DOCUMENTATION OF THE RETREAT OF A SMALL DEBRIS-COVERED CIRQUE GLACIER (GOESSNITZKEES, AUSTRIAN ALPS) BY MEANS OF TERRESTRIAL PHOTOGRAMMETRY

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ABSTRACT

The mapping of glacier fluctuations is an important task of environmental research. Several methods of glacier mapping on a local, regional and global scale are available. From a historical point of view, terrestrial photogrammetry was the first powerful tool in obtaining reliable metric information about glaciers in mountainous landscapes. Today, however, terrestrial photogrammetry is only applied occasionally in glacier studies, if at all.
In this paper we seek to show that the availability of low-cost high resolution digital (consumer) cameras opens up new perspectives in glacier monitoring. Since digital photogrammetric software is readily available for 3D data capture, we conclude that there is a good chance of a revival of classical terrestrial photogrammetry in the digital domain.
The potential of a fully digital approach using a low-cost digital consumer camera has been investigated in a case study. The main task of the study was to obtain parameters quantifying the retreat of the Goessnitzkees glacier from ground-based photographs taken at three different time periods (1988, 1997, 2003).

1 INTRODUCTION

Goessnitzkees (12°45' E, 46°58' N) is a small debris-covered cirque glacier located in the Schober group of the Hohe Tauern range, Austrian Alps. The glacier covered an area of some 0.75 km² in 1997. The Russian KFA-1000 space image from 1991 shows the location of the study area (Figure 1). Remark: "kees" is the local name for glacier.

In 1982 Goessnitzkees was included into the network of annual glacier measurements of the Austrian Alpine Club (ÖAV). Currently 107 glaciers of the Austrian Alps are surveyed every year by an ambitious team of volunteers who measure the position of the glacier termini using quite simple means: distances are measured from marked points located in the forefield of the glacier to the terminus using a measuring tape. The results of these measurements are published every year by the Austrian Alpine Club (e.g. Patzelt, 2004). These reports list whether a glacier is advancing, retreating or stagnant, and furthermore, the amount of glacier length change in comparison to the previous year is given.

In the case of Goessnitzkees, however, this simple measuring technique was modified by installing two reference points (marked with color dots on solid rock) in the forefield of the glacier from which distinct points of the terminus were measured applying basic trilateration using a measuring tape. The coordinates of the measured points were computed in a local coordinate system (Lieb & Kaufmann, 1985). The drawbacks of this method are: time-intensive measuring of many triangles in the case of large retreat rates, missing of non-moving points in the forefield of the glacier, swinging of the measuring tape at windy conditions, and inaccuracies due to sloping distance measurements. In 1996 a hand-held LeicaDISTO laser meter was used for the first time in order to facilitate the measurement of longer distances, thereby reducing working time in the field. This more advanced measuring technique has now been discontinued, however, in favor of the simpler ÖAV measuring technique. Since 1982 until now all annual measurements (mid-September) on Goessnitzkees have been carried out by members of the Institute of Geography and Regional Science of the University of Graz (UNI Graz).

In 1996 the Institute of Geodesy (now Institute of Remote Sensing and Photogrammetry and Institute of Navigation and Satellite Geodesy) of Graz University of Technology (TU Graz) selected Goessnitzkees as a test site for high-mountain studies. A three-dimensional geodetic network was installed for this purpose, comprising also some reference points of the previously described annual measurements for ÖAV. The network is embedded in the Austrian Gauss-Krueger coordinate system. Since then annual glacier measurements based on this network have been carried out every year

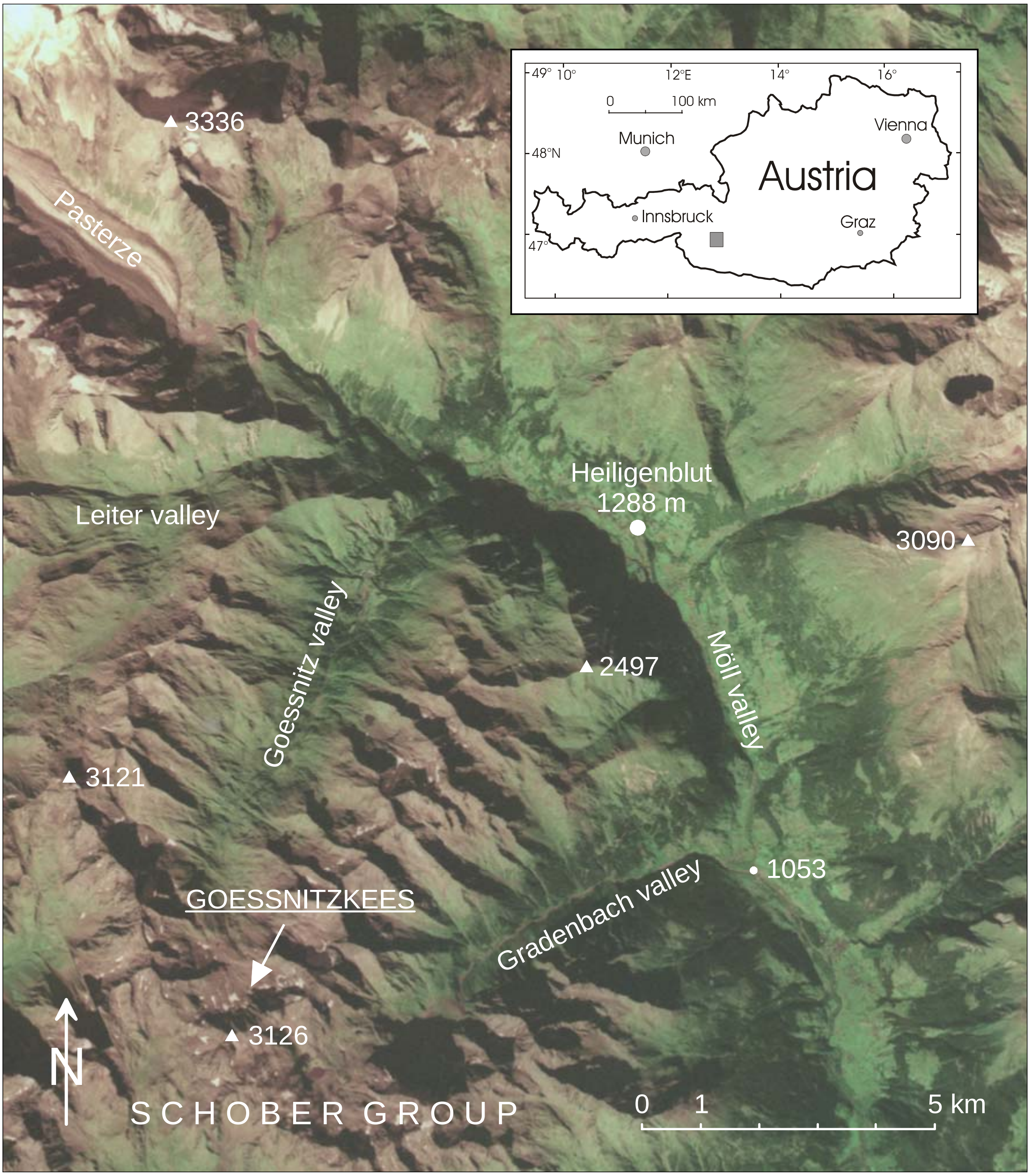

Figure 1. Russian KFA-1000 space photograph (spectrozonal film emulsion) showing parts of the Schober group with Goessnitzkees. The photograph (original scale 1:410.000) was taken from MIR space station on 25 September 1991 during the Austrian-Russian AUSTROMIR project. The photograph shown is an orthoimage which has been obtained through the process of orthorectification using a digital elevation model with a grid spacing of 25 m. In the upper left corner of the image the tongue of Pasterze glacier can be seen. Pasterze glacier is the largest glacier of the Eastern Alps, Europe. Goessnitzkees and also Pasterze glacier are part of the Austrian Hohe Tauern National Park.
(The KFA-1000 photograph has been provided by R. Kalliany, ICG, Graz University of Technology.)

(mid-August) until the present time. As an example, Figure 2 shows the retreat of Goessnitzkees for a longitudinal profile measured each year between 1996 and 2004. Remark: The location of the profile is shown in Figure 9.

From 1996 to 1998 a glacier study under the leadership of G.K. Lieb (Institute of Geography and Regional Science, UNI Graz) was carried out in order to reconstruct the glacier history of Goessnitzkees from 1850 (maximum extent of glaciation) until 1997. Results obtained have been published, e.g., in Kaufmann & Lieb (2002). One specific task of this project was to visualize the retreat of Goessnitzkees in terms of thematic maps and also computer animations (Kaufmann & Plösch, 2000; see also http://www.cis.tugraz.at/photo/viktor.kaufmann/animations.html).

Terrestrial photogrammetric surveys of Goessnitzkees were carried out in 1988, 1996, 1997, and 2003. The older photographs of the 1980s and 1990s have been archived at the Institute of Remote Sensing and Photogrammetry, TU Graz, a comparative analysis of these data was not done, however, for various reasons. In 2003 a low-cost SLR digital camera was used for the first time in the glacier study. With the availability of an in-house digital photogrammetric workstation (DPW) for 3D data capture, the authors decided to evaluate the photographs. This paper describes the details of this work. Two main tasks have been addressed: (1) documentation of the retreat of Goessnitzkees using the terrestrial photographs of 1988, 1997 and 2003, and (2) assessment of a possible revival of classical terrestrial photogrammetry in the digital domain using low-cost digital consumer cameras for glacier studies.

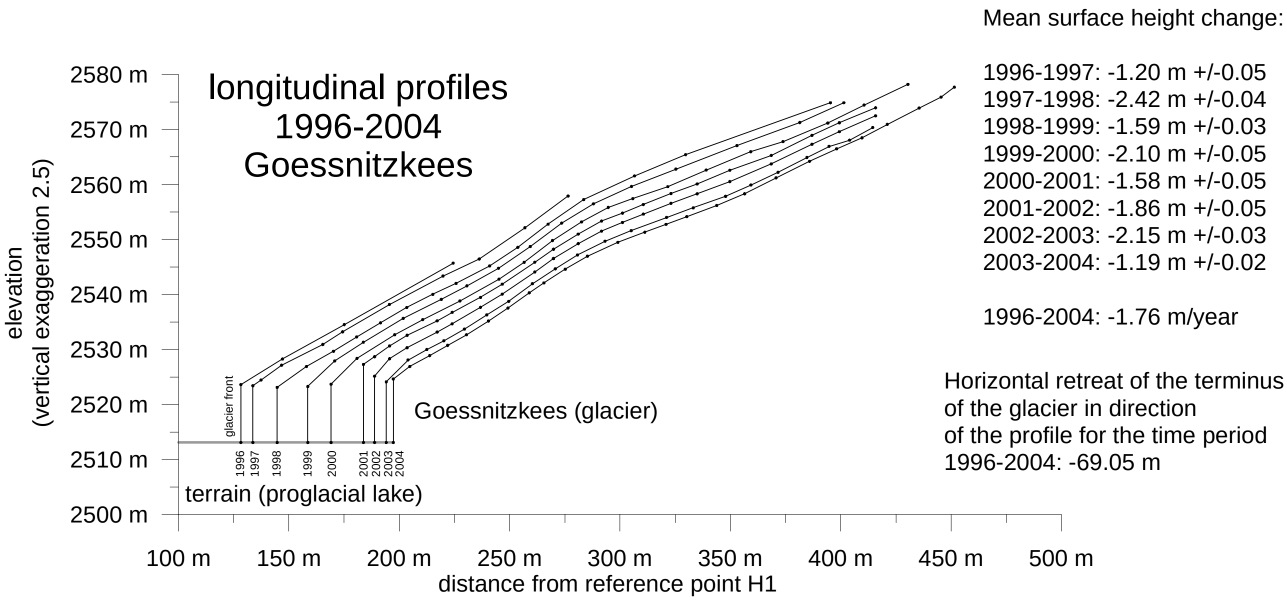

Figure 2. Graphical representation of the geodetically measured profiles 1996-2004. The mean surface height change (loss of ice thickness) and the total glacier length change of Goessnitzkees are given numerically.

2 DATA ACQUISITION

The Institute of Remote Sensing and Photogrammetry of TU Graz carried out four terrestrial (ground-based) photogrammetric surveys of the central part of Goessnitzkees showing also the glacier terminus. The second survey from 9 September 1996 was undertaken after a snowfall in the preceding night. The photographic conditions were quite good, but due to the snow cover of 20-30 cm the photographs were not usable for photogrammetric purposes. In the following year the photogrammetric survey of Goessnitzkees was repeated successfully.

During the photogrammetric survey of 1988 seven control points were measured within a local coordinate system using the integrated theodolite of the camera used. Since these control points were not of sufficient quality for our proposed study, a set of new control points were determined in 2003 (see section 2.4).

2.1 Glacial stage 1988 – documentation with Zeiss TAL phototheodolite

A first photogrammetric survey of Goessnitzkees was carried out by R. Kostka and V. Kaufmann, both with the TU Graz, using a Zeiss TAL phototheodolite (Figure 3). On 7 September 1988, a stereo pair of glass plates was obtained (Figure 4). The endpoints of the stereo baseline were marked by cairns. Some technical parameters of the phototheodolite used are listed in Table 1. Hubeny (1948) gives a detailed description of TAL (German "Terrestrische Ausrüstung leicht") and its use, and he also addresses accuracy issues of practical mapping projects.

Figure 3. Zeiss TAL phototheodolite

principal distance: 55.62 mm
format of glass plates: 6.5 cm x 9 cm
optical system (lens): Topogon 1:6.3
shutter: lens cap
The optical system (lens) is vertically movable in steps of 5 mm.

Orthochromatic glass plates (Topo-Platten TO1) of the former ORWO VEB Filmfabrik Wolfen, GDR, were used.

Table 1. Technical parameters of Zeiss TAL

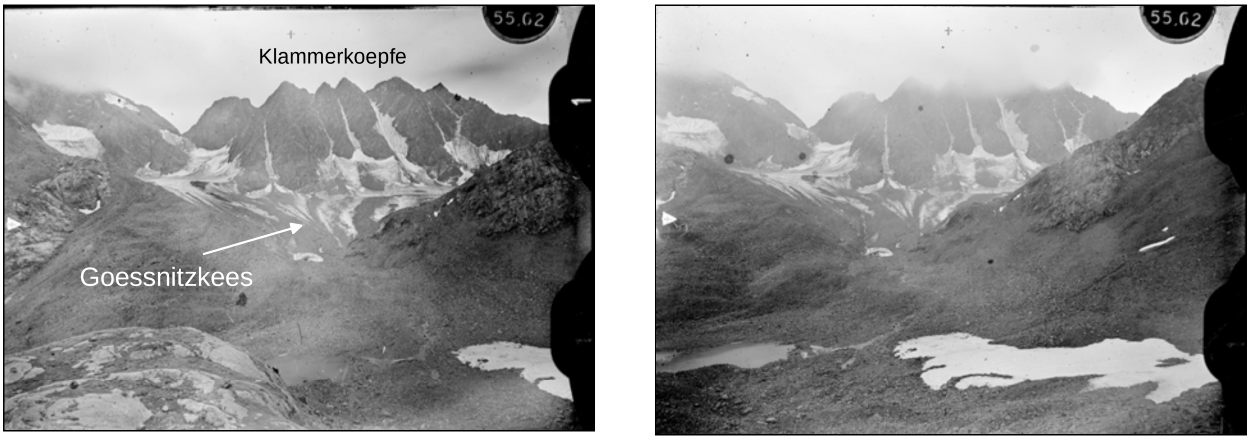

Figure 4. Goessnitzkees: Zeiss TAL stereo pair taken on 7 September 1988

2.2 Glacial stages 1997 and 2003 – documentation with Rolleiflex 6006 réseau camera

The photogrammetric survey of 1988 was repeated by V. Kaufmann on 11 August 1997 and on 23 August 2003. Both data takes were done with the same semi-metric Rolleiflex 6006 réseau camera. In the 1990s photographic glass plates for the TAL phototheodolite were no longer available on the market. During the 1997 survey a third camera position (M1) was introduced in the middle of the baseline of 1988 for obtaining an appropriate stereo triplet (see Figure 9).

After completion of the photogrammetric orientation procedures (cp. chapter 5) it was found that the left camera position of 1988 could not be located correctly in the field. The correct position (and also the respective cairn) was found during a follow-up photogrammetric survey in 2004 using a hand-held GPS receiver. This is the reason why five different positions have been in use up to now (see Figures 9 and 10). All points in the field are color-marked.

The principles of using a Rolleiflex 6006 réseau camera in photogrammetric projects have already been outlined by Wester-Ebbinghaus, 1983. Some important technical parameters of the camera used are given in Table 2.

Figure 5. Rolleiflex 6006 réseau camera

principal distance: 151.608 mm
format of photographs: 6 cm x 6 cm
optical system (lens): Sonnar 1:4
réseau glass plate: 121 réseau crosses

Kodak Ektachrome 120 EPN (color reversal film, 100 ASA)
was used in both surveys.

Table 2. Technical parameters of Rolleiflex 6006

Figure 6. Goessnitzkees: Rolleiflex 6006 stereo pair taken on 11 August 1997. The réseau crosses have been digitally masked out by a pre-processing step.

2.3 Glacial stage 2003 – documentation with Nikon D100 digital camera

In 2003 two camera systems were used at the same time, i.e., the previously mentioned Rolleiflex 6006 and a digital Nikon D100 still camera, which is a low-cost SLR digital camera with an image resolution of 3008 by 2000 pixels. Some more technical parameters of the camera can be found in Table 3. The stereo pair selected for photogrammetric mapping is shown in Figure 8.

Figure 7. Nikon D100 digital camera

principal distance: 51.579 mm (focus at infinity)
pixel size: 7.8 µm
size of CCD array: 15.600 mm x 23.462 mm
optical system (lens): Nikkor 50 mm 1:1.8 (effective 75 mm)
color image formation: filter layer-based (Bayer filter)
data storage: 1 Gigabyte IBM Microdrive

1 IBM Microdrive can hold 59 digital images (uncompressed TIFF).

Table 3. Technical parameters of Nikon D100

Figure 8. Goessnitzkees: Nikon D100 stereo pair taken on 23 August 2003. (Note: Figures 4, 6 and 8 are true to scale.)

2.4 Geodetic measurements

The photographic documentations in 1997 and 2003 were accompanied by geodetic measurements as already outlined in chapter 1. The annual measurements include 3-dimensional data capture of (1) the outline of the terminus of the glacier, (2) the shoreline of the proglacial lake, (3) additional points of the glacier surface (= velocity markers), and (4) a longitudinal profile. Additionally, photogrammetric control points (N) were measured during the field campaign of 2003. See Figure 11.

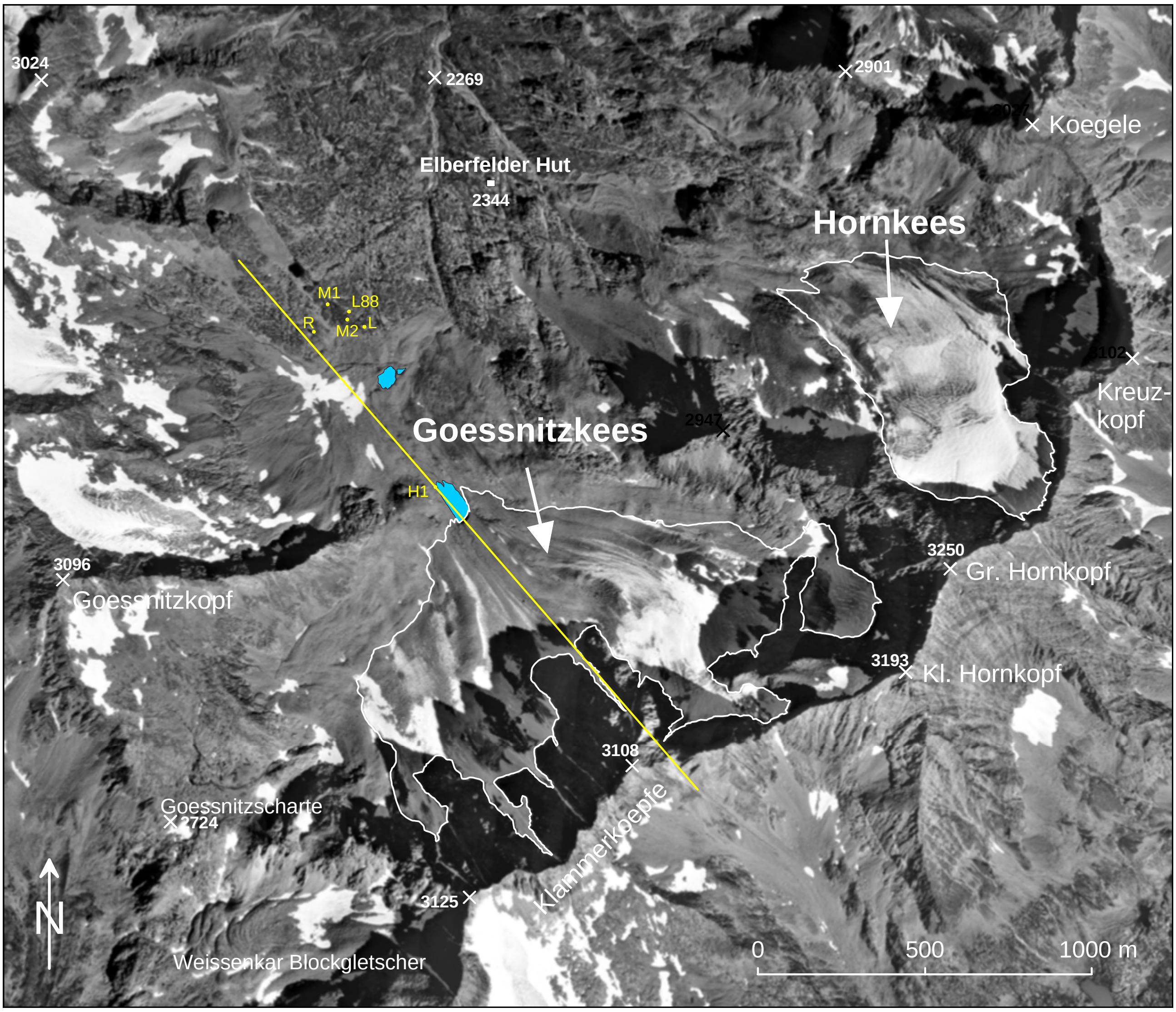

Figure 9. Orthophoto of 1 September 1997 showing the camera positions (L, M1, M2, L88, R) and the direction of the longitudinal profile. The yellow line corresponds with the cross section of Figure 10.

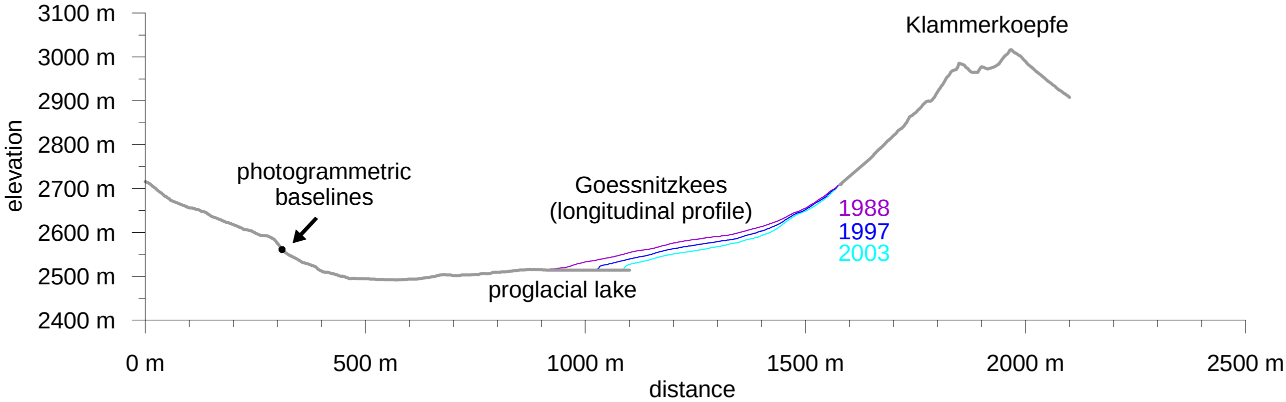

Figure 10. Location of the photogrammetric baselines. The cross section shown is indicated in Figure 9.

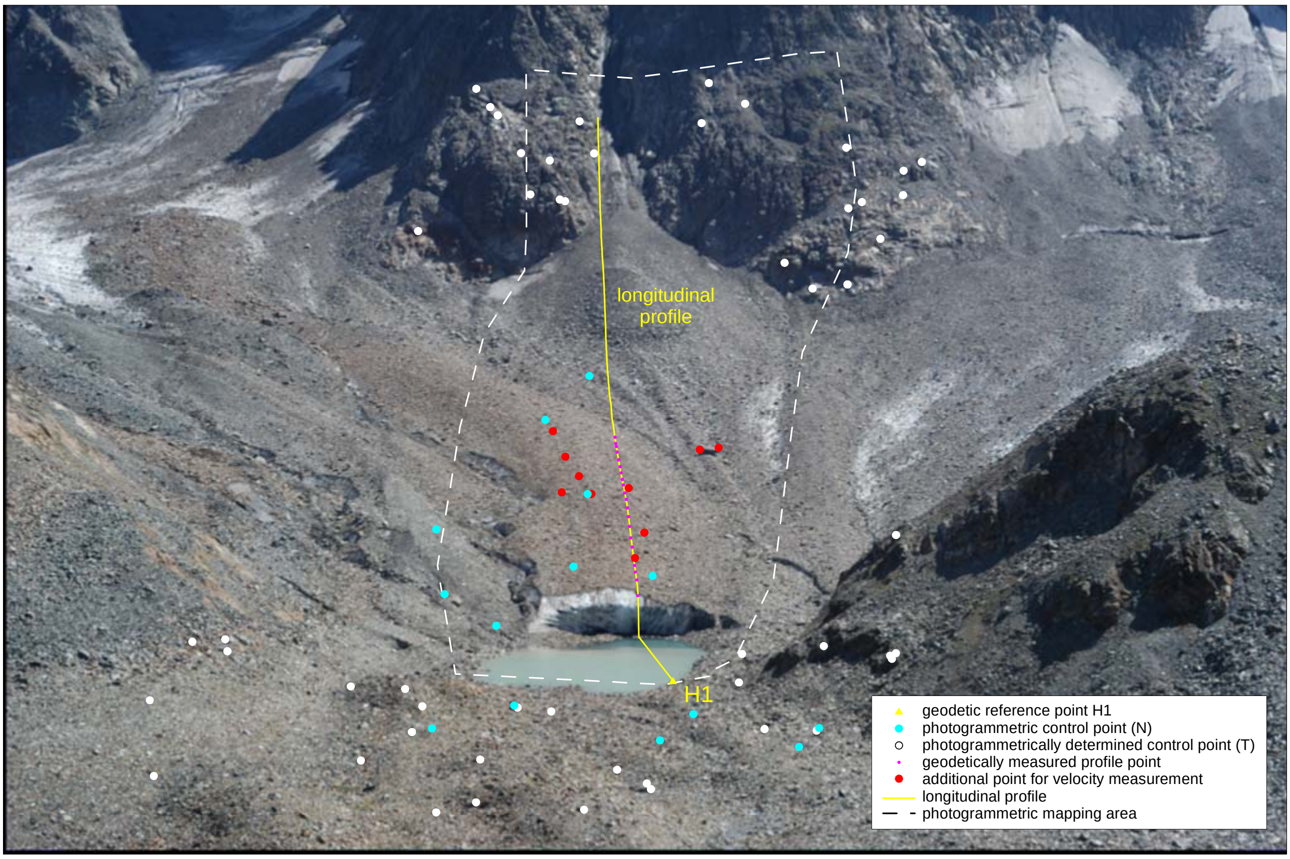

Figure 11. Digital image of Nikon D100 showing geodetic and photogrammetric points and the longitudinal profile.

3 ANALOG-TO-DIGITAL CONVERSION

In order to achieve a fully digital data flow in the photogrammetric evaluation process, all analog photographs were digitized at 10 µm scanning resolution using the UltraScan 5000 photogrammetric scanner of VEXCEL Imaging Austria (Gruber & Leberl, 2001).

4 GEOMETRICAL PRE-PROCESSING

The elements of interior orientation of the cameras must be known in advance for our terrestrial photogrammetric mapping scheme. Furthermore, the digital data must be subjected to some geometrical pre-processing steps in order to compensate for film unflatness, film distortion and chromatic aberration, if necessary. Appropriate software has been developed for this purpose at the Institute of Remote Sensing and Photogrammetry. The basic idea of this pre-processing step was not only to eliminate the previously mentioned image errors but also to cancel out e.g. lens distortion. The result of this pre-processing step is – so to speak – a perfect metric perspective image with its principal point positioned at the image center. Such an image could have been taken by an ideal camera. While no further technical details on the pre-processing procedure can be given within the scope of this paper, some comments are given in the following paragraphs for the sake of clarity.

Since there was no camera calibration certificate available for the Zeiss TAL phototheodolite, but the calibrated focal length was exposed on the glass plate, the proper coordinates of the 5 fiducial marks were determined through metric measurements in the digital images. Lens distortion was assumed to be negligible. With this data set no pre-processing step was necessary.

A special computer program was written to deal with the digitized photographs of the Rolleiflex 6006. Réseau crosses were measured interactively on the screen using a cursor. By comparing the pixel coordinates measured with the given coordinates, film unflatness and film distortion (shrinkage) were numerically modeled. In the rectification procedure of this pre-processing step the many réseau crosses were removed digitally through masking and gray-value interpolation.

This possibility of elimination of the réseau crosses is quite useful for undisturbed stereoscopic viewing and also automatic image matching. Nevertheless, images with crosses are not very attractive for visual presentations. This pre-processing step led to ideal central-perspective images, consisting of 6001 by 6001 pixels of exactly 10 µm resolution. The parameters of the interior orientation were known from an earlier investigation.

In contrast to both cameras previously mentioned, the interior orientation of the Nikon D100 digital camera had to be determined by camera calibration. The well-known PhotoModeler 4.0 software from Eos Systems Inc. was used for this purpose. A two-dimensional calibration field provided by PhotoModeler was photographed from various viewing angles and evaluated as described in the user manual (Eos, 1997; see also Wiggenhagen, 2002). The largest amount of radial-symmetric lens distortion is 1.4 pixels (= 10.9 µm) in the image corners. Furthermore, color fringes visible in the digital Nikon D100 image data, caused by oblique chromatic aberration of the lens, were minimized by appropriate scaling of the red and blue spectral bands in respect to the green one. The maximum radial-symmetric point displacement is +0.3 pixel for the red and -0.5 pixel for the blue spectral band in the image corners. The size of the pre-processed Nikon D100 images remains the same, however, the image geometry is optimized from a geometrical point of view.

5 PHOTOGRAMMETRIC EVALUATION

Recent reports on practical terrestrial photogrammetric surveys of glaciers are quite scarce. Representative examples are given in Brecher & Thompson, 1993, Palà et al., 1999, Triglav et al., 2000, Gruber & Slupetzky, 2002, and Pitkänen & Kajuutti, 2004.

5.1 Photogrammetric orientation

Photogrammetric orientation of all image data and subsequent 3-dimensional data collection were carried out using an ImageStation SSK of Z/I Imaging. For the sake of simplicity a procedure based on single stereo models is proposed and tested. The authors of this paper argue that a bundle adjustment using multiple overlapping photographs (of either one epoch or even several different epochs) is not easy for a non-photogrammetrist. The evaluation of a single stereo model is straightforward in most of the commercially available digital photogrammetric workstations, and therefore the proposed task can be accomplished even by a photogrammetric novice.

Appropriate stereo models covering the area of interest were selected for each epoch (glacial stage) and camera used (Table 4).

glacial stage	camera	baseline
1988	TAL	L88 – R
1997	Rolleiflex 6006	M1 – R
2003	Rolleiflex 6006	M1 – R
2003	Nikon D100	M2 – R

Table 4. Stereo models selected for photogrammetric evaluation

Absolute orientation of the stereo models was carried out as follows: The Rolleiflex 6006 stereo model of 2003 was selected as a reference model for subsequent absolute orientation of the other stereo models. The absolute orientation of this reference model was performed using the photogrammetric control points (N) measured geodetically at the same time of data collection (see Figure 11). The coordinate system selected for orientation is the Austrian Gauss-Krueger system.

After successful orientation of the stereo model, some 55 tie points (T) were selected in areas of the deglaciated forefield of Goessnitzkees and in the steep back walls of the cirque glacier (see Figure 11). These tie points were measured independently three times and the coordinates were averaged. Finally, the other three stereo models were orientated using this new set of control points.

As already indicated at the beginning of this chapter, the orientation of all available images could have been done using photogrammetric triangulation. Since automatic point transfer (= measuring of homologous/conjugate points by means of image matching techniques) is already implemented in nearly all digital photogrammetric workstations the measurement of the tie points (T) could also be feasible with this strategy.

5.2 Photogrammetric mapping

Photogrammetric mapping was restricted to the area indicated in Figure 11. This area covers the central part of Goessnitzkees, including the terminus of the glacier and the proglacial lake. From a glaciological point of view the selected area is largely representative of the whole glacier.

Digital elevation models (DEMs) were obtained for all four stereo pairs through manual measurement of a regular grid of surface points with a sampling distance of 5 m. Furthermore, linear features, e.g., the outline of the glacier terminus, other glacier boundaries, shoreline of the proglacial lake, breakline and drainage lines, were compiled. These data were also considered in the computation of the DEMs. Stereoscopic viewing was quite difficult in some areas of the older stereo pairs where the viewing direction was virtually surface parallel. With the passage of time the surface of the glacier will subside, and therefore this problem will diminish. Large parallax differences in the field of vision looking at certain geometrically critical areas, however, will still hamper good stereo vision.

6 RESULTS

6.1 Accuracy assessment

Accuracy was assessed empirically. The geometric quality of both DEMs derived from the Rolleiflex stereo models 1997 and 2003 were checked independently by means of the geodetic measurements. A comparison along the longitudinal profile showed that the photogrammetrically and the geodetically derived surfaces fit with an RMS (root mean square) value of ±22 cm for 1997, and ±13 cm for 2003. In both cases significant positive offsets of the photogrammetrically derived profiles in vertical direction in the order of 10 cm were observed. Furthermore, the DEM of 1997 was compared with another DEM, which was derived from aerial photographs taken three weeks after the terrestrial photographs. After elimination of a constant height offset between both data sets, which was inherent to the aerial case, an RMSE (root mean square error) of ±15 cm was computed for the whole mapping area. It was possible to visually verify this high quality by overlaying the respective contour lines.

In a further analysis the longitudinal profiles interpolated from both DEMs of 2003 were compared with each other. The height differences obtained have an RMS value of ±12 cm. No significant offset between the surfaces was observed. See Figure 12.

6.2 Documentation of glacier retreat

Numerical values quantifying the glacier retreat were obtained from the 3-dimensional data showing the amount of change of ice thickness and the horizontal recession of the terminus (cp. Table 5). Moreover, various graphs and thematic maps were produced for visualization purposes (e.g. Figures 12-14).

time period	mean change of ice thickness⁺	glacier length change⁺⁺
1988-1997	-1.51 m/year	-85.2 m (= -9.47 m/year)
1997-2003*	-2.03 m/year	-61.5 m (= -10.26 m/year)
1988-2003*	-1.67 m/year	-144.9 m (= -9.66 m/year)

*stereo models of Rolleiflex 2003
+only for the elevation interval 2530-2560 m
++ measured along the direction of the longitudinal profile

Table 5. Change of ice thickness and glacier length change of Goessnitzkees

Vertical mass balance profiles (1988-1997, 1997-2003, 1988-2003) were computed for the longitudinal profile. Assuming a linear function between altitude and the mean specific mass balance, the mass balance gradient (the rate at which the specific balance changes with altitude) and the equilibrium line altitude (ELA) were numerically computed. For the time period 1988-2003 the mean annual mass balance gradient amounts to 0.00969 mwe m^{-1} yr^{-1} (meters of water equivalent per 1 m height interval per year) and the mean equilibrium line altitude was estimated at 2708 m. This means that nearly the whole glaciated area mapped has been affected by ablation (mass loss) throughout the last 15 years. Basic concepts of glacier research, e.g. modeling of glacier mass balance, can be found in Oerlemans, 2001.

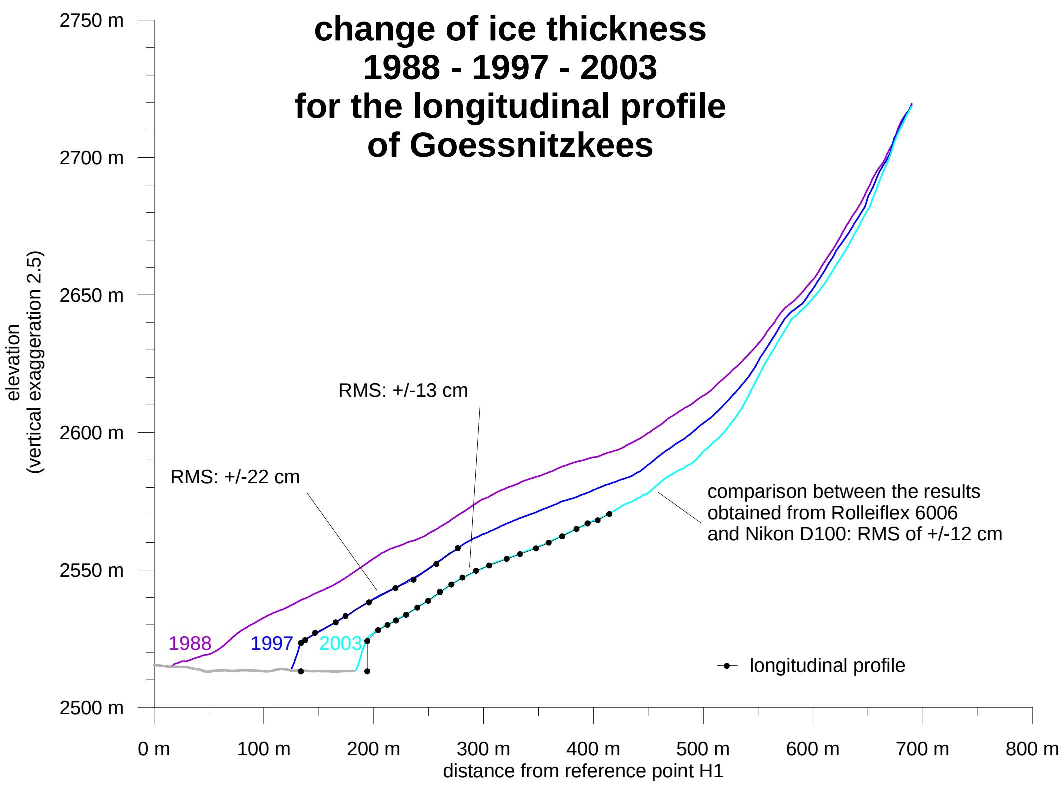

Figure 12. Change of ice thickness along the longitudinal profile of Goessnitzkees for the time period 1988-1997-2003

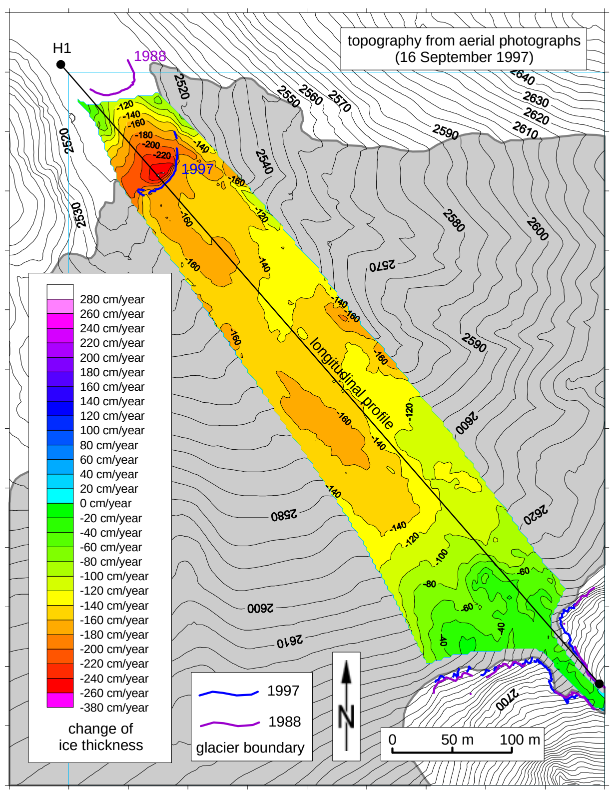

Figure 13. Terrestrial photogrammetric documentation of change of ice thickness at Goessnitzkees for the time period 1988-1997

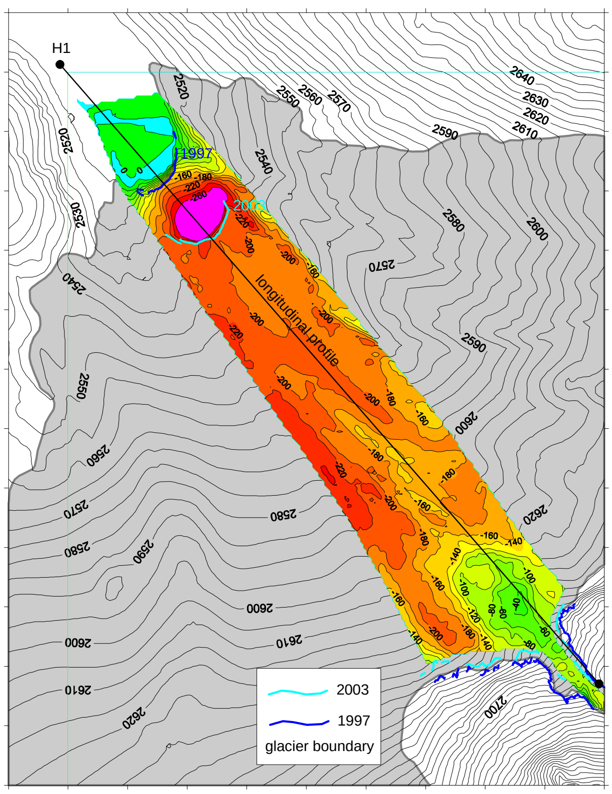

Figure 14. Terrestrial photogrammetric documentation of change of ice thickness at Goessnitzkees for the time period 1997-2003

7 RECOMMENDATION AND OUTLOOK

The usefulness of low-cost SLR digital consumer cameras for terrestrial photogrammetric glacier surveys was demonstrated. The comparatively low imaging resolution of the digital cameras compared to large format photographic cameras, however, is still a problem. 8-Megapixel digital cameras are currently available on the market, and Kodak has recently introduced a 14-Megapixel SLR digital (consumer) camera. The authors believe that it is only a matter of time (2-3 years from now) until that camera will be available for the same price as the 6- or 8-Megapixel cameras today.

Another prerequisite for the proposed terrestrial photogrammetric workflow is a digital photogrammetric workstation. Some years ago a DPW was an expensive item because dedicated hardware was needed and software was overpriced. Solutions are now running on a consumer PC with a relatively good performance and software is getting cheaper. Automation and ease of work is a big issue of current developments. Several vendors of GIS software offer add-on software for 3D data capture, which provides full photogrammetric functionality. The application of terrestrial photogrammetry in glacier studies will doubtless benefit from the integration of digital photogrammetry in GIS. The software packages will become even more user-friendly, thus negating the need for in-depth photogrammetric knowledge.

In respect to Goessnitzkees we conclude that the annual change of ice thickness can probably be computed with an accuracy of ±20 cm using the Nikon D100 digital camera. Assuming a mean annual surface lowering of about 2 m, a relative measurement error not worse than ±10 % can be expected. In August/September 2004 another follow-up field campaign was carried out. The evaluation of the geodetic and photogrammetric data is now underway.

In summary, it can be said that terrestrial photogrammetry, as described in this paper, can be applied successfully in long-term monitoring projects for small glaciers or selected areas of a glacier, e.g. outline of the terminus, if a sufficient number of stable points (natural control points) is available in the vicinity of the area of interest.

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