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The use of GPS and DGPS for glacier monitoring at the tongue of Pasterze Glacier between 2003 and 2008

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Summary

The Global Positioning System (GPS) and the differential Global Positioning System (DGPS) have been applied for this study at the 4.5 km^2 large tongue of Pasterze Glacier, the largest glacier of the Austrian Alps located in the Hohe Tauern National Park. D/GPS research presented here has been carried out during the period 2003 to 2008. The D/GPS measurements were carried out partly to support other monitoring techniques. In total, D/GPS measurements focussed on (a) positioning and tracking of aligned stone locations at three cross profiles at the glacier tongue where elevation change and movement is measured annually by tachymetric surveys, (b) precise displacement measurements of single point locations at the central cross profile for flow direction studies, (c) measurement of the retreat of the glacier terminus, (d) glacier shrinkage at its lateral margin, (e) positioning of control points for terrestrial laser scanning (TLS) at the glacier surface, and (f) tracking of selected large rocks for glacier flow velocity and flow direction studies. The presented und discussed results demonstrate the high potential of the D/GPS for detailed glacier monitoring detecting even small changes.

Keywords

Pasterze Glacier, glacier monitoring, GPS, differential GPS, Hohe Tauern National Park.

Introduction

Detecting and monitoring changes in glacier behaviour is crucial in understanding the effects of the ongoing climate change on alpine environments. Detailed mapping is a difficult task in areas with minor topographic information where the landform scale is too small for the precise location or where the surface is changing rather rapidly as for instance in glaciated areas in the European Alps at present. However, detailed maps regarding the size and shape are required in order to establish climate-glacier relationships. The development of Global Positioning Systems (GPS) is a significant contribution for detailed glaciological surveying and mapping. By applying this method it is possible to map with a high accuracy at much faster rates than before, when this could only be achieved by traditional (and time-consuming) geodetically surveys. Achieving high accuracy is especially true using a differential GPS (DGPS) system that allows mapping continuously points or lines in a low-relief terrain with an error of a few centimetres.

The aim of this contribution is to present different applications of GPS and DPGS for glacier monitoring exemplary demonstrated at the tongue of Pasterze Glacier in Austria. The research presented here was carried out during annual glaciological surveys as well as in the project "ALPCHANGE - Climate change and impacts in southern Austrian alpine regions".

Study area

The Pasterze Glacier (47°05'N, 12°44'E) is situated at the foot of the Großglockner mountain (3798 m a.s.l.), the highest summit of Austria, in the Hohe Tauern Range, Austria (Fig. 1). The studied glacier is a compound valley glacier fed by a number of tributaries. Pasterze Glacier reaches a length of 8.4 km, comprises a volume of about 1.8 km^3 (Lieb 2004), ranges from 2065 to ca. 3500 m a.s.l. and covered in 2002 an area of 17.5 km^2. The glacier is the largest ice mass in Austria. According to the most recent Austrian glacier inventory, the glacier extent was 18.4 km^2 in 1998 (A. Lambrecht, pers. com. 2007) indicating substantial recent glacier recession (details in Kellerer-Pirklbauer 2008, Kellerer-Pirklbauer et al. 2008).

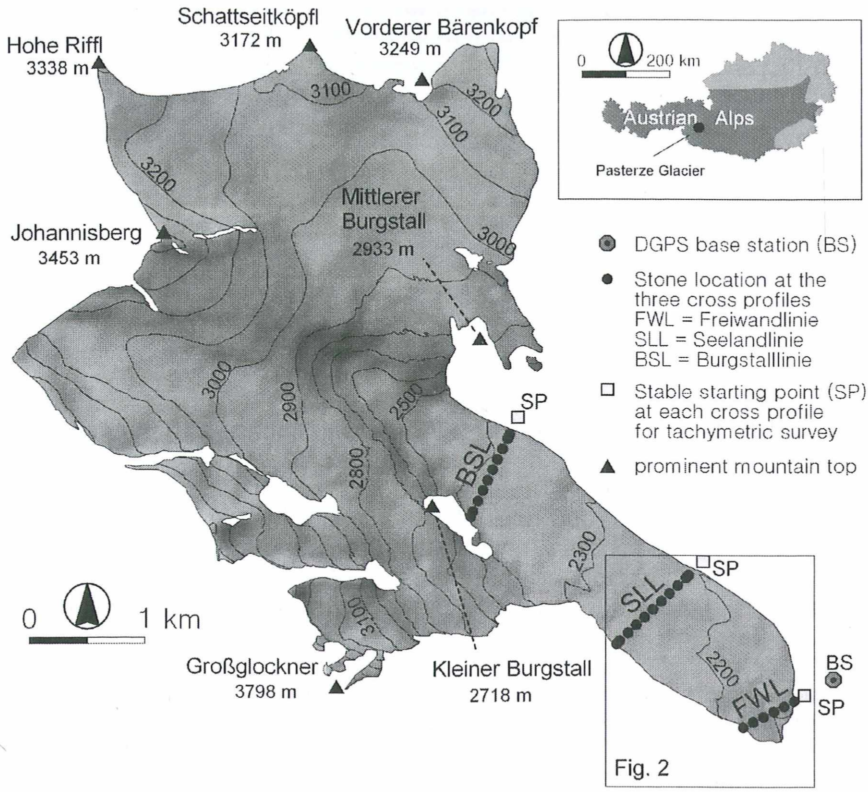

Figure 1: The Pasterze Glacier and its spatial extent in 2000. Stone locations of the three cross profiles at the glacier tongue where elevation change and movement is measured annually by tachymetric surveys, the stable starting points (SP) for these surveys as well as the location of the DGPS base station (BS) are indicated. The background map is based on glacier contour lines from 2000 of the topographical map ÖK1:50000 sheet 153 (Großglockner), Federal Office of Metrology and Surveying.

Method

Originally the GPS was conceived to indicate positions in the Earth surface in any place independently of the meteorological conditions. Even more precise positioning is possible if two GPS receivers are used. One receiver (mobile station) is used in the field for mapping (i.e. glacier margin) and a second receiver is located at a nearby known position (base station). The data of the base station can be used to correct most of the errors that are intrinsic to the system. The correction factors can be either transmitted directly via radio to the mobile station enhancing spatial accuracy, or the corrections factors can be used for later post-processing of the data. This setup is called differential GPS (DGPS; LEICK 1990). The accuracy of the GPS-results diminishes with increasing distance between the mobile and base stations. For measurements on the Pasterze Glacier the base station was located at the Franz-Josefs-Höhe hence the base station was located within a distance of 3.5 km from the remotest target point.

For this study the global positioning system (GPS) and in particular the differential GPS (DGPS) has been applied during the period 2003 to 2008 for the following glaciological research objectives: (a) positioning and tracking of aligned stone locations at three cross profiles at the glacier tongue where elevation change and movement is measured annually by tachymetric surveys, (b) precise displacement measurements of single point locations at the central cross profile for flow direction studies, (c) measurement of the retreat of the glacier terminus, (d) glacier shrinkage at its lateral margin, (e) positioning of control points for terrestrial laser scanning (TLS) at the glacier surface, and (f) tracking of large rocks for glacier flow velocity and flow direction studies.

Measurements taken by DGPS are naturally of higher accuracy compared to the ones taken by GPS. The accuracy of the DGPS measurements at Pasterze Glacier has been exemplarily calculated for the measurements at the glacier cross profile "Seelandlinie" (Figs. 1 & 2) in 2004. Results show that at the total number of 224 single DGPS measurements the accuracies are as follows: in *x*-dimension ±20.4cm, in *y*-dimension ±28.9cm and in *z*-dimension ±39.8cm. This indicates that at Pasterze Glacier – with its high-relief topography negatively influencing the GPS-signal quality – the *x* and *y* accuracies are in the order of 20-30cm. The accuracy of the GPS measurements at Pasterze Glacier might be regarded as at least one order of magnitude lower as the ones of the DGPS measurements. Only in 2008 the GPS approach was applied by using the GARMIN GPSMap

60CSx device. GPS-based mapping of the glacier margin was partly tricky because of difficulties in the distinction between slopes free of buried glacier ice and slopes underlain by quasi-relict glacier ice, glacier crevasses, unstable ice margins as well as steep ice cliffs formed by e.g. incising meltwater channels.

Results and brief discussion

Results regarding the positioning and tracking of aligned stone locations at three cross profiles at the glacier tongue where elevation change and movement is measured annually by tachymetric surveys are presented in Fig. 1 for the entire glacier tongue and in Fig. 2 for the lower two cross profiles SLL and FWL. The scientific background, the glaciological relevance of these stone locations as well as the tachymetric survey principle is explained in KELLERER-PIRKLBAUER et al. (2008)

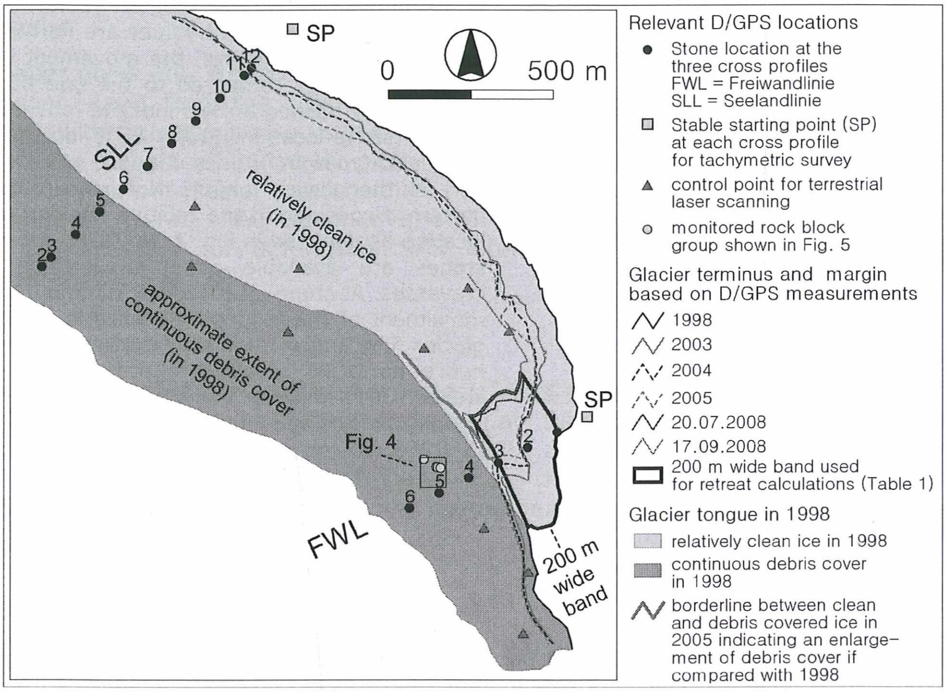

Figure 2: The lower part of the tongue of Pasterze Glacier in 1998, spatial changes during the period 1998-2008, and D/GPS measurement locations. The continuous supraglacial debris cover in 1998 and – to some extent its shift towards the east until 2005 – are indicated. The glacier margins are indicated for 1998 (based on orthophotographs from Sept. 1998), 2003 (16.09.; DGPS), 2004 (20.09.; DGPS), 2005 (21.09.; DGPS) and two times for 2008 (20.07. and 17.09.; twice GPS). The 200 m wide band at the clean ice part of the glacier terminus used for the retreat calculations presented in Table 1 is outlined.

Results regarding precise displacement measurements of single point locations at the central cross profile SLL for flow direction studies are depicted and explained in Fig. 3. These results indicate that the movement along this cross profile behaves in a radial manner meaning that supraglacial stones at the glacier margin move oblique outward whereas supraglacial stones at the valley centre move relatively straight downvalley, parallel to the main flowing direction.

Results regarding the retreat of the glacier terminus as well as glacier shrinkage at its lateral margins are depicted in Fig. 2. Table 2 gives a summary on the analysis of the glacier retreat along a 200 m wide band at the clean ice part (Fig. 2) during the ten year period 1998 to 2008 as well as during the summer of 2008. Within 10 years this glacier lost along a 200 m wide band at the glacier terminus 0.07 km^2 which is equivalent to about 1/250 of the entire glacier area in 2002. Interesting is the fact that the areal glacier loss during the two months July-September 2008 was larger than during the entire years 2003-2004 and 2004-2005.

Results regarding the positioning of control points (reflective targets) at the glacier surface for TLS are depicted in Fig. 2. The glaciological relevance of the control points for TLS are explained in AVIAN et al. (2007). Results regarding the tracking of large rocks for glacier flow velocity and direction studies are exemplarily depicted and explained in Fig. 4 for a prominent rock block group close to the glacier terminus which moved ca. 58 m during the period 1998 to 2008. Results show that the flow direction at this site differs substantially from the main valley axis. This can be explained by changes in the glacier surface geometry caused by differences in glacier ablation due to the shielding effect of a partly existing continuous debris cover. Ablation close to the glacier terminus at the debris-covered side is reduced by about 50% compared to the clean ice side (KELLERER-PIRKLBAUER et al. 2008). This affects also the subglacial ice flow dynamics as evidenced by the striation pattern of glacially reshaped rock outcrops in the proglacial area (Fig. 5).

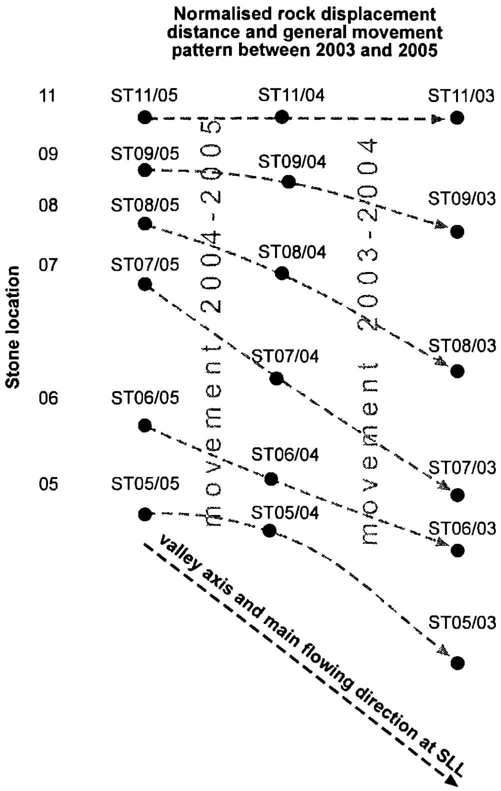

Figure 3: Stone displacement at the glacier surface relative to the valley axis (main flow direction indicated as black dashed arrow) at the cross profile "Seelandlinie" (SLL) during the two glaciological years 2003-2004 and 2004-2005. Displacement values are normalised at each stone location. In general, the movement in the second period was lower compared to the one during the first period. Grey dashed arrows indicate movement direction at each stone location. Stone 11 is located close to the left glacier margin, stones 5 and 6 close at the central part of the glacier tongue. Note the radial movement pattern if considering the relative position of each stone location as depicted in Fig. 2. No DGPS measurements of stones are available at stone location 10 due to crevasses. At stone locations 04, 03 and 02 the observed movement of the respective stones is a mixed signal of glacier flow and surface sliding of stones on ice surface, hence no DGPS results are presented here for these stones. DGPS-data for this graph were collected in 2005. See Fig. 2 for stone locations.

Table 1: Areal losses along a 200 m wide band at the clean ice part of the glacier terminus due to glacier retreat between 1998 and 2008 indicated in Fig. 2. The margin of 1998 is based on orthophotographs from Sept. 1998. The margins for September 2003, 2004 and 2005 as well as for July and September 2008 are based on D/GPS measurements.

Glacier retreat on an annual basis (glaciological year: Sept. to Sept.)		
Period (number of glac. years)	Areal loss (m²)	Average per year (m²)
09.1998-09.2003 (5)	37788	7558
09.2003-09.2004 (1)	3857	3857
09.2004-09.2005 (1)	3704	3704
09.2005-09.2008 (3)	23031	7677
09.1998-09.2008 (10)	68380	6838

Glacier retreat during two months in summer 2008 (July to Sept.)	
Summer 2008	Areal loss (m²)
07.2008-09.2008	4481

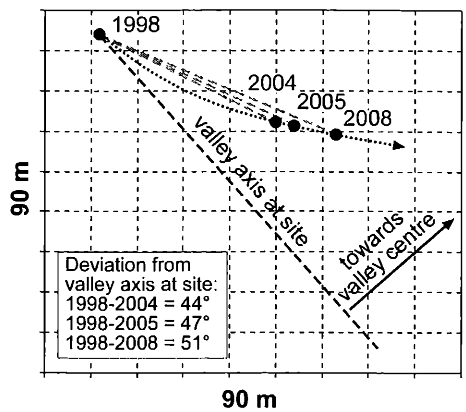

Figure 4: Change in main flow direction of a prominent rock block group due to changes in the ice flow dynamics. At this site the increasing deviation of the flow direction from the valley axis over time can be explained by an increasing glacier flow component from the valley side towards the valley centre. This movement is caused by higher ablation rates at the valley centre due to the absence of a protecting debris cover compared to the site of the rock block group which itself is protected by a debris cover. This difference in ablation caused a change in the surface geometry of the glacier (see Kellerer-Pirklbauer et al. 2008 for details on this process). For location of the site and the distribution of supraglacial debris at the site and areas free of debris (clean ice) to the NW see Fig. 2.

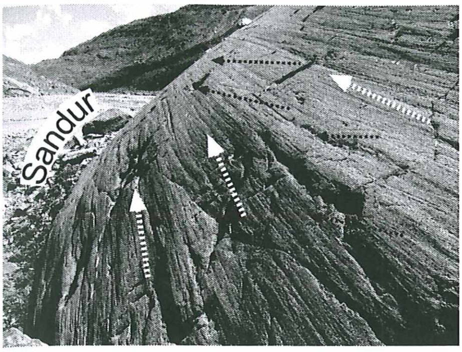

Figure. 5: Glacially reshaped rock outcrop at the proglazial area of Pasterze Glacier showing two different generations of striations related to a former (primary) flowing direction indicated by white arrows and a later (secondary) flowing direction indicated by black arrows. The primary flowing direction was following the valley axis during periods of larger glacier extent. The secondary flowing direction was more orientated from the valley side to the valley centre related to the degrading ice mass and related changes in the ice flow dynamics. The proglacial outwash plain (Sandur) is indicated. Photograph 19.07.2008, view towards SE.

Final remarks

This short paper gives only a brief overview of the use of GPS and DGPS in glaciological studies at Pasterze Glacier. Apart form the different glaciological aspects mentioned here, one should point out that DGPS at this glacier is also used for other purposes such as mapping peat pieces and wood fragments in the proglacial outwash plain (*cf.* KELLERER-PIRKLBAUER & DRESCHER-SCHNEIDER, this volume), for carrying out glacier mass balance measurements (by Central Institute for Meteorology and Geodynamics, Vienna; W. Schöner and B. Hynek) or for precise ice thickness change measurements necessary for differential SAR interferometry/DINSAR (by Joanneum Research, Graz; R. Wack and A. Sharov).

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