

MAPPING AND VISUALIZATION OF THE RETREAT OF TWO CIRQUE GLACIERS IN THE AUSTRIAN HOHE TAUERN NATIONAL PARK

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ABSTRACT

This paper describes the three-dimensional reconstruction of the glaciation of two neighboring cirques from the Little Ice Age advance of 1850 up to the present (1997), and the visualization of its spatio-temporal changes during this time period by means of standard methods of cartography and modern computer animation. The glaciers (Goessnitzkees and Hornkees) are located in the Schober group (Hohe Tauern range, Central Alps, Austria). A total of 9 different glacial stages were reconstructed. Computer-based analysis of the given time series was performed using a special digital database for glacier studies. Various numerical and graphical results show the course of deglaciation. Since the glaciers are largely covered by debris, a digital-photogrammetric procedure based on the Least Squares Matching (LSM) algorithm was developed in order to automate the generation of digital terrain models and the computation of three-dimensional flow vectors from the multi-year aerial photographs. This procedure facilitates the combination of aerial photographs of any scale and geometry. Practical results prove the applicability of this method in glacier mapping. The computer animation ("glacier movie") of the glacier retreat has been implemented in the PC-based information system of the Austrian Hohe Tauern National Park for public access.

KURZFASSUNG

Die vorliegende Arbeit beschreibt die dreidimensionale Rekonstruktion und Kartierung der Vergletscherung von zwei benachbarten Karen seit dem Ende der "Kleinen Eiszeit" (um etwa 1850) bis zur Gegenwart (1997) und desweiteren die Visualisierung der raum-zeitlichen Veränderung der Vergletscherung mit Hilfe klassischer kartographischer Methoden und moderner Computeranimation. Die beiden Gletscher (Goessnitz- und Hornkees) liegen in der Schobergruppe (Hohe Tauern, Zentralalpen) in Österreich. Insgesamt wurden 9 verschiedene Gletscherstände rekonstruiert. Die computergestützte Auswertung der vorliegenden Zeitreihe basiert auf einer speziellen digitalen Datenbasis für Gletscherstudien. Numerische und graphische Auswertergebnisse belegen den Gletscherrückgang. Da die beiden Gletscher im unteren Bereich größtenteils von Blockschutt bedeckt sind, konnte ein digital-photogrammetrisches Verfahren, welches auf der Bildzuordnung nach kleinsten Quadraten basiert, zur automatischen Ableitung von digitalen Geländemodellen und zur Berechnung von dreidimensionalen Fließvektoren entwickelt werden. Das vorgeschlagene Verfahren ermöglicht die Verknüpfung von geometrisch stark unterschiedlichen Luftbildern. Praktische Ergebnisse bestätigen die Anwendbarkeit dieser Methode in der Gletscherkartierung. Die Computeranimation ("Gletschervideo") über den Gletscherrückgang wurde in das PC-gestützte Informationssystem des Nationalparks Hohe Tauern integriert und kann von den Nationalparkbesuchern interaktiv abgerufen werden.

1 INTRODUCTION

1.1 Objectives

The present work has been carried out within the framework of a research project (1996-1998) financed by the Hohe Tauern National Park Fund. The scope of the work was to reconstruct the glacier history of two small cirque glaciers, Goessnitzkees and Hornkees, since the middle of the 19th century, which marked the last maximum extent of glaciation in the European Alps. This information is especially interesting in the context of regional and global climate change. The project was initiated and coordinated by project leader G.K. Lieb from the Institute of Geography (University of Graz), who was also responsible for glaciological interpretation. The Institute of Applied Geodesy (Graz University of Technology) was in charge of mapping and visualization. The project was intended to comprise the following tasks: (1)

reconstruction and mapping of glacial stages from 1850 to 1997 with the highest possible temporal and spatial resolution; (2) quantification of the areal and volumetric changes of the two glaciers based on the established digital database; (3) visualization of the glacier retreat by means of digital maps and computer animation; (4) investigation of advanced methods of digital photogrammetry, e.g. automatic point transfer, for speeding up certain mapping tasks, such as surface reconstruction of glaciated areas and determination of glacier flow velocities.

1.2 Geographical setting

Goessnitzkees and Hornkees ("kees" is the local name for glacier) are situated in the S of the main crest of the Hohe Tauern range (Central Alps) in Austria. The study area with the two glaciers is also part of the inner zone of the Austrian Hohe Tauern National Park (Figure 1). Due to the rough topography of the Schober group (steep rock faces, narrow crests, lack of flat surfaces at high elevations) the mean size of the glaciers does not exceed 0.18 km², making Goessnitzkees the largest glacier of this mountain group. The general exposure of the glaciers is NW with high crests and mountain tops to the S in both cases (Figure 2). Snow accumulation on both glaciers is mainly caused by avalanches. The surface substrate in both glacier forefields is dominated by coarse boulders, which also cover large parts of the glaciers themselves and originate from the rock faces in the S (cp. Figure 2). Further geographical and glaciological information about the study area can be found in Lang and Lieb (1993) and Lieb (2000).

