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Satellite-based measurement of the surface displacement of the largest glacier in Austria

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Summary

Surface displacement at Pasterze Glacier (47°05'N, 12°44'E, 17.5 km²), the largest glacier in Austria, has been measured by means of differential SAR interferometry (DINSAR). SAR imagery recorded during the summer periods between 1995 and 2001 was available for this analysis. One out of three analysed image pairs of the ERS (European Remote Sensing Satellite) Tandem Mission (20.8.1995-21.8.1995) showed sufficient coherence at the partly debris-covered glacier tongue for deriving a significant displacement image (interferogram). Maximum surface displacement rates of 30-40 mm per day in the SAR line-of-sight have been calculated for this image pair. Based on these results and additional reasonable assumptions a maximum annual surface displacement rate of 20-30 m valid for 1995 can be estimated. The calculated annual displacement values are comparable to the values measured directly in the field tachymetrically. This underlines the high potential of ERS-Tandem-Mission images with a time interval of one day for glacier monitoring at mid latitudes during the summer period for such large areas as for instance the Hohe Tauern National Park with its 1800 km².

Keywords

Pasterze Glacier, DINSAR, ERS Tandem Mission, Hohe Tauern National Park.

Introduction and objective

Detecting changes in surface elevation and velocity of glaciers is relevant for a number of glaciological research questions such as mass balance studies or 3D modelling (Oerlemans 2001, Kääb 2005). To observe such changes area-wide over entire valley glaciers, remote sensing techniques such as photogrammetry (Kääb 2005) or radar imagery techniques – in particular the interferometric SAR (=Synthetic Aperture Radar) method (Kenyi & Kaufmann 2003)– are required.

This study discusses the detection and satellite-based measurement of the surface displacement of Pasterze Glacier (47°05'N, 12°44'E, 17.5 km²), the largest glacier of the Eastern Alps, by means of differential SAR interferometry (DINSAR).

Study area

The Pasterze Glacier (47°05'N, 12°44'E) is the largest glacier of the Austrian Alps with a surface area of about 17.5 km² in 2002 ranging in elevation between 2065 and 3500 m a.s.l. The glacier is a compound valley glacier fed by a number of tributaries located in the heart of the Hohe Tauern National Park at the foot of Mt. Großglockner (3798 m a.s.l.), the highest mountain of Austria. The ablation area is primarily formed by a glacier tongue covering about 3.6 km². The glacier tongue is connected to the main accumulation area by a distinct icefall named "Hufeisenbruch". In particular the right part of the *c.*5km long glacier tongue is covered by a pronounced debris mantle with an extent of *c.*1.2 km² in 2002 (Fig. 1) affecting ice ablation (Kellerer-Pirklbauer 2008, Kellerer-Pirklbauer et al. 2008).

