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Glacier monitoring by means of terrestrial photogrammetry: A case study in the Hohe Tauern National Park

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Abstract

Glaciers respond to changes in climate. Mass gain and loss change the geometrical and also the kinematic properties of a glacier. Their monitoring and quantification are of great interest to glaciologists, because these properties, i.e. glacier area, surface elevation, position of terminus and surficial flow velocity, can be linked to mass balance. During the first half of the 20th century terrestrial, i.e. ground-based, photogrammetry was the only means to efficiently map glaciers and their changes in space and time. Modern remote sensing techniques, i.e. airborne and spaceborne photogrammetry, airborne and terrestrial laser scanning, and differential SAR-interferometry, have pushed away terrestrial photogrammetry. In this paper we want to show that the availability of low-cost high resolution digital (consumer) cameras opens up new perspectives in glacier monitoring. A case study was carried out at Goessnitzkees, which is a small debris-covered glacier located in the Schober group of the Hohe Tauern range, Austria. Terrestrial photographs (stereo pairs) of three different periods (1988, 1997, 2003) were evaluated by means of digital photogrammetric techniques. As a result, glacier retreat could be mapped and quantified numerically. The potential of a fully digital approach using a low-cost digital consumer camera is highlighted.

Keywords

Glacier monitoring, terrestrial photogrammetry, digital photogrammetry, Zeiss TAL phototheodolite, Rolleiflex 6006 réseau camera, Nikon D100 digital camera, Goessnitzkees, Schober group, Hohe Tauern National Park.

Introduction

Goessnitzkees is a small (1997: 0.75 km²) debris-covered cirque glacier located in the Schober group, Hohe Tauern range, Austria. The course of deglaciation has already been documented for the time period 1850-1997 within a research project funded by the Hohe Tauern National Park (LIEB 2000).

Data Acquisition

The Institute of Remote Sensing and Photogrammetry additionally carried out three terrestrial (ground-based) photogrammetric surveys of the central part of the glacier showing also the glacier terminus: A first survey was done in 1988 using a Zeiss TAL (German "Terrestrische Ausrüstung Leicht") phototheodolite obtaining a stereo pair of glass plates. The endpoints of the baseline were marked by cairns. The photogrammetric survey was repeated in 1997, this time using a semi-metric Rolleiflex 6006 réseau camera, since photographic glass plates for the TAL phototheodolite were no longer available on the market. During the second survey a third camera position was introduced in the middle of the baseline of 1988 for obtaining an appropriate stereo triplet. Finally, the third photogrammetric survey took place in 2003. At this time we used two camera systems, i.e. the Rolleiflex 6006 of 1997 and a digital Nikon D100 still camera, which is a lost-cost SLR digital camera with an image resolution of 6 megapixels. See Figures 1-3, 5 and 6.

For the photogrammetric evaluation process the parameters of inner orientation must be known accurately. The calibrated focal length of TAL is 55.62 mm, the optical distortion is assumed to be negligible. Both cameras, however, the Rolleiflex 6006 (150mm lens) and the Nikon D100 (50mm lens) had to be calibrated using photogrammetric test fields.

Geodetic Measurements

Geodetic measurements using a total station were carried out during the photographic documentations in 1997 and 2003 (KIENAST & KAUFMANN 2004). 3-dimensional data was captured:

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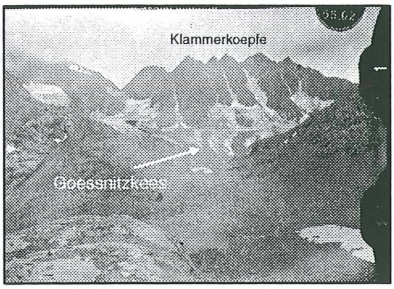
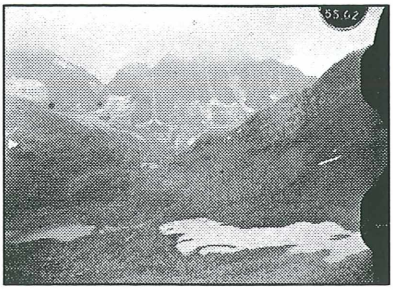
(1) The outline of the terminus of the glacier, (2) the shoreline of the proglacial lake, (3) additional points of the glacier surface (= velocity markers), and (4) a longitudinal profile. Additionally, photogrammetric control points which had been temporarily signalized were measured during the field campaign of 2003.