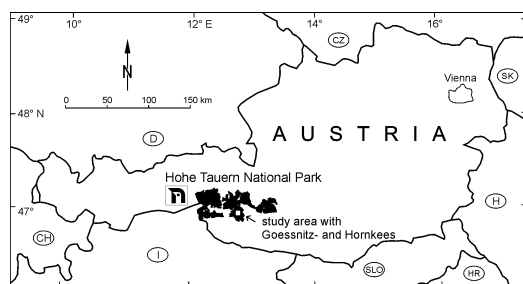


Figure 1. Location map

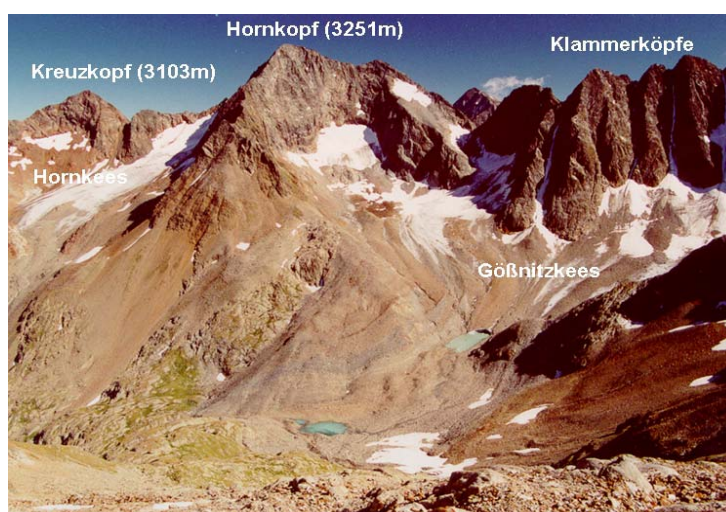


Figure 2. Terrestrial photograph of the study area taken from WNW towards both glaciers (August 8th, 1997)

2 RECONSTRUCTION AND MAPPING OF THE GLACIAL STAGES

2.1 Glacial stages of 1850, 1873 and 1929

The possibilities of reconstruction of older glacial stages are discussed in Lang and Lieb (1993). Since neither aerial nor terrestrial photographs of the glaciers are available for the period before 1954, the reconstruction of earlier glacial stages had to be based on field evidence (1850) and old maps (1873 and 1929). The areal extent of the 1850 stage was reconstructed quite well with the help of the Little Ice Age moraines, however, the reconstruction of the glacier surface based on contour lines had to be done hypothetically using longitudinal transects and cross-sections. The latter also applies to the 1873 stage, because the cartographic representation of the two glaciers in the map is rather poor and fuzzy. The first map showing contour lines and glacier boundaries with good quality is dated with 1929. The reconstruction of all 3 glacial stages was an iterative procedure, adjusting the glacier surfaces to each other based on glaciological constraints and using the 1:5,000-scale photogrammetric manuscript of the year 1997 (cf. next section) as a topographic reference.

2.2 Glacial stages of 1954, 1969, 1974, 1983, 1992 and 1997

Aerial photographs (1954-1997) were obtained from the aerial photograph archive of the Austrian Federal Office of Metrology and Surveying. Additional aerial surveys were carried out by a private company in 1997 and 1998. This heterogeneous set of photographs shown in Table 1 was mapped into a common coordinate system (Austrian Gauss-Krueger map projection). Detailed photogrammetric mapping (contour lines, break lines, ridge lines, drainage lines, spot heights, snow patches, glacier boundaries and other thematic features) at 1:5,000 scale was carried out using the

Kern DSR-1 analytical plotter. The delimitation of the glacier boundaries was sometimes quite difficult in areas where debris covered the glacier ice completely. However, the uncertainties could be sorted out by overlaying contour line plots of successive glacial stages. Another problem was encountered at the higher elevations of the glaciers where high albedo of snow covering the glacier prevented proper stereoscopy and therefore drawing of contour lines.

date of acquisition	number of photographs	focal length [mm]	image scale	film type
September 9, 1954	8	210.230	1:12,600-1:17,100	black-and-white
October 10, 1969	3	152.670	1:25,000-1:31,200	black-and-white
September 5, 1974	11	210.440	1:6,900-1:11,400	black-and-white
July 23, 1983	3	213.790	1:27,800-1:32,300	color infra-red
September 18, 1992	4	214.760	1:11,400-1:15,800	color infra-red
September 1, 1997	3	152.383	1:15,600-1:21,900	black-and-white
*September 16, 1997	2	152.700	1:28,300-1:34,500	black-and-white
+August 26, 1998	2	152.383	1:7,500-1:12,000	black-and-white

*These photographs were only used for orthophoto production.