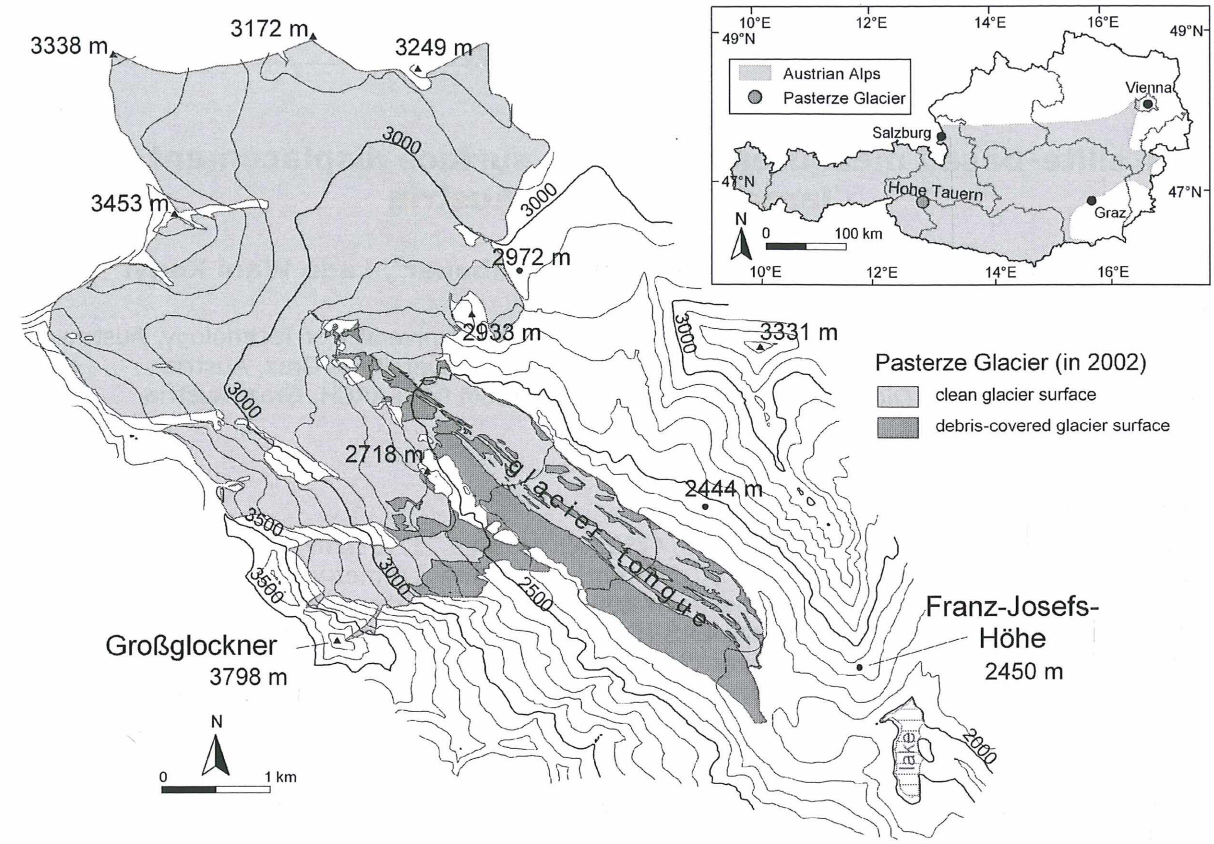

Figure 1: The Pasterze Glacier and its supraglacial debris cover in 2002 (based on the map Alpenvereinskarte Glocknergruppe, 9th Edition, published by the German Alpine Association in 2006, scale 1:25 000).

Method and data base

Both the amplitude and the phase of the backscattered echoes are normally recorded in a SAR system. However, the phase of a single SAR image is of no use and therefore, conventionally the amplitude or intensity image is usually provided to the end users. In contrast, the phase difference of two backscattered SAR echoes of the same area on the ground taken at slightly different view angles can be utilized to generate digital elevation model (DEM) of the imaged terrain (PRATI et al. 1992, ZEBKER et al. 1994, KENYI & RAGGAM 1996). This technique is known as SAR interferometry (INSAR) and can be extended to differential SAR interferometry (DINSAR) to detect small surface changes in the order of few centimeters (GABRIEL et al. 1989).

For this present study, fifteen SAR-images recorded during the summer period were available for the period 1995 to 2001. Five SAR-image pairs with a low normal baseline (between +153 and -89 m) were analysed. One out of the five analysed image pairs (20.-21.8.1995) of the European Remote Sensing Satellite/ERS Tandem Mission showed sufficient coherence at the tongue of Pasterze Glacier for deriving a significant displacement image or interferogram (Table 1). The computation of the interferogram was possible despite the fact that only SAR-imagery of descending orbit (geometrically less favourable for displacement measurements) was available.

Table 1: ERS-1/2 SAR image pairs used for interferometric analyses. Only the second image pair from 20.8.1995 and 21.8.1995 (ERS Tandem Mission) showed sufficient coherence for deriving a significant interferogram for the glacier tongue below the icefall.

Orbit-image pair	parallel baseline (m)	normal baseline (m)	temporal baseline (days)
(1) 1.8.1995-2.8.1995	-18	-52	1
(2) 20.8.1995-21.8.1995	40	-89	1
(3) 6.7.1999- 7.7.1999	45	85	1
(4) 15.10.1997-26.8.1998	49	153	315
(5) 30.8.2000-15.8.2001	-77	-20	350

Results and Discussion

Figure 2 illustrates the geocoded ERS SAR amplitude image of the orbit image pair 20.8.1995-21.8.1995. SAR-echoes in overlay areas are stretched out in the SAR viewing direction (or SAR line-of-sight) and therefore do not deliver useful information. Figure 3 depicts the geocoded differential SAR interferogram of the orbit image pair 20.8.1995-21.8.1995. Most parts of the glacier tongue below the ice fall show sufficient coherence.

The measured difference in the phase depicted in Figure 3 was corrected from its phase ambiguity by applying an unwrapping process (Brunch-cut method). As a next step, a displacement image with displacement rates given in mm was calculated by using large areas of stable bedrock outcrops near the mountain Fuscherkarkopf. The results show that during the one-day observation period 20.-21.8.1995 maximum surface displacement rates of 30-45 mm/day in the SAR line-of-sight have been calculated (Fig. 4).

Our one-day displacement results and additional simplifying assumptions allow the estimation of a maximum annual surface displacement rate for the year 1995. The simplifying assumptions are primarily glacier flow parallel to the surface, ablation or ice melt of 2 cm for the one day observation period and steady glacier displacement all year round.

The estimated ablation value of 2 cm for the one day observation period in August 1995 is based on averaging field measurements (LIEB 1995, G.K. Lieb pers. comm.). However, the high coherence of the image pair 20.8.1995-21.8.1995 indicates rather stable surface conditions suggesting even a lower ablation value. In this regard it is important to consider that - mathematically - a daily ablation value of 1 cm changes the surface displacement rate for the year 1995 by 10.3 m. Regarding the last assumption one has to point out that glacier velocity is certainly not steady depending on temperature and presence of water and hence stresses within the glacier and at its basis (*cf.* BENN & EVANS 1998: 166-169).

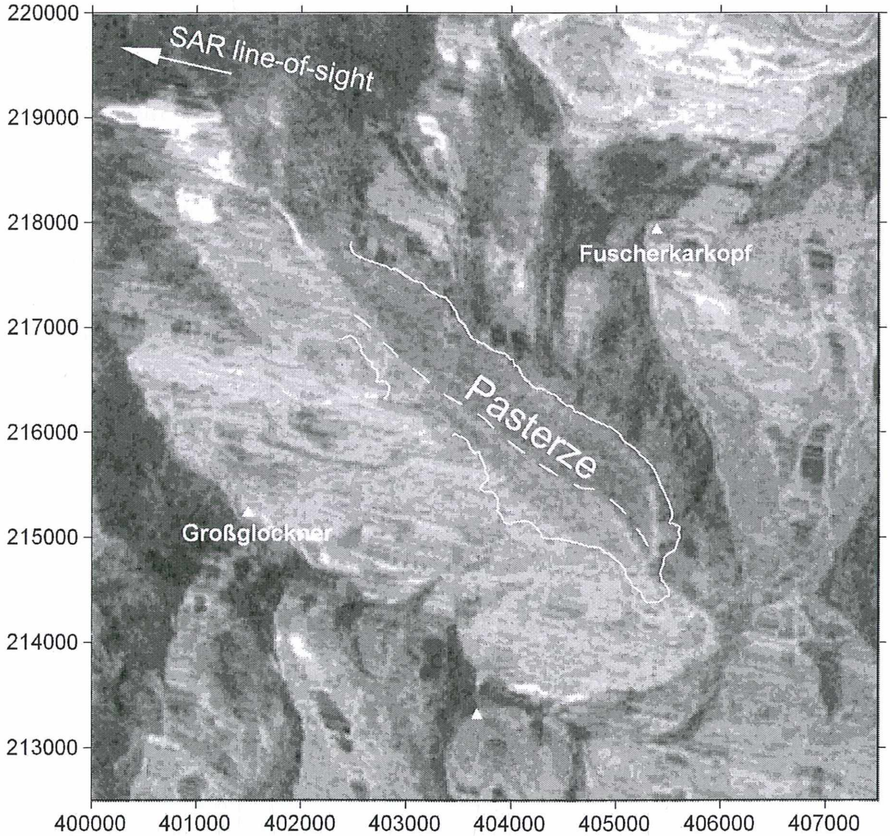

Figure 2: Geocoded ERS SAR-amplitude image of the orbit image pair 20.8.1995-21.8.1995. The outline of the glacier tongue (full line) and the boundary between the debris-covered and the clean ice part (dashed line) are indicated.