left stereo partner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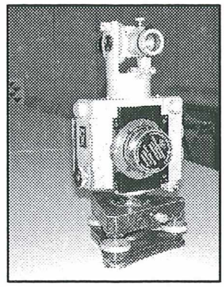
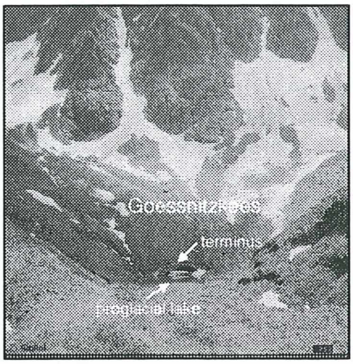

Zeiss TAL phototheodolite

Fig. 1: Goessnitzkees: Zeiss TAL stereo pair taken on 7 September 1988.



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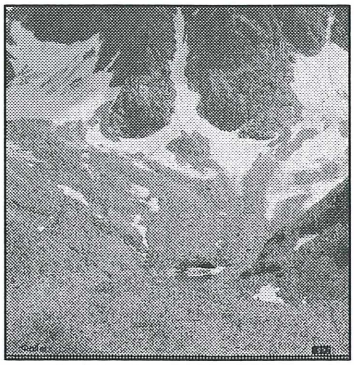
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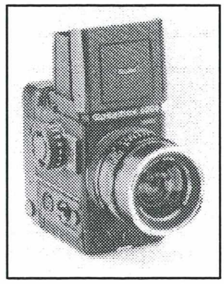
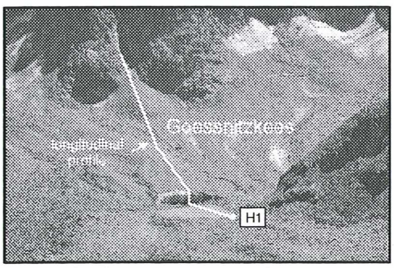

Rolleiflex 6006 réseau camera

Fig. 2: Goessnitzkees: Rolleiflex 6006 stereo pair taken on 11 August 1997.



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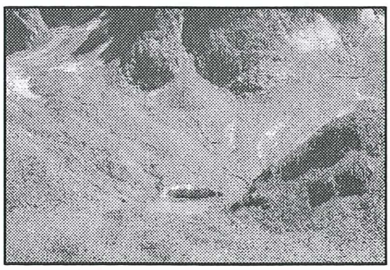
right stereo partner

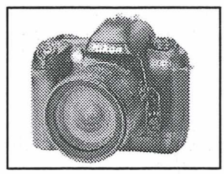
Nikon D100 digital camera

Fig. 3: Goessnitzkees: Nikon D100 stereo pair taken on 23 August 2003.

Photogrammetric Mapping

In order to facilitate a fully digital data flow in the photogrammetric evaluation process, all analogue photographs were digitized at 10 μm scanning resolution using the UltraScan 5000 photogrammetric scanner of Vexcel Imaging Austria. In a preprocessing step the many réseau crosses of the digitized Rolleiflex 6006 images were removed digitally, and furthermore, color fringes visible in the digital Nikon D100 photographs due to chromatic aberration of the optics used were minimized by appropriate scaling of the red and blue spectral bands in respect to the green one.

Photogrammetric orientation of all image data and subsequent 3D data collection were carried out using an ImageStation of Z/I Imaging. Absolute orientation of the multi-temporal stereo models was done as follows: A Rolleiflex stereo model of 2003 was selected as a reference model for obtaining tie points which could be used as control points in the other models. Such tie points were selected in areas of the deglaciated forefield of the Goessnitzkees and in the steep back walls of the cirque glacier.

Digital elevation models were obtained for all four stereo pairs through manual measurement of a regular grid of surface points. The terminus of the glacier was also mapped for the three glacial stages. From these data numerical values quantifying the glacier retreat were obtained, i.e. change of ice thickness and horizontal recession of the terminus. Mean annual flow velocities of selected points of the glacier surface could also be estimated.

Results

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.

Numerical values quantifying the glacier retreat are shown in Tab. 1. Moreover, various graphs and thematic maps were produced for visualization purposes (see Fig. 4 and also KAUFMANN & LADSTÄDTER 2004).

