAGE PRE-PROCESSING

3.1 Camera calibration

Calibrated cameras must be used for metric point reconstruction. The following intrinsic parameters must thus be known for each camera system:

- Coordinates of the principle point (x_0, y_0),
- Focal length c,
- Lens distortion (coefficients k_1, k_2, k_3),

Since no calibration certificate was available for the Photheo 19/1318, the coordinates of the four fiducial marks were determined by metric measurements in the scanned image. The focal length has been determined by the manufacturer and is exposed on each glass plate.

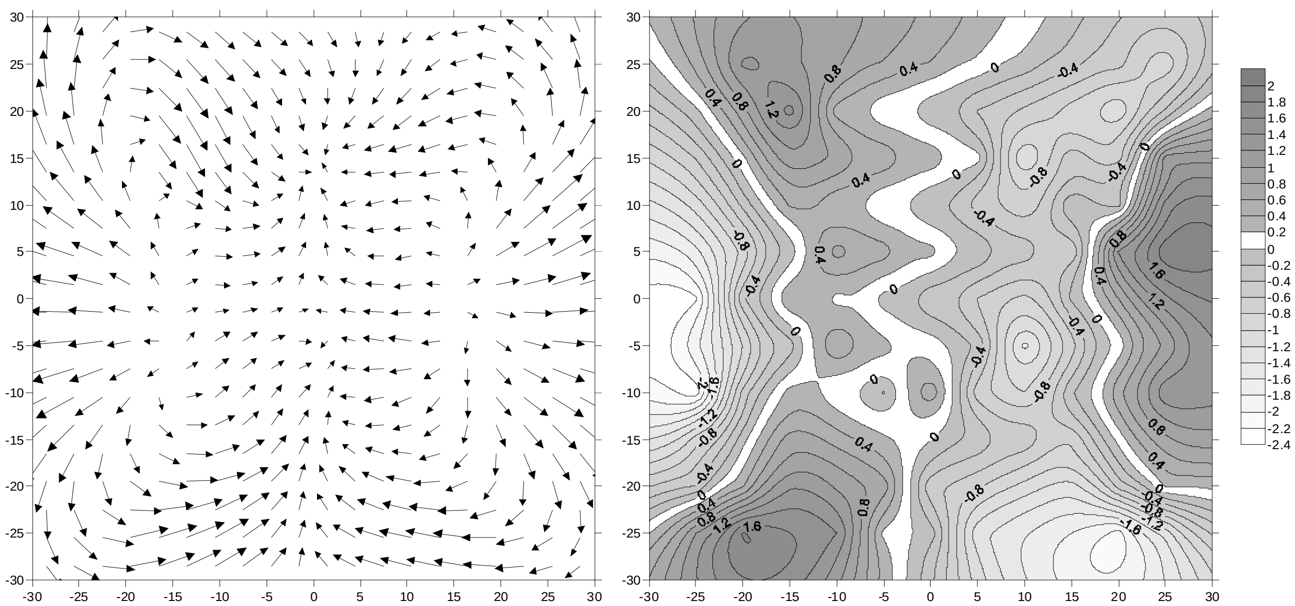
Camera calibration for both the Linhof Metrika and the Rolleiflex 6006 was performed using a 3-dimensional test field at our Institute. The Nikon D100 digital camera was calibrated using the PhotoModeler 4.0 software from EOS Systems Inc. using the calibration procedure proposed in the user manual. Intrinsic parameters are derived from several oblique views of a 2-dimensional calibration target (see Figure 8) by a bundle adjustment.

3.2 Modeling film deformation and film unflatness

Geometric errors are introduced if the film is not exactly plane at exposure time. This problem occurs with the Rolleiflex 6006, because of the film transport mechanism used. The same problem also exists with the Linhof Metrika, though in a very reduced form because of the built-in vacuum magazine.

These geometric errors can be determined by measuring the réseau crosses in the image scan and comparing their position with the calibrated positions of the réseau glass plate. The transformation from image to camera coordinates can be computed in an adjustment by using an affine transformation model. The residuals computed for each réseau cross can be interpreted as a result of the film unflatness (see Figure 6a) while the linear part of the film deformation is compensated by the computed affine transformation.

A special software tool called *ReseauCorr* was developed to remove these geometric errors. This program evaluates the measured réseau cross positions and estimates affine transformation parameters from the calibrated réseau cross positions. The X- and Y-component of the remaining film deformation caused by film unflatness (measured in [pixel]) is estimated for the whole image by the Krige interpolation algorithm (see Figure 6b). The resulting distortion maps are used for unwrapping the image using a resampling procedure. Rows and columns of the output image correspond to the X- and Y-axes of an orthogonal camera coordinate system, with its origin in the image center. The resulting images can thus be treated the same way as images obtained directly by a digital sensor in the further processing steps.



(a) *(b)*

Figure 6. Residuals measured in a Rolleiflex 6006 image (a) and derived distortion map for the x-component (b).

In the corrected image, the position of the réseau crosses is exactly known and they are oriented strictly in row/column direction. This allows for digital removal of the réseau crosses (which are no longer needed) by interpolating the neighboring gray values (see Figure 7). This fully automated process has been integrated in the *ReseauCorr* utility as an additional feature.

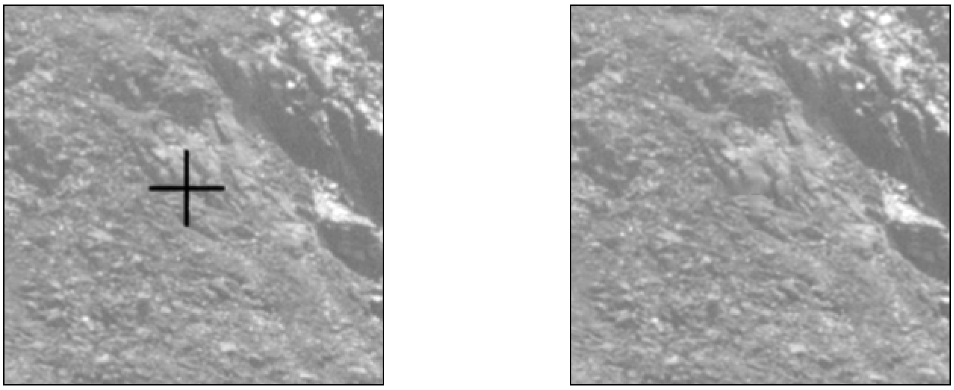


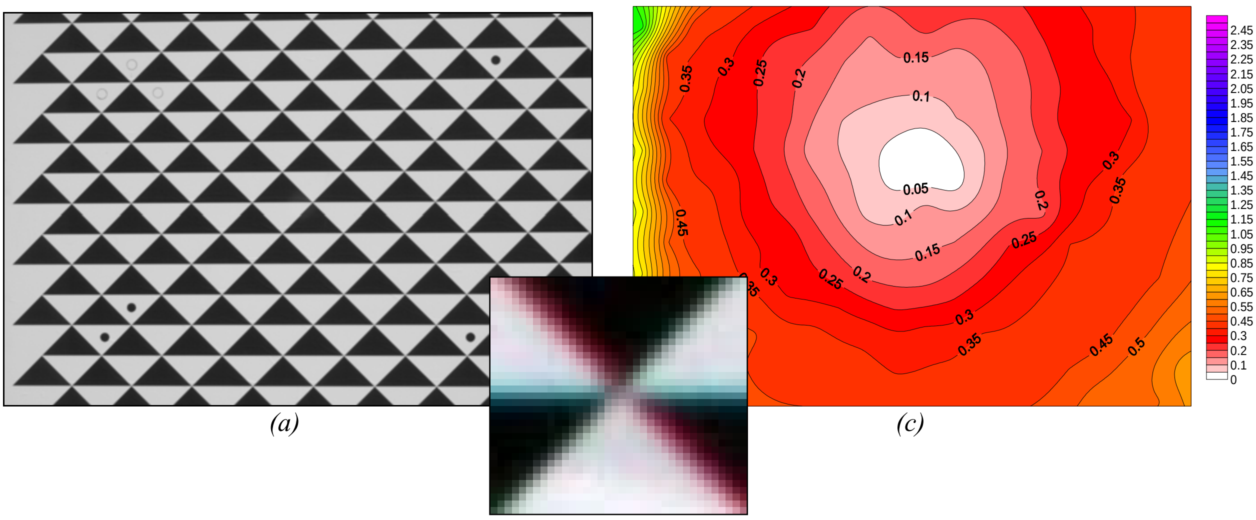
Figure 7. Digital removal of réseau crosses in a Rolleiflex 6006 scan.

3.3 Correction of lens distortion

The software tool *DistCorr* was specially developed to remove lens distortion from images taken by a digital camera. By providing the three coefficients of radial lens distortion, the original image can be unwrapped in a resampling procedure. The program also offers the possibility to center the image onto the principle point and to choose a user defined output pixel size. As mentioned above, imagery digitized from analog sources can also be processed with *DistCorr*, if it has been pre-processed with the *ReseauCorr* utility.

3.4 Correction of chromatic aberration

A significant oblique (lateral) chromatic aberration was observed in the images taken with the Nikon D100 digital camera (see Figure 8b). This error occurs when the different refraction indices of the red, green and blue color bands are not compensated by the lens system. A point will thus be projected at different radial distances in the red, green and blue channels of the RGB image. In order to determine the scale factors of the red and blue channels with respect to the green one, a calibration image (see Figure 8a) was split into its three color components. Well distributed points were then matched from the green channel into the red and green ones using a least-squares matching algorithm. The results of these measurements are shown in Figure 8c. They provided the basis for computing radial corrections for the red and blue channels as a function of the distance from the principle point. Finally, a new coefficient k_1 was derived for the red and blue channels. The *DistCorr* software is able to use a different set of lens distortion parameters for each color channel. This makes it possible to remove to a great extent the errors caused by chromatic aberration in the output image.



(a) (b) (c)

Figure 8. Black-and-white target used for camera calibration (a), chromatic aberration observed in a Nikon D100 image(b) and radial distortion(in pixel units) caused by chromatic aberration measured in the blue channel (c).

4 DIGITAL PHOTOGRAMMETRIC WORKFLOW

4.1 Terrestrial coordinate system

Aerial mapping is based on a three dimensional photogrammetric object coordinate system (OCS) linked to the Austrian Gauss-Krueger map projection system. For the evaluation of ground based photographs, a terrestrial coordinate system (TCS) was introduced (see also Figure 3). This system is derived from the OCS by a first rotation of 90° about the X-axis and a second rotation of 205° about the vertical Y-axis. The axes of this new system are denoted as U, V and W to distinguish them from the respective axes in the OCS.

The origin of the terrestrial system is chosen at position X=2500 m, Y=9000 m in the OCS. The W-axis is oriented parallel to the main viewing direction (from camera positions 1 and 2). The V-axis corresponds directly to the Z-axis (Height) in the OCS.

Using this system, the whole rock glacier can be mapped using only positive U-coordinates. As can be seen from Figure 3, the W-coordinates will also be positive for the lower part of the rock glacier.

4.2 Exterior orientation of the images

After the geometric correction of the images in the pre-processing step, stereo pairs, triplets or even bundles of photographs were oriented in the terrestrial coordinate system. A digital photogrammetric workstation (ImageStation ISSK of Z/I Imaging) was used for this task. In a first step, 70 control points were measured in an aerial stereo model of 2003. These points had been selected in such a way that they could also be identified in the terrestrial images, which proved a difficult task. After the control points had been transformed into the terrestrial coordinate system, they were used for the exterior orientation of the ground based images. Table 2 lists all of the terrestrial models computed and accuracies achieved.

Model	*Nr. of Images*	*R.M.S.- X [m]*	*R.M.S.-Y [m]*	*R.M.S.-Z [m]*
Photheo / 1986	2	0.28 (< 0.9)*	0.15 (< 0.4)	0.42 (< 1.3)
Linhof M. / 1999	3	0.72 (< 1.5)	0.37 (< 0.9)	0.82 (< 2.3)
Rolleiflex / 1999	3	0.35 (< 0.8)	0.23 (< 0.7)	1.05 (< 2.7)
Linhof M. / 2003	3	0.37 (< 2.0)	0.20 (< 0.7)	0.80 (< 2.4)
Rolleiflex / 2003	4	0.69 (< 1.5)	0.34 (< 0.7)	1.40 (< 3.9)
Nikon D100 / 2003	6	0.40 (< 1.0)	0.25 (< 0.6)	0.87 (< 1.9)

*Maximum residual is given within the brackets.

Table 2. Terrestrial stereo models of Outer Hochebenkar rockglacier.

4.3 Transformation into quasi-orthophotos

Perspective distortion caused by the different viewing angles and topography should be removed prior to matching in order to facilitate automatic point transfer in the multi-temporal images. For this purpose a concept of image rectification using a rough digital terrain model (DTM) has been proposed in earlier studies (e.g. Kaufmann & Ladstädter, 2002b and 2003). The pre-rectified images obtained by this method are called ”quasi-orthophotos”. These images contain small radial distortions caused by the erroneous heights of the rough DTM, but in general they have the same properties as orthophotos, i.e. unique scale and orientation, lack of perspective distortions, user defined ground sampling distance (GSD) and area of coverage. As can be easily shown, strict photogrammetric 3D reconstruction of object points is feasible using a pair (or a bundle) of quasi-orthophotos.

The concept of using quasi-orthophotos was originally developed for aerial photographs and had to be adapted to the terrestrial configuration. First of all, a terrain model of the project area defined in the terrestrial coordinate system (TCS) had to be provided. The DTM available for this study, however, had been derived from aerial photographs of 1997 and therefore was given in the object coordinate system.

In order to use this DTM for the pre-rectification of the terrestrial photographs it had to be transformed into the TCS first. DTM data is stored as a regular grid of Z-values $Z(X_i,Y_j)$ and can only be handled in this format by the software module used for image rectification (ISBR: Image Station Base Rectifier). This caused some problems, because after transformation, the 3D surface can no longer be modeled in this way, as some points on the surface become invisible when viewed from a terrestrial position. It was thus necessary to check the visibility of each point transformed into the terrestrial DTM and to filter out all points hidden by the new surface constructed.

For this task, another program utility was developed called *GridTrafo,* which was used for grid transformation and for visibility checking. As a result, a 3D point cloud was obtained in the TCS. After triangulation, W-values were interpolated on a regular grid using a grid spacing of 0.5m. Finally low pass filtering was applied in order to obtain a smoother surface.

Using this DTM, all of the available photographs (21 in total) were pre-rectified and thus transformed into the quasi-orthophoto geometry. They all cover the same area in the U-, V-plane of the TCS, which is defined by the boundaries of the project area (U_{min}=500; V_{min}=2250; U_{max}=1500; V_{max}=2800). A common pixel size of 0.1 m was chosen (0.2 m for the Nikon D100 images because of their lower resolution) for all quasi-orthophotos.

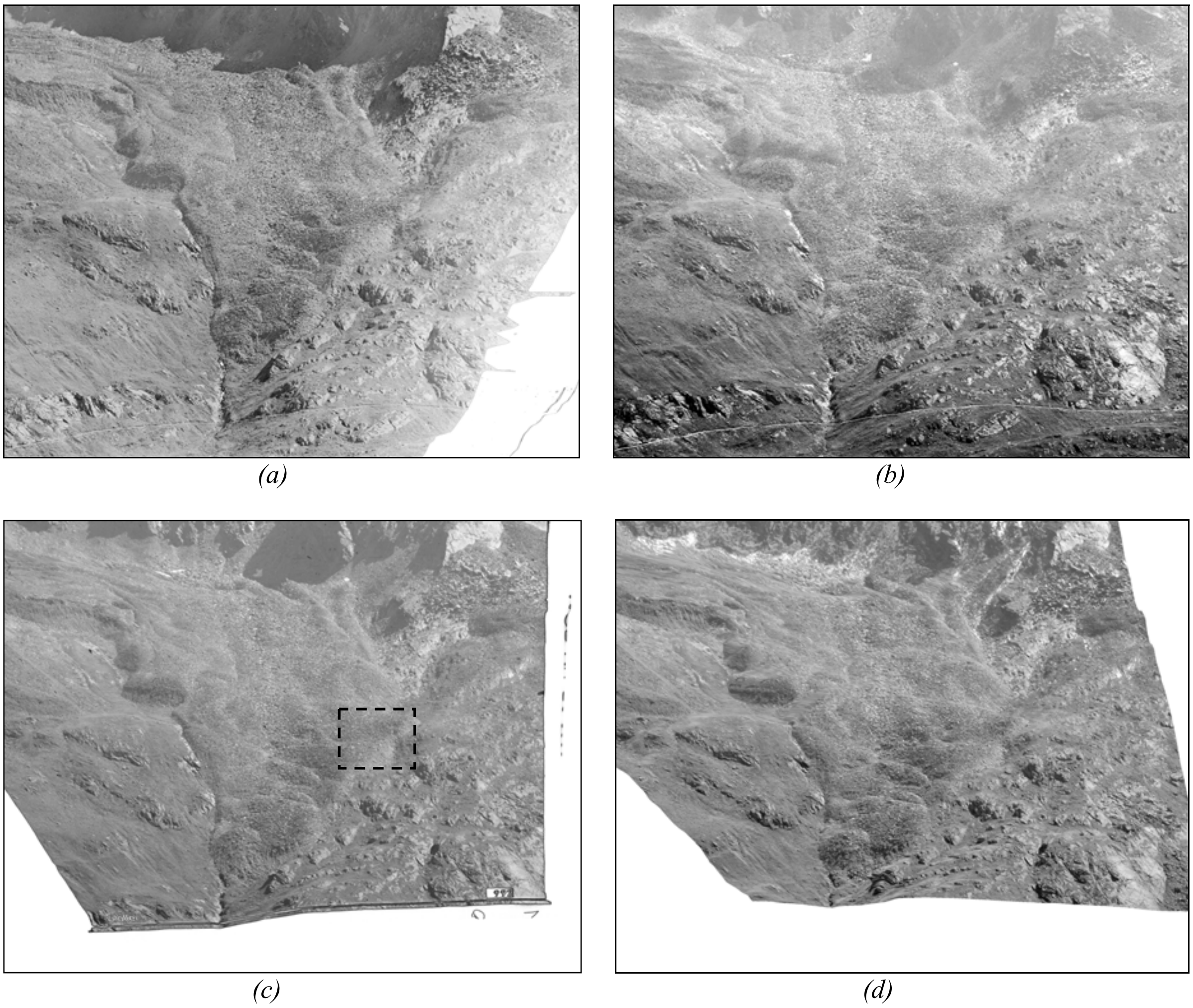


Figure 9. Multi-temporal quasi-orthophotos derived from photographs taken with (a) Photheo 19/1318, 1986, at camera position nr. 1, (b) Linhof Metrica, 1999, cam. pos. nr. 2, (c) Rolleiflex 6006, 1999, cam. pos. nr. 4 and (d) Nikon D100, 2003, cam. pos. nr. 6. The marked area in Figure 9c corresponds to the area shown in Fig. 11.

4.4 Automatic image processing using the ADVM software package

The *ADVM 2.0* monitoring software package has been developed for measuring rock glacier creep using multi-temporal quasi-orthophotos (cp. Kaufmann & Ladstädter, 2003). The software consists of three main modules:

- *INTEREST*: Extraction of interest points using the Förstner interest operator,
- *PREDICT*: Generation of disparity maps needed for the prediction of homologous point positions,
- *MPC_MATCH*: Multi-photo constrained matching in quasi-orthophotos with simultaneous point reconstruction in object space.

Each module is controlled by a number of configuration parameters, which can be defined using a graphical user interface (GUI). After defining a job, the respective *ADVM* module can be started from the GUI and will run as a batch job without further user interaction.

Image processing with the *ADVM* modules results in *(1)* 3D object points for each epoch and *(2)* a dense flow vector field describing the 3D deformation that occurred between two epochs.

5 RESULTS

5.1 Digital terrain models

DTMs can be derived by triangulation of the reconstructed object points of a single epoch followed by an interpolation of heights on a regular grid. This was done using a grid spacing of 1m for the models listed in Table 3:

Epoch	*Camera system*	*Nr. of points*
1986	Photheo	30890
1999	Linhof Metrika	26870
2003	Linhof Metrika	32180
2003	Nikon D100	7960

Table 3. Digital measured DTMs.

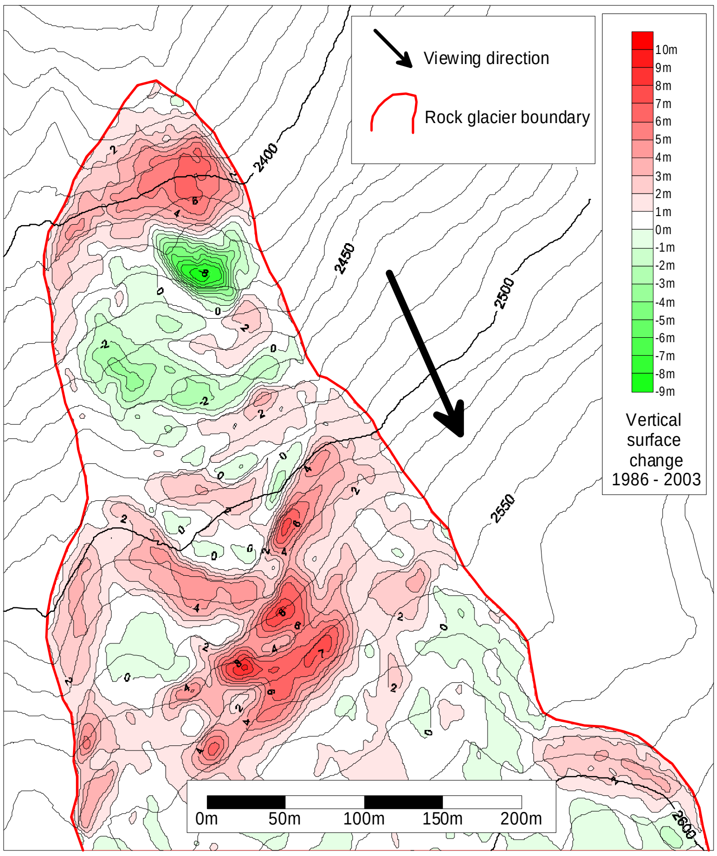


Figure 10. Vertical surface changes in the time period 1986 – 2003.

Surface changes can be detected by comparing the DTMs of two different epochs. This was done for the period 1986-2003 (see Figure 10). In order to derive vertical surface changes, the DTMs were transformed back into the object coordinate system first.

The quality of the DTMs cannot be readily assessed without having any ground truth. Because of the explicit 3D structure of the lower part of the rock glacier, not all of the surface is visible and therefore some of the ridges and furrows cannot be modeled correctly. DTMs derived from image data of different camera systems can, however, be compared. This was done for the DTMs computed from Linhof Metrika and Nikon D100 images for the epoch 2003.

The Linhof Metrika model was used as a reference DTM. W-residuals of the objectpoints of the Nikon D100 model were computed. The mean W-offset was -0.7 m with a standard deviation of ±1.1 m (max: -18 m).

5.2 Flow vector fields

Flow vectors are derived from identical point measurements in the stereo models of two different epochs. This is a much more difficult task than matching between the images of a single epoch, because of the motion of the rock glacier and the resulting surface changes. The camera systems used in these epochs may also be different, which results in images of different scale, resolution and quality. Nevertheless, dense flow vector fields were measured for the following epochs using quasi-orthophotos:

Epoch I	*Camera system*	*Epoch II*	*Camera system*	*Nr. of vectors*
1986	Photheo	1999	Linhof Metrika	24600
1999	Linhof Metrika	2003	Linhof Metrika	14900
1999	Rolleiflex 6006	2003	Nikon D100	4671

Table 4. Combinations of epochs used for flow vector measurements.

From vectors measured in the stable area surrounding the rock glacier, systematic shifts can be derived, which are caused by errors in the absolute orientation of the models. The flow vectors have to be corrected by this shift.

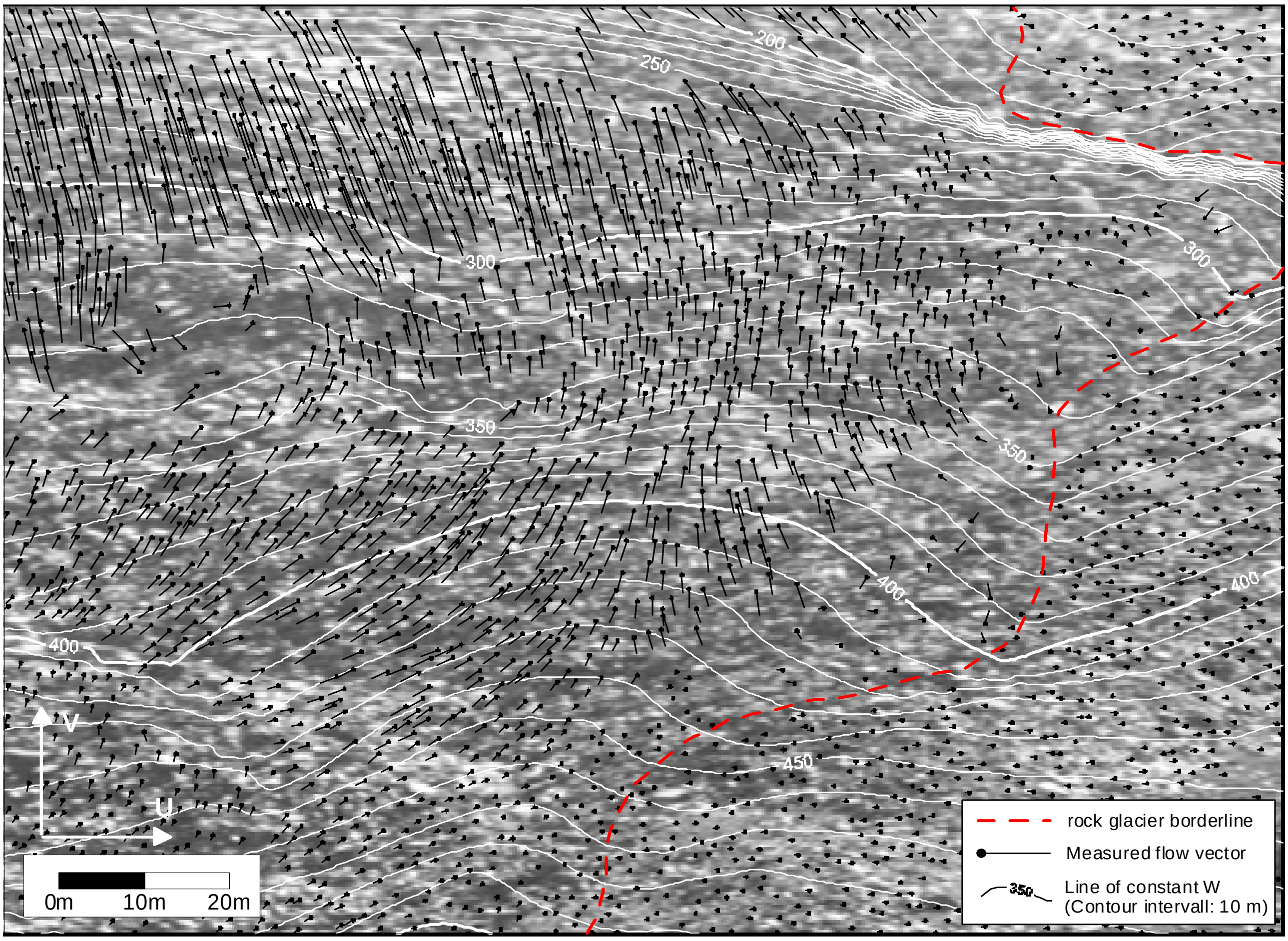


Figure 11. Flow vector field of a small area selected in the terrestrial system (150 m x 110 m). A quasi-orthophoto is used as background. Lines of constant W-values have been superimposed to give an impression of the rock glacier surface. Mismatches (found mainly in shaded regions) have to be manually removed from the data set. Density of the vector field is generally high, except for relatively flat regions.

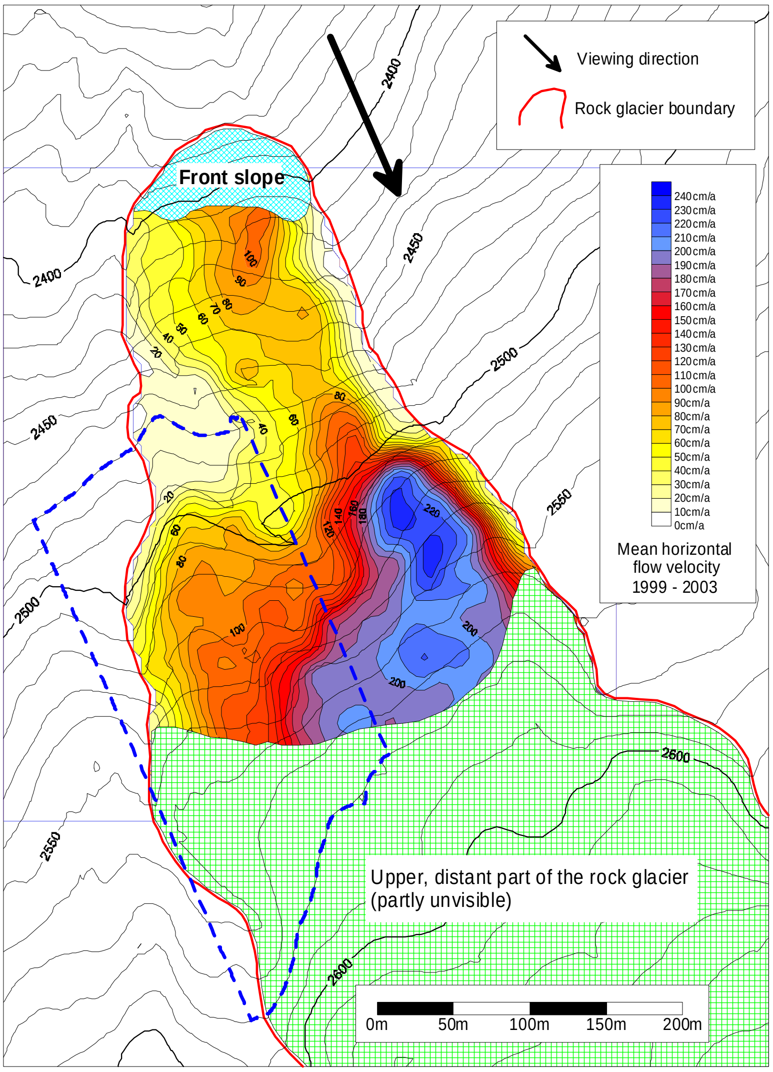


Figure 12. Mean horizontal flow velocity derived from the flow vector field (transformed back into the OCS for visualization). The area outlined by the blue dotted line corresponds to the area depicted in Figure 11.

Several kinematic parameters, e.g. the mean horizontal flow velocity or strain rates, can be derived from the measured 3D flow vectors. Flow velocity can be visualized in thematic maps showing lines of constant velocity. These maps make it possible to study the spatial distribution of the flow velocity in detail (see Figure 12).

Visualization can be done using the vectors measured in the terrestrial coordinate system (TCS) or with the vectors transformed back into the object coordinate system (OCS). Because of the unusually front view geometry, interpretation of the flow velocity is not so easy in the TCS. Therefore, flow vectors have been transformed back into the OCS for visualization. This makes it also easier to compare the results with velocity measurements, derived from aerial photogrammetry.

For the period 199-2003 very high flow velocities were detected. The maximum velocity of about 2.3 m/yr was measured at the orographic right side of the rock glacier at about 2530 m a.s.l. On the orographic left side, a rather inactive zone can be identified. This results are in good accordance to the geodetic measurements (Schneider & Schneider, 2001) and also with aerial photogrammetric measurements of the period 1997-2003 (not yet published).

6 CONCLUSIONS

In this study a terrestrial photogrammetric approach to the monitoring of an active rock glacier was tested. Four different camera systems (analog/digital; metric/non-metric) were combined using a special digital-photogrammetric workflow adapted from a concept successfully used in aerial photogrammetric monitoring projects. The main findings can be summarized as follows:

- Ground-based photogrammetry can be a valuable and inexpensive supplement to aerial photogrammetric surveys used for rock glacier monitoring tasks. Terrestrial surveys are restricted to comparatively small areas (such as the rock glacier snout), however, and will work best in steep terrain (horizontal viewing direction).

- By using an automated digital workflow, high resolution DTMs as well as dense flow vector fields can be derived from the terrestrial photographs. This makes it possible to study surface deformation of a selected part of the rock glacier at very high spatial resolution, which cannot be obtained by geodetic measurements nor by aerial photogrammetry.

- One of the biggest problems in terrestrial photogrammetry is the big range in depth, which causes inhomogeneous accuracy of the reconstructed object points depending on their camera distance. Problems also occur in areas where the terrain is rather flat because of the viewing direction being virtually surface parallel.

Photographs should thus be taken from a slightly higher position and not too far from the object. This results in an optimal, oblique viewing direction. Because of the given topography, the optimal terrestrial configuration (distance, length of the baseline, viewing directions) cannot be achieved in most cases.

- The use of a digital consumer camera has the advantage of low price and easy handling. Digital image data can directly be processed in a digital photogrammetric workflow. The resolution of the 6 MegaPixel CCD of the Nikon D100 camera is not sufficient, however, for large object distances (> 1 km) as used in this study.

- The large image format and image scale of the more or less historic Photheo 19/1318 and the Linhof Metrika metric film camera allow for detailed photogrammetric studies of the rock glacier surface. Despite its reduced image format and somewhat lower image quality, the semi-metric Rolleiflex 6006 was also successfully used in this project. The main disadvantages are the significant geometric distortions caused by film unflatness, which must be eliminated in a somewhat complex pre-processing step.

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