+These photographs were only used in the work described in section 4.

Table 1. Aerial photographs used in the glacier study

2.3 Digital database for glacier studies

A new concept of a digital database for glacier studies has been implemented. The database consists of 4 different layers, i.e., (1) digital terrain model, (2) glacier boundaries and glacier masks, (3) orthophotos, and (4) collateral information, as shown in Figure 3.

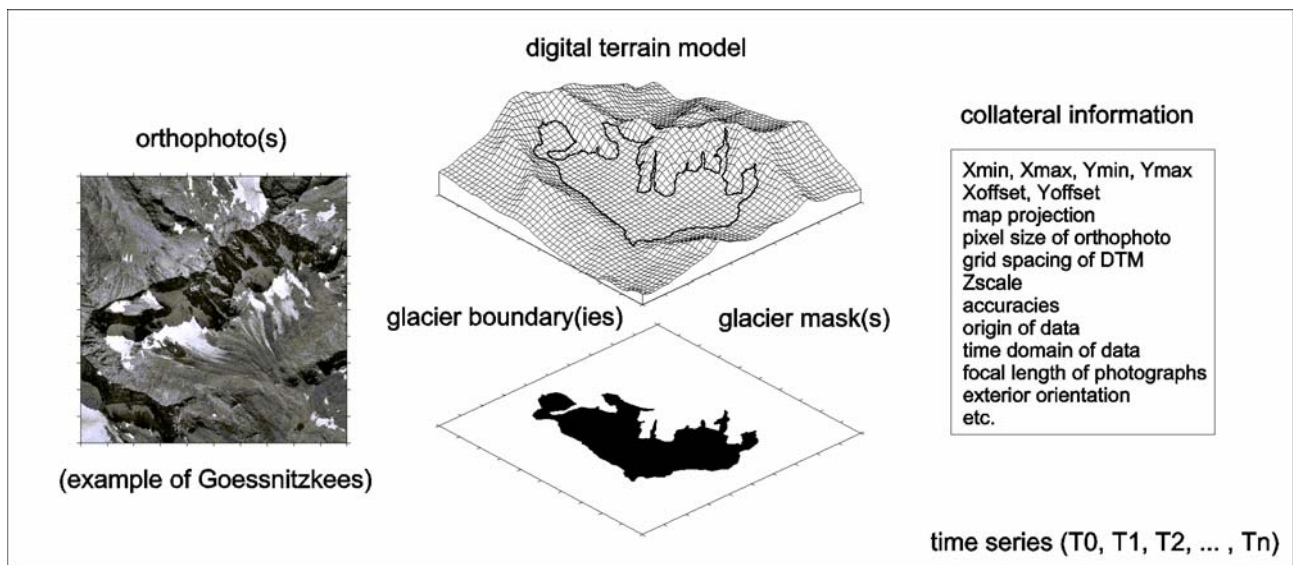


Figure 3. Layer structure of the digital database for glacier studies

Additional layers, e.g., containing photogrammetric manuscripts (".dxf", ".dwg" or ".dgn"), rectified satellite images, digital terrain models as triangulated irregular networks (TIN), geocoded terrestrial or airborne laser scanner data, value-added products etc., can be added easily.

The spatio-temporal analysis of one or more glaciers (2 in our case) located within a rectangular area, i.e., the study area, can be completely automated using standard GIS packages or in-house developed software, assuming that all elements of the various layers refer to the same three-dimensional (3D) cartesian coordinate system and have a unique time tag *T* representing the temporal domain. Wuerlaender and Eder (1998) have proposed a similar concept for setting up a digital glacier inventory of Austria. In the following the set-up of the digital database for the concrete project is outlined and some general remarks are given.

The digital terrain model (DTM) is of major importance for spatio-temporal glacier analysis (cp. Rentsch et al. 1990 and Schoener 1996) and for orthophoto production. High-resolution DTMs of all 9 glacial stages with a grid spacing of 2.5 m were derived using the software "MGE Terrain Modeler" of Intergraph (actually, a TIN was first computed and

afterwards gridded). Glacier boundaries are closed polygons whose height values z are interpolated from the respective DTMs. In order to facilitate the numerical analysis in a raster-based GIS, the polygons were gridded to fit the pixel geometry of the DTM. Binary glacier masks were obtained as a result. Multi-temporal orthophotos were produced for three reasons: (1) they allow detailed photo interpretation of glaciological, periglacial and other geomorphic features, e.g., crevasses, firn line, perennial snow patches, ice lakes, landslides and avalanches; (2) in addition to orthophoto maps, secondary products, such as axonometric/perspective views or stereo-orthophotos can be produced; (3) tandem orthophotos, i.e., 2 orthophotos derived from a stereopair or 3 orthophotos derived from a stereotriplet, can be used to improve the existing DTM and to derive 3D flow vectors by means of modern techniques of digital photogrammetry, e.g. point transfer based on Least Squares Matching (cp. section 4).

The fourth layer comprises project-relevant parameters and descriptions, i.e. non-graphical information required for proper interpretation of all other layers in the course of immediate and future evaluations. General parameters define the limits of the study area, the geometric properties of the cartographic projection, the various spatial resolutions (pixel size and grid spacing), and possible coordinate offsets and scaling factors. Most important, this layer should hold numbers for the assessment of the relative (inner) and absolute (outer) accuracy of each multi-temporal element. These numbers are needed for calculating the error budget (cp. Schoener 1996 and Kaufmann et al. 1999) of derivatives, e.g. volumetric changes. Referring to section 4 this layer should also include information for each tandem orthophoto, such as focal length and the elements of exterior orientation of the photograph used for the generation of the orthophoto, and the source of the DTM. The descriptions are supposed to be a loose collection of text files, progress reports, and computer listings.

2.4 Quantification of the glacier retreat

Any raster-based GIS may be used to analyze the content of the glacial database. At the beginning we used "Idrisi for Windows" from Clark University. However, due to obvious limitations of Idrisi Macro Language (IML) we decided to develop our own analysis software. The current version of this software package accounts better for the wide scope of requirements, i.e., glaciological questions, cartographic needs, output formats (readable listings and tables), batch processing, and computing speed. Changes in volume and surface height according to elevational intervals, e.g. 50 m or 100 m, were determined stringently as explained in Reinhardt and Rentsch (1986) and Schoener (1996). For reasons of comparison the classical methods of Finsterwalder (1953) and Hofmann (1958) were also implemented. Furthermore, glaciological parameters describing each glacial stage and the respective changes were computed. Results, shown in tables and graphs, and a comprehensive glaciological interpretation (given by Lieb) can be found in Kaufmann et al. (1999) as well as in Lieb (2000). In short, it can be said that the two glaciers have lost 52% (Goessnitzkees) and 61% (Hornkees) of their respective area since 1850, the decrease in volume was 77.5 mill. m³ and 38.2 mill m³, respectively. These values as well as some other data on changes in area and volume according to elevational intervals correspond quite well with results from other glaciers of the Central Alps.

3 VISUALIZATION OF THE GLACIER RETREAT

3.1 Digital maps

Within the framework of the glacier study an orthophoto map "Gößnitzkees- und Hornkees, Schobergruppe" at 1:10,000 scale was published in order to show the present glaciation. A copy of the black-and-white combined image-line map can be found in Lieb (2000). A more ambitious task of the present study was to visualize the course of the obvious deglaciation. Haeberling (1998) summarizes various possibilities of the cartographic representation of single glacial stages. In our case the low-cost grid-based graphics program SURFER was used as a cartographic authoring tool to produce maps of single glacial stages. SURFER offers the possibility to import, merge and visualize all digital data of the glacial database. In addition to this map type, other thematic maps showing the change of glaciation were produced. Figure 4 presents a black-and-white map showing the change in surface area for both glaciers from 1850 to 1997. The most important glacial stages were depicted in order to keep the map readable. A modification of this map also includes lines indicating selected longitudinal and cross profiles of the glaciers in order to visualize the vertical change of surface height of the glaciers in separate profile plots (shown in Kaufmann et al. 1999). Furthermore, color-coded thematic maps showing the elevational change of the glacier surfaces (change of ice thickness) between two periods of time were produced. The simultaneous presentation of elevational changes of more than one time period in a single map is questionable (cp. Kaeab 1998). Other solutions, such as computer animation, have to be addressed.

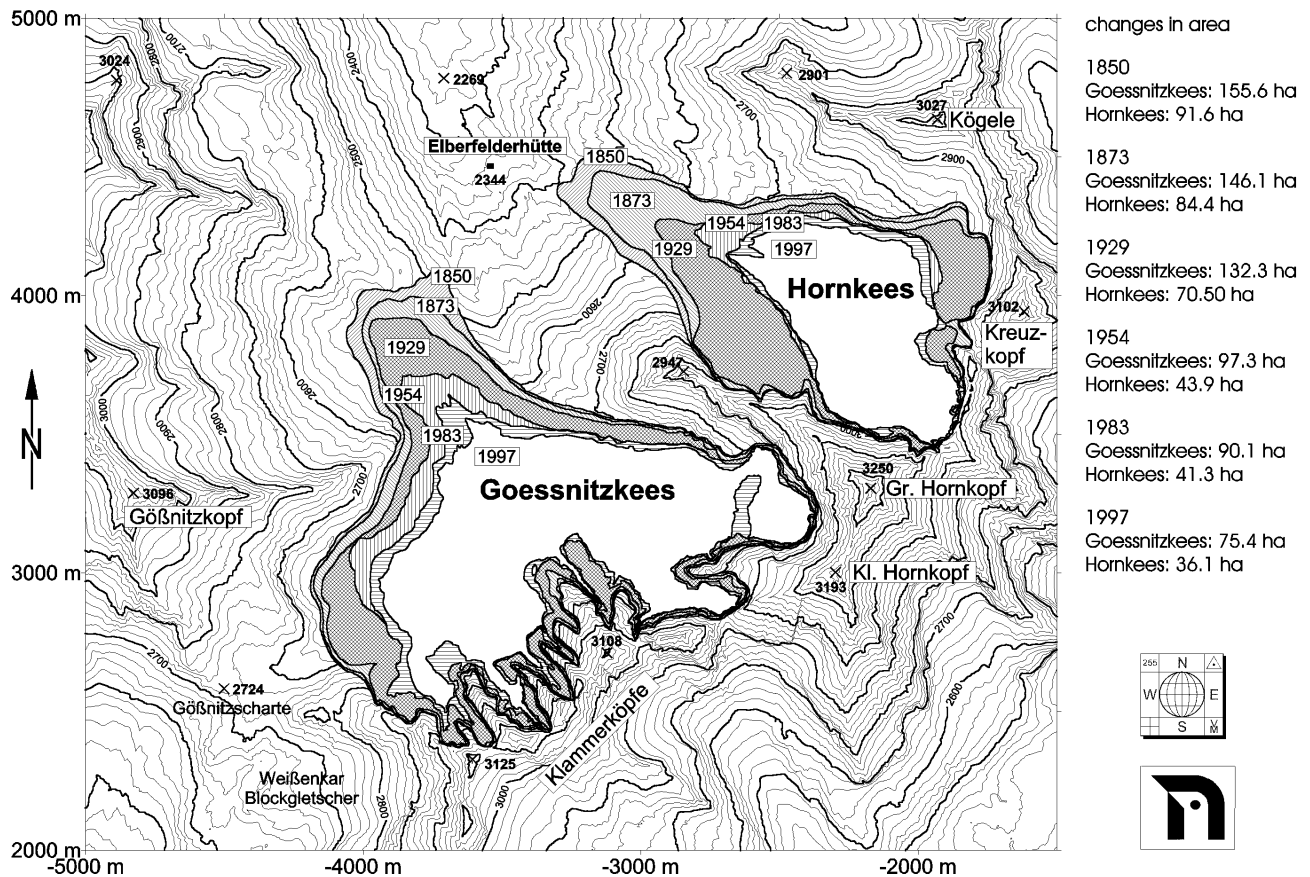


Figure 4. Thematic map showing the change in surface area of Goessnitzkees and Hornkees since 1850

3.2 Computer animation

Computer animation is used to visualize dynamic processes (good overview is given in WATT 1992). In contrast to computer simulation, where mathematical models provide numerical results, i.e. geometric properties are measurable, animation focuses on the graphical display of these results for visual perception. Therefore data accuracy is not of prime importance. Furthermore, the amount of data has to be limited in order to keep the data manageable and processing time low.

In the present study the dynamic change of glaciation has to be shown in a time-accelerator. All necessary data for this type of visualization is available through the digital database. The grid spacing of the DTMs has been increased to 15 m by means of averaging over a 6 by 6 window. Since only 9 glacial stages are available, irregularly distributed over the whole time period of 147 years, other intermediate glacial stages have to be interpolated from them, either based on a scientific glacier flow model (WAGNER 1996) or any other simplified geometric model. The first refers to computer simulation, whereas the second is adequate for the proposed task, especially because there was no theoretical glacier flow model available, at least for this type of small cirque glacier. In short, appropriate wireframe models (see Figure 3) of the surfaces can be generated on the basis of the DTMs. Any other glacial stage "in between" must be linearly interpolated in vertical direction with reference to the given time mark. The computation of this dynamic (glacier) model was accomplished by the interpolation module of the animation software (Maya of Alias|Wavefront). For the visualization the software computes images of the 3D model for the pre-defined time interval, i.e. the frame rate. The latter depends on the media used for presenting the animation, e.g. 25 frames/sec for PAL video, and it also defines the total amount of frames for a single animation sequence, e.g., 10 sec of animation require 250 (= 10 times 25) frames. The visualization requires not only the dynamic geometric model as input but also information on illumination and surface properties of the 3D object, both the glaciated and non-glaciated area. The animation software allows the selection of an appropriate light source, which can be positioned anywhere in the virtual space. The light source produces shades based on a Phong reflection model and, moreover, the relief of the surface casts shadows, which increase the visual perception of the 3D scene content. Surfaces are also associated with material properties, i.e. either procedural or mapped shaders. Glaciers are shown using procedural shaders, i.e. without texture in cyan color, and non-glaciated areas are mapped by means of a draped digital image, i.e. the orthophoto of 1997 with a spatial resolution of 1 m. Once all those settings have been defined a virtual camera can be positioned in the scene. Finally, the rendering

program calculates all frames within the specified time lapse as seen from the camera position. Each frame is stored in a single file, and subsequently transferred to a mass storage, i.e. a harddisk recorder. Animated sequences or even individual frames can be retrieved from this recorder, e.g. for producing a video film. Since the video resolution of 720 by 576 is not sufficient for high-quality printouts, higher resolution renderings are necessary for this purpose (see Figure 5).

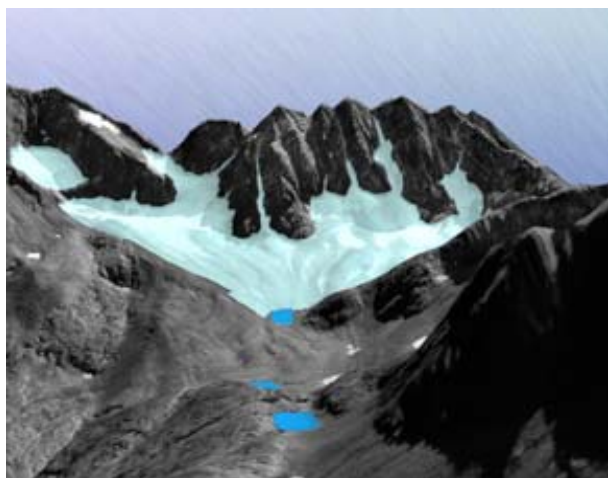


Figure 5. Single frame of the computer animation showing Goessnitzkees

The association with time in the animation is achieved visually by an inserted animated icon, i.e. a digital clock counting the years, like a mileage indicator in a car. In fact, an educational video film "glacier movie" has been produced which covers the scope of this paper and, as a highlight, shows the retreat of both glaciers as a very realistic animation. The monotonic sound track to the animation intensifies quite well the visual impression of the continuous glacier retreat. Short sequences of the computer animation can be downloaded from <http://www.cis.tu-graz.ac.at/photo/viktor.kaufmann/>.

4 AUTOMATION BY MEANS OF DIGITAL PHOTOGRAMMETRY

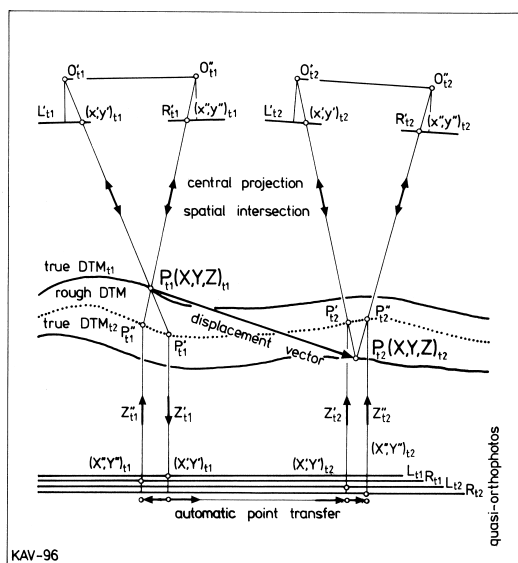


Figure 6. Determination of the displacement vector

show that the identification of homologous points in the multi-temporal stereopairs is quite troublesome and tedious. The number of successful measurements is limited. Kaeab (1996) has developed a method ("simultaneous monoplotting in multi-temporal stereomodels") which is principally based on the direct measurement of motion parallaxes using the analytical plotter.

Our proposed concept for measuring displacement vectors in digital multi-temporal photographs using digital photogrammetry is outlined in Figure 6. The basic ideas of this procedure have been taken from Baltsavias (1996). The photogrammetric orientation of the two stereopairs from the time periods t_1 and t_2 is assumed to be known, either using an analytical plotter or a digital photogrammetric plotter. 4 "quasi-orthophotos" are generated using a preliminary (rough) DTM. The algorithm of automatic point transfer is based on image pyramids, interest operators (e.g. Foerstner operator) and area-based Least Squares Matching (Ackermann 1984). The 4 homologous points obtained in the quasi-orthophotos are then back-projected into the respective photographs. Finally, the 3D coordinates of the homologous object points are calculated by means of spatial intersection and used for defining the displacement vector. At this stage multi-photo and multi-constraints matching (cp. Baltsavias 1991) is not implemented. Results are tested on γ -parallaxes.

4.1 Concept

An Intergraph digital photogrammetric workstation (ImageStation ZII) was available for the second half of the project. Until then only software for stereomodel set-up, photogrammetric feature collection and orthophoto production had been at our disposal. This digital system could have been used for the photogrammetric work of section 2.2 and would have rendered more or less the same results. Actually, digital photogrammetry benefits from a high degree of automation which is mainly based on the substitution of manual measurements by equivalent computer techniques, such as digital image matching. Baltsavias et al. (1996) have tested digital photogrammetric systems with emphasis on DTM generation for glacier studies. One of the objectives of our study was to determine mean annual surface flow velocities of the glaciers. 3D displacement vectors can be determined by tracking individual boulders of the debris covering the glacier in the multi-year aerial photographs. Practical results using the analytical plotter

An independent control of the x -parallax is only possible in the case that a stereotriplet of the study area is available. Both true DTMs can be derived if the number of match points is sufficiently high. In areas where there is no surface height change the calculated object points should be identical.

4.2 Practical experiment

The above mentioned concept has been implemented by Ladstaedter (1999) on a Windows-NT platform. The developed software consists of 4 independent modules with the following functions: (1) selection of interest points; (2) prediction of approximate positions for image matching; (3) Least Squares Matching; (4) photogrammetric point reconstruction. The practical experiment comprises the determination of both the surface height change and the flow velocity of Goessnitzkees for the time period 1997-1998. The area of interest is covered by a stereotriplet (1997) and a stereopair (1998) as listed in Table 1. The flight lines of both surveys differ in yaw by 60 degrees. A Kern DSR-1 was used for high-precision photogrammetric orientation. All 5 photographs were scanned with a pixel size of 12 μm using the Wehrli RM-1 film scanner. The elements of exterior orientation of each photograph were directly imported into the ImageStation. Subsequent to inner orientation, 5 orthophotos with a pixel size of 25 cm were computed covering an area of 500 m by 600 m in the lower part of the glacier, which is largely covered by debris. Areas at the higher elevations with dark shadows and high albedo were excluded because image matching was expected to produce no or incorrect results. A strongly smoothed version of the existing DTM of 1997 was taken as a preliminary DTM. The possibility of batch processing within this software proved to be useful since the tuning of various parameters, e.g. window size for matching, error limits, etc., made an iterative procedure necessary.

4.3 Results

In the stereotriplet of 1997 a total of 4226 match points were found, whereas in the stereopair 3942 points were successfully matched. Using this data set 2914 glacier flow vectors were computed in addition to the true DTMs of the 1997 and 1998 stage. Detailed error analysis confirmed the high accuracy of the implemented image matching algorithm. Flow vectors and interpolated contour lines can be checked visually in 3D when simultaneously displayed with an appropriate stereomodel using the digital photogrammetric system. However, the most interesting result of this experiment was that we could prove that the RM-1 scanner causes cyclic geometric scanning errors in swath direction. This effect can be seen perfectly well when plotting iso-lines of the resulting y -parallaxes of the stereomodels. The matching accuracy is about 1-2 μm . Of course, systematic errors may also be due to inconsistent inner orientation with respect to the analytical plotter. In our opinion great attention has to be placed on the geometric as well as radiometric quality of image scans.

5 CONCLUSIONS AND OUTLOOK

Various glacier studies are presently carried out all over the world in order to monitor glaciation. Ongoing global warming suggests that the process of deglaciation is still continuing. Glaciers in high mountain areas have been the subject of photogrammetric surveys ever since the very beginning of photogrammetry. Digital photogrammetry offers great potential to increase productivity and cost efficiency. However, well-known factors, such as strong relief displacement, shadows and low contrast in areas with high albedo, still hamper successful automation of photogrammetric mapping. An experienced operator will be needed more than ever to interact with manual measurements. Concerning glaciers (= ice glaciers and rock glaciers) a future monitoring system should run on an operational basis, not only for some selected glaciers but for many glaciers evenly distributed in the high mountains of the globe. Geometric and radiometric quality of image scans is of crucial importance, at least for high precision measurements. Aerial or even terrestrial laser scanning is a new option for automatic DTM generation of glaciated areas in high mountain terrain. In summer 2000, the Institute of Applied Geodesy (Technical University of Graz) and the Institute of Image Processing (Joanneum Research Graz) are going to investigate a terrestrial laser scanning system (by Riegel, Austria) for glacier monitoring. Computer animation is a valuable tool for visualizing complex time-dependent phenomena. The produced video sequences of glacial retreat give a vividly realistic picture and can be easily integrated in multimedia systems. It is a means to sharpen the public awareness concerning environmental change.

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REFERENCES

- Ackermann, F., 1984. High precision digital image correlation. In: Vorträge der 39. Photogrammetrischen Woche 1983, Schriftenreihe des Instituts für Photogrammetrie, Stuttgart, pp. 231-243.
- Baltsavias, E.P., 1991. Multiphoto geometrically constrained matching. Institute of Geodesy and Photogrammetry, ETH Zurich, Mitteilungen, 49, 221 p.
- 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, pp. 63-67.
- Baltsavias, E.P., Li, H., Stefanidis, A., Sinnig, M., Mason, S., 1996. Comparison of two digital photogrammetric systems with emphasis on DTM generation: case study glacier measurement. In: International Archives of Photogrammetry and Remote Sensing, Vienna, Vol. XXXI, Part B4, pp. 104-109.
- Finsterwalder, R., 1953. Die zahlenmäßige Erfassung des Gletscherrückgangs an den Ostalpen. Zeitschrift für Gletscherkunde und Glazialgeologie, 2/2, pp. 189-239.
- Haerberling, Ch., 1998. Benutzerbedürfnisse und Anforderungen zu neuartigen Gletscherdarstellungen. In: Hochgebirgskartographie/ Silvretta '98 – High Mountain Cartography, Wiener Schriften zur Geographie und Kartographie, 11, pp. 81-93.
- Hofmann, W., 1958. Der Vorstoß des Nisqually-Gletschers am Mt. Rainier, USA, von 1952 bis 1956. Zeitschrift für Gletscherkunde und Glazialgeologie, 4/1-2, pp. 47-60.
- Kaeab, A., 1996. Photogrammetrische Analyse von Gletschern und Permafrost. Vermessung, Photogrammetrie, Kulturtechnik, 12/96, pp. 639-644.
- Kaeab, A., 1998. Visualisierung glazialer und periglazialer Prozesse: Probleme und Ansätze. In: Hochgebirgskartographie/ Silvretta '98 – High Mountain Cartography, Wiener Schriften zur Geographie und Kartographie, 11, pp. 94-101.
- Kaufmann, V., Krobath, M., Lieb, G.K., Sulzer, W., 1999: Gössnitz- und Hornkees – die Entwicklung zweier Kargletscher der Schobergruppe (Nationalpark Hohe Tauern, Kärnten) seit dem Hochstand von 1850. Unpublished report, Institute of Geography, University of Graz, 76 p.
- Ladstaedter, R., 1999. Automatisierte Messung von Geländemodellen und Fließvektoren aus digitalen, multitemporalen Orthophotos – ein neuer Ansatz für das Blockgletscher-Monitoring. Unpublished thesis, Institute of Applied Geodesy, Graz University of Technology, 185 p.
- Lang, H., Lieb, G.K., 1993. Die Gletscher Kärntens. Verlag des Naturwissenschaftlichen Vereins für Kärnten, 184 p.
- Lieb, G.K., 2000. Die Flächenänderung von Gößnitz- und Hornkees (Schobergruppe, Hohe Tauern) von 1850 bis 1997. In: Festschrift für Heinz Slupetzky zum 60. Geburtstag, Salzburger Geographische Arbeiten, 36, pp. 83-96.
- Reinhardt, W., Rentsch, H., 1986. Determination of changes in volume and elevation of glaciers using digital elevation models for the Vernagtferner, Ötztal Alps, Austria. Annals of Glaciology, 8, pp. 151-155.
- Rentsch, H., Welsch, W., Heipke, Ch., Miller, M., 1990. Digital terrain models as a tool for glacier studies. Journal of Glaciology, 36 (124), pp. 273-278.
- Schoener, M., Schoener, W., 1996. Photogrammetrische und glaziologische Untersuchungen am Gåsbre (Ergebnisse der Spitzbergenexpedition 1991). Geowissenschaftliche Mitteilungen TU Wien, 42, 118 p.
- Wagner, St., 1996. Dreidimensionale Modellierung zweier Gletscher und Deformationsanalyse von eisreichem Permafrost Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, 146, 135 p.
- Watt, A., Watt, M., 1992. Advanced animation and rendering techniques – theory and practice. ACM Press, 455 p.
- Wuerlaender, R., Eder, K., 1998. Leistungsfähigkeit aktueller photogrammetrischer Auswertemethoden zum Aufbau eines digitalen Gletscherkatasters. Zeitschrift für Gletscherkunde und Glazialgeologie, 34, pp. 167-185.