Change of ice thickness:	**Change of glacier length:**	**Equilibrium line altitude (ELA):** 2708 m (time period 1988-2003)
1988 – 1997: -13.6 m (= -1.51 m/year)	1988 – 1997: -85.2 m (= -9.47 m/year)	**Ablation gradient:** [100 m] 0.969 m w.e.
1997 – 2003: -12.2 m (= -2.03 m/year)	1997 – 2003: -61.5 m (= -10.26 m/year)	**Mean annual**
valid for elevation range [2530 m - 2560 m]		**horizontal flow velocity:** 30-60 cm/year

Tab. 1: 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.

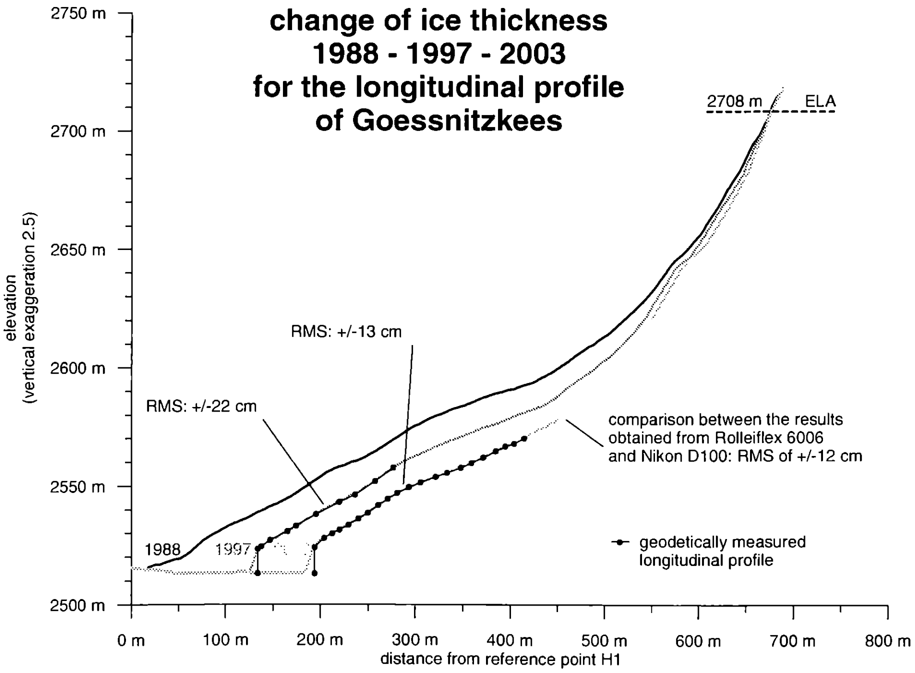

Fig. 4: Change of ice thickness along the longitudinal profile of Goessnitzkees for the time period 1988-1997-2003.

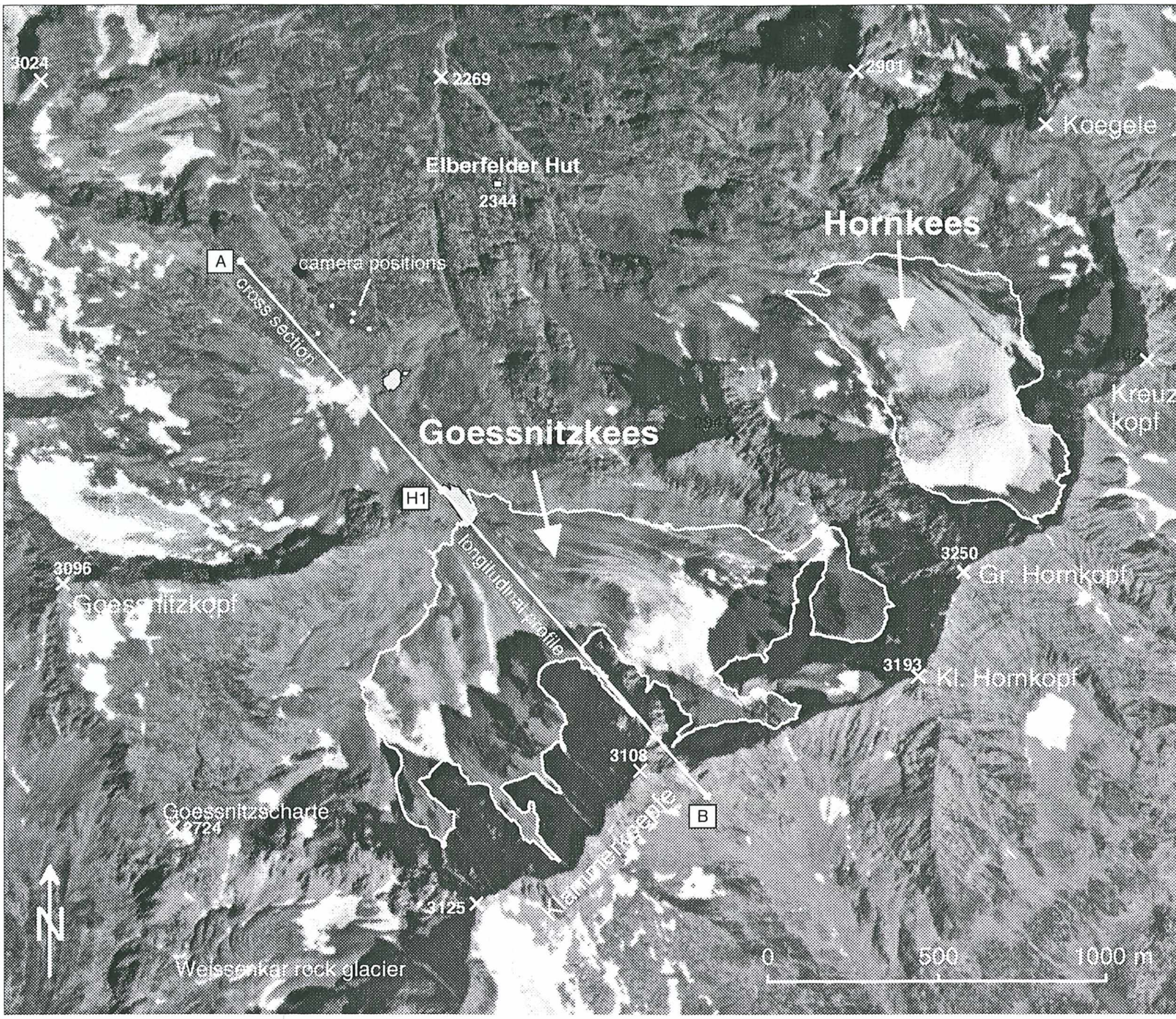

Fig. 5: Orthophoto of 1 September 1997 showing the camera positions and the position of the cross-section.

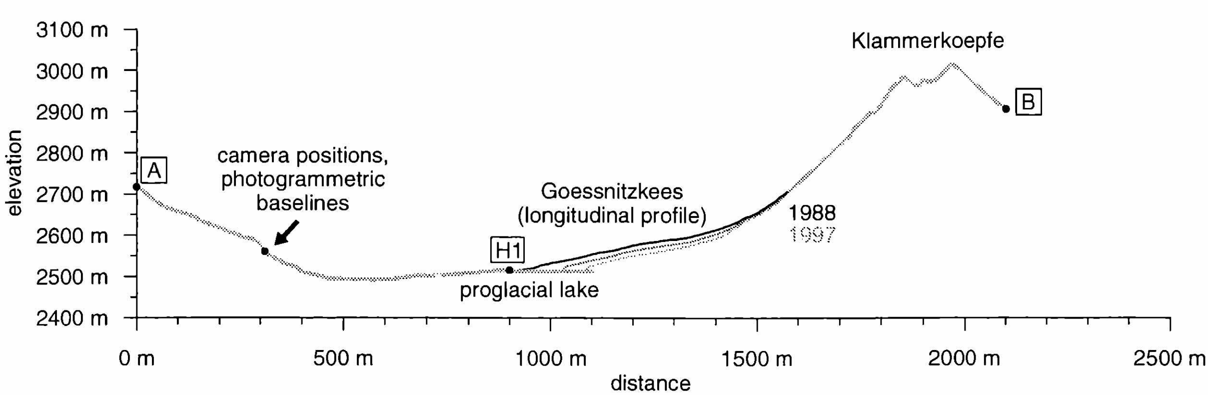

Fig. 6: Cross-section of Fig. 5 showing the longitudinal profiles of Goessnitzkees.

Discussion

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.

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 2004 and 2005 follow-up field campaigns were carried out. The results obtained will be published elsewhere.

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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