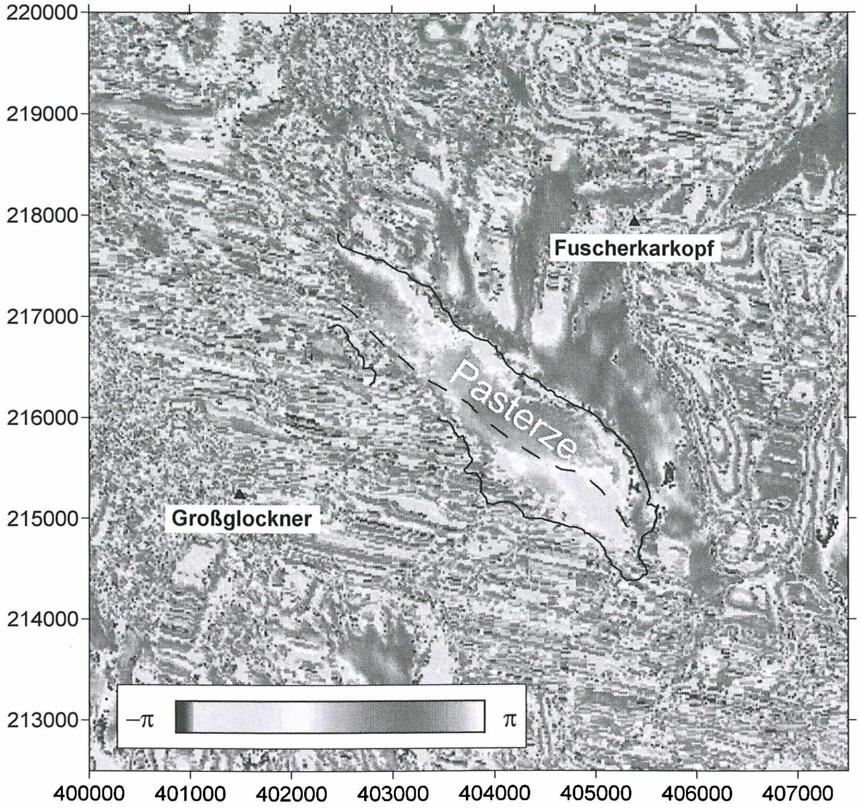

Figure 3: Geocoded differential SAR interferogram of the orbit image pair 20.8.1995-21.8.1995 depicting the difference in the phase (modulo 2π). Most parts of the glacier tongue below the ice fall show sufficient coherence. The measured difference in the phase indicates the terrain displacement in the SAR viewing direction. The outline of the glacier tongue (full line) and the boundary between the debris-covered and the clean ice part (dashed line) are indicated.

Based on our results and the previously mentioned assumptions a maximum annual surface displacement rate of 20-30 m valid for 1995 can be estimated. These displacement rates are comparable with the glacier velocities measured tachymetrically directly in the field at the three cross profiles (*cf.* Fig. 4) Freiwandlinie (close to the glacier terminus), Seelandlinie (central part of the glacier tongue) and Burgstalllinie (below the icefall) (LIEB 1995).

Refer to KAUFMANN et al. (in press) for a detailed methological description, analysis and discussion on the DINSAR example at Pasterze Glacier presented here. However, note that this publication is written in German.

Conclusion

This example of a DINSAR application clearly shows the potential of the technique for alpine glacier monitoring in mid latitude environments with high relief. It also demonstrates the high importance of sufficient coherence which is strongly reduced by high rates of ice ablation typical at low and mid latitudes. To conclude, only ERS-1/2 Tandem Mission images with a time interval of one day can be applied at mid latitude glaciers for surface displacement analyses during the summer period. This underlines the high potential of this method for glacier monitoring for such large areas as the Hohe Tauern National Park with its 1800 km^2.

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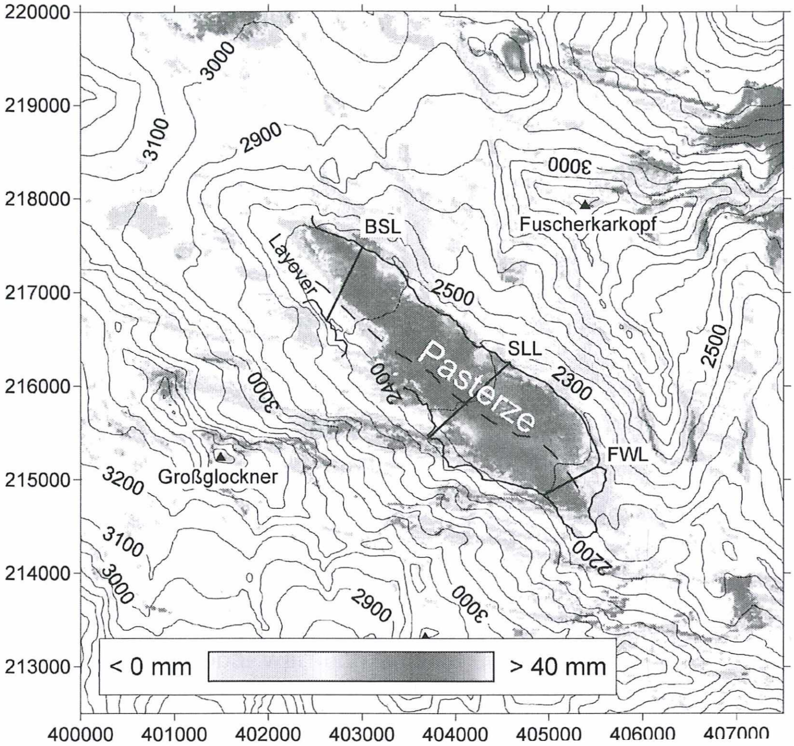

Figure 4: Geocoded differential SAR interferogram of the orbit image pair 20.8.1995-21.8.1995 depicting the calculated displacement in mm. The outline of the glacier tongue (full line), the boundary between the debris-covered and the clean ice part (dashed line) as well as the location of the three cross profiles with annual surface velocity measurements carried out by the Institute of Geography and Regional Science, University of Graz (measured tachymetrically: FWL=Freiwandlinie, SLL=Seelandlinie and BSL=Burgstalllinie) are indicated.

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