FEASIBILTY OF DINSAR FOR MAPPING COMPLEX MOTION FIELDS OF ALPINE ICE- AND ROCK-GLACIERS

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ABSTRACT

Possibilities and methods of differential SAR interferometry (DINSAR) for mapping the motion of alpine ice and rock glaciers of small spatial extent were investigated. Test sites for these studies were the glacier Hintereisferner (covering 8 km^2 in area) and several of its small side glaciers, and the rock glaciers Inner and Outer Hochebenkar, located in the Ötztaler mountains, Austria. For mapping the motion of the ice glaciers only one-day repeat pass SAR images from the ERS Tandem Mission, acquired during winter, were useful. 35-day repeat pass interferometric images did not show sufficient coherence. On the rock glaciers the coherence is preserved over longer periods. 35-day ERS SAR repeat pass interferograms from summer were used for motion analysis. The topographic phase was derived by differential methods using several one-day tandem pairs and applying the multi-baseline technique. The surface-parallel flow assumption was used for estimating the velocity vectors. The accuracy of the interferometric motion is assessed by comparison with field measurements and aerial photogrammetric analysis. The detail of the interferometric motion does not match the photogrammetric maps, but spaceborne DINSAR is a very cost-effective tool for comprehensive regional surveys and monitoring of ice and rock glaciers with good accuracy.

INTRODUCTION

Differential SAR interferometry (DINSAR) has been widely applied for mapping ice motion in polar areas and of mountain glaciers of medium to large spatial extent (Rosen at al., 2000). In this paper we investigate the potential of this technique to map the motion field of small alpine ice and rock glaciers and compare the satellite data with field measurements and air photo analysis. Information on the dynamics of glaciers is of interest for climate research and hydrology, but only very few glaciers are surveyed by means of field measurements. The Austrian glacier inventory, for example, lists 925 glaciers covering a total area of about 500 km^2, pointing out that the majority of glaciers is smaller than 1 km^2, which is also the case for most rockglaciers.

It is obvious that in situ measurements of motion can be performed only on few glaciers, though information on a larger number of glaciers would be needed to obtain a comprehensive picture of the climatic response. Remote sensing offers an economic tool for glacier surveys over extended regions. In particular, ERS-1 and ERS 2 SAR data represent a very valuable archive for studying the motion of ice and rock glaciers.

TEST AREAS

Ice and rock glaciers in the Ötztal Alps, Tyrol, Austria were selected for case studies. The Landsat-7 ETM+ image from 13 September 1999 shows the locations of the test sites (Fig. 1).

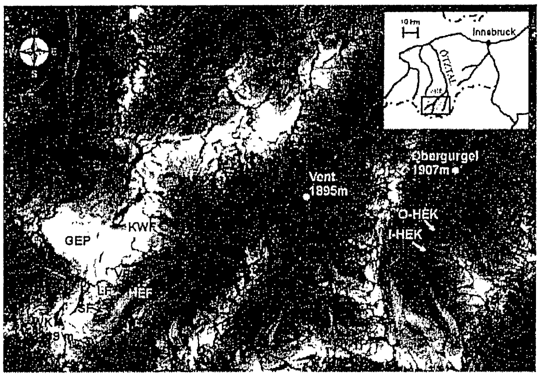

Figure 1: Landsat-7 ETM+ image (panchromatic band) of the test area Ötztal, Austria, from 13 September 1999. Glaciers: HEF – Hintereisferner, KWF – Kesselwandferner, GEP - Gepatschferner, SF - Stationsferner, LF – Langtauferer Joch Ferner, VF – Vernaglwandferner. Rock-glaciers: O-HEK – Outer Hochebenkar; I-HEK - Inner Hochebenkar.

The study on the use of DINSAR for ice motion analysis was carried out on the glacier Hintereisferner (HEF) and several of its small side glaciers. HEF covers an area of 8.1 km^2 and extends in elevation from 2500 m above sea level (a.s.l.) to the peak Weisskugel at 3739 m. The glacier is about 7 km long, the width of the terminus in the ablation area decreases from 1 km at the equilibrium line to about 300 m near the front. Two side-glaciers, Stationsferner (SF) and

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Langtauferer-Joch-Ferner (LF), are loosely connected with the main glacier. In addition, the motion of Vernaglwandferner (VF) was analysed, which covers a total area of 0.8 km^2 and can be separated in two parts according to the ice flow. Measurements of mass balance and dynamics of Hintereisferner have been carried out at an annual basis since 1952 (Kuhn *et al.*, 1999). Due to strongly negative balance during the last twenty years the motion slowed down considerably since 1980. In the 1970s and 1980s annual ice motion measurements were made at an extended network of stakes, but for recent years motion data are available only for a few points.

Rock glaciers are ice-rock mixtures subject to creep. The surface layer usually consists of boulders and rocks of various size with very little vegetation. In the Alps rock glaciers can be found at elevations above about 2300 m and are usually considered to be of permafrost origin. Investigations of rock glaciers are of interest for studies of climate change, hydrogeology and hazards related to mass movements. Active Alpine rock glaciers typically show motions between centimeters up to several meter per year, depending on the size, topography, and internal composition. Inactive rock glaciers, which do not move, are usually relicts from previous colder climatic conditions.

The Hochebenkar rock glaciers near Obergurgl (Fig. 1) were selected for the study, because motion data from field surveys (Schneider, 1999) and from aerial photogrammetry (Kaufmann and Ladstädter, 2000) are available for comparison with the DINSAR analysis. The rock glacier Outer Hochebenkar extends from 2800 down to 2350 m a.s.l. and is about 1200 m long. The active layer, which is up to 50 m thick, is made up of ice mixed with sand, silt and rock fragments. On top are several meters of coarse rock debris. The upper section of the rock glacier, which is slowly moving, is about 500 m wide, whereas the main part of the terminus, which shows faster motion, is about 300 m wide. During the most active period in the 1960s up to 5 m per year were measured near the front (Vietoris, 1972). The rock glacier Inner Hochebenkar is 1300 m long and extends from 2650 m to 2950 m in elevation. Its main part is inactive. There are two active regions on the southern and northern sections of the tongue which are separated by an inactive zone. These two active zones were first identified by means of ERS DINSAR analysis (Rott and Siegel, 1998) and later on confirmed by means of photogrammetric motion analysis (Kaufmann and Ladstädter, 2000).

DINSAR ANALYSIS

The motion fields of the investigated targets are characterised by comparatively small spatial extent and significant spatial variability. On Hintereisferner the velocity ranges from 0 to about 30 m/a. The side glaciers are considered to be slower, but no field measurements are available. The velocity of the rock glaciers shows significant temporal variability. Maximum velocities of about 2 m/a were measured on the lower terminus of Outer Hochebenkar rock glacier in the period 1997 to 1999 (Schneider, 1999), whereas the upper, wider part is characterised by velocities between 0.1 and 0.5 m/a.

The selection of the time span for the DINSAR analysis depends on the coherence of the target and on the magnitude of velocity. For the glaciers in the Ötztal Alps we found that phase coherence is completely lost for 35 day repeat pass data even in winter when snow and ice do not melt (Rott and Siegel, 1997). Over one day time spans the coherence can decrease significantly in case of snow fall or wind erosion and deposition of snow. In summer, when the surfaces melt, the coherence is usually very low even for one day repeat pass pairs. Therefore only one-day repeat pass data from the ERS Tandem Mission from winter were used for the DINSAR analysis.

Because of the lack of vegetation, rock glacier surfaces are in principle well suited for interferometric analysis over long time spans. However, in particular in zones of strong shear the signal may decorrelate within comparatively short time if individual rocks within a SAR resolution element follow different trajectories. Another reason for decorrelation is winter snow which usually results in complete decorrelation within the time scale of a few weeks. Considering that the velocities of the main area of the Hochebenkar rock glaciers are below one meter per year and taking into account the loss of coherence in winter due to differences in propagation through the snow pack, we selected 35 day repeat pass data from summer for the motion analysis.

The interferometric data base is specified in Table 1. For Hintereisferner images from the ascending pass of ERS were selected because in these images the glacier is located on a back slope and the main flow direction is across track. The images from the descending pass are of little use because of extensive foreshortening and layover. Four Tandem Pairs over one-day repeat pass periods from winter were available. The coherence in the image pairs Nr. 2, 3 and 4 is good (degree of coherence above 0.5) and the DINSAR analysis was carried out with these pairs. Pair Nr. 1 (6/7 December 1995) was not used because the coherence was low on parts of the glacier surfaces.

The motion analysis on the Hochebenkar rock glaciers is based on the five week repeat data from the descending passes of July and August 1995 (image pairs Nr. 8 and 9). Both pairs have short perpendicular baselines (22 m and 2 m, respectively) which is a good basis for accurate elimination of the topographic phase. For determining the topographic phase, the three tandem pairs with one-day time span (Nr. 5, Nr. 6 and Nr.7) were used. The coherence is slightly lower in the image data from 6/7 December 1995 (Nr. 7) than in the other two pairs, but it is still useful for interferometric analysis. Because reduced coherence is observed in the image pairs from both the descending (Nr. 7) and ascending orbit (Nr. 1), it can be concluded that a meteorological event is responsible for the partial decorrelation. According to weather data foehn winds causing snow drift were blowing on the mountains.

Table 1. ERS-1/2 Interferograms used in the study.

Nr.	*Dates*	*B*
Track 444, Frame 927, Ascending orbit (Hintereisferner)		
1	6/7 December 1995	209
2	10/11 January 1996	160
3	14/15 February 1996	135
4	20/21 March 1996	293
Track 437, Frame 2655, Descending orbit (Hochebenkar)		
5	19/20 July 1995	-20
6	23/24 August 1995	-81
7	6/7 December 1995	-100
8	19 July/23 August 1995	-22
9	20 July/23 August 1995	-2

For separating the displacement- and topography-dependent phase components, we applied the differential technique based on several SAR images (Joughin et al., 1998). Another option would be the use of synthetic interferograms calculated from accurate digital elevation data (DEM). However, the available DEMs are based on aerial surveys from more than 20 years ago, and the topography of the investigated ice and rock glaciers changed significantly during that period. In order to reduce possible disturbing effects resulting from different atmospheric propagation conditions in the various images and to minimise phase unwrapping errors, the topographic phase was derived by combined processing of multiple interferometric image pairs with different baselines (multi-baseline interferometry; Ferretti *et al.*, 1999).

Each differential interferogram used for calculating the topographic phase was based on two one- day repeat pass tandem pairs (4 images). It was assumed that the motion is the same in the various tandem pairs. This is a valid approach for comparatively slowly moving Alpine glaciers in winter. On Alpine glaciers temporal changes of motion are usually related to changes of water pressure in summer. The tandem pairs used for the interferometric motion analysis of Hintereisferner are separated only by 5 and 10 weeks in time (between 10 January and 21 March 1996). The three differential interferograms used for multi-baseline processing of topography reveal perpendicular baselines (B_{perp}) of 25 m (derived from image pairs Nr. 2 and Nr. 3), 133 m (Nr. 2 and Nr. 4), and 163 m (Nr. 3 and Nr. 4). For calculating the topography of the rock glaciers and the surrounding areas, two differential interferograms with baselines of 60 m (Nr. 5 and Nr. 6) and 80 m (Nr. 5 and Nr. 7) were used. On the main parts of the rock glaciers the displacement-dependent phase in the one-day repeat pass data is very small, so that possible temporal changes of velocity should have very little impact for differential processing of the topographic phase.

For quantitative studies of the dynamics and mass fluxes of ice and rock glaciers the velocity vector is needed. We assumed surface *[S(x,y)]* parallel flow (Joughin et al., 1998) for which the three-component velocity vector, **v**, can be written as

$$\mathbf{v} = \mathbf{v}_h + \left[\nabla_{xy} S(x,y)\right]^T \mathbf{v}_h \hat{z}$$

where $\mathbf{v}_h$ is the horizontal velocity vector, and $\hat{z}$ is the unit vector in the vertical direction. The second term on the right hand side is the vertical velocity. In the two test sites, Hintereisferner and Hochebenkar, we solved for the velocity vector by using only single pass data and estimating the flow direction from the direction of the downhill slope. This is suitable in these cases because the main flow direction of the ice and rock glaciers is close to the across track direction.

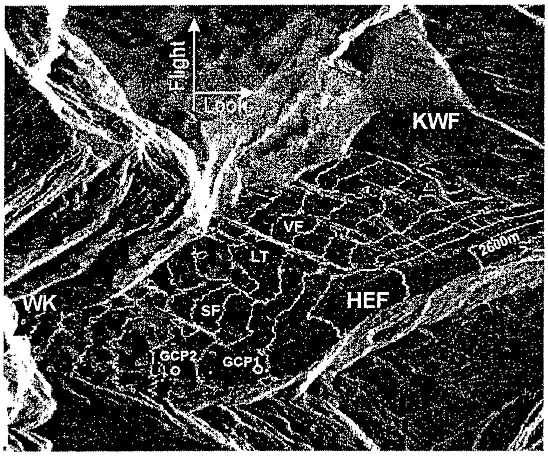

Figure 2: Section of multitemporal average ERS SAR amplitude image of the Hintereisferner area. . White lines are 100 m elevation contours from the DINSAR analysis.

MOTION OF HINTEREISFERNER

Several products of the interferometric processing chain are shown in Figures 2 to 5. The amplitude image (Fig. 2) is a multitemporal composite from the 8 images of the interferometric pairs Nr. 1 to 4 listed in Table 1. The bright layover zones of the steep slopes facing the radar are dominating features in the image. Due to strong volume scattering in the frozen firn below the winter snow, the firn areas of the glaciers, in particular the large plateau of Kesselwand- and Gepatschferner, show higher reflectivity than the ice areas. Topographic contour lines in 100 m altitude intervals, derived from the interferometric data, are superimposed to the amplitude image. The topography of the main part of the Hintereis terminus is comparatively flat (about 5° inclination), whereas the side glaciers are steeper (about 15°to 20°).

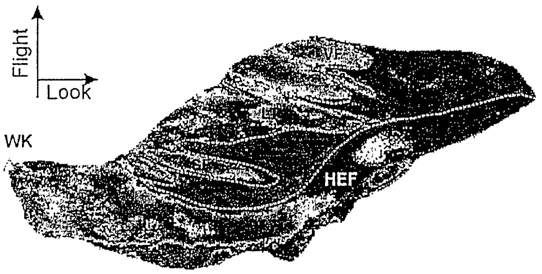

Figure 3: Image of motion-dependent relative phase on Hintereisferner and side glaciers, derived from the ERS tandem pair Nr. 4 (20/21 March 1996). On cycle of the grey scale corresponds to a phase shift of 2 π.

Fig. 3 shows the image of the motion-dependent relative phase derived from the ERS tandem pair of 20/21 March 1996. The analyses of the tandem pairs of January and February 1996 result in the same velocities. Because the phase differences are sensitive to the velocity component in range only, changes of ice flow direction cause phase differences. This is evident on the tongue of Hintereisferner, where a secondary minimum of the motion phase is apparent at the elevation of about 2800 m due to a deviation of the flow direction by about 40° from across-track.

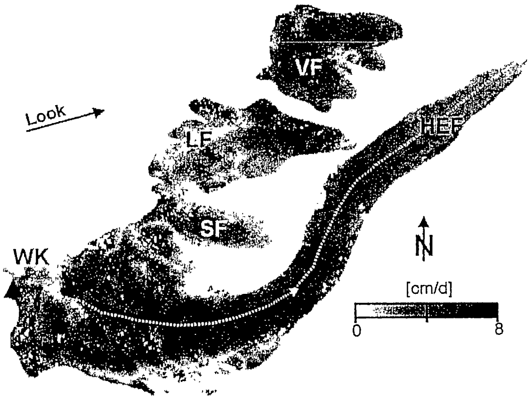

Figure 4: Map of the magnitude of the velocity vector, derived from ERS tandem pair Nr. 4 (20/21 March 1996) under the surface-parallel flow assumption. The dotted white line indicates the central flow line.

In order to facilitate the interpretation of the interferometric analysis, the ice velocity was calculated with the surface-parallel flow assumption and geocoded (Fig. 4.). This assumption is exactly valid only if the surface is strictly steady state during the time interval spanned by the interferometric pair. Also for glaciers which are in steady state in terms of mass over annual intervals, the flow is not strictly surface-parallel. In the ablation zone the ice velocity vector is inclined slightly upward and in the accumulation zone slightly downward. Taking into account the measured accumulation and ablation rates and annual field measurements of motion, it can be concluded that the deviations from the surface-parallel assumption on Hintereisferner are small. In winter, when there is no ablation, the upward movement of the surface in the ablation area is estimated to range from about 0 mm/day near the equilibrium line to about 3 mm/day at 2600 m elevation. Related errors should have very little effect on the horizontal velocity and on the magnitude of the velocity vector retrieved by DINSAR.

More critical errors for deriving the flow direction result from the topographic phase. In particular in areas where the glacier is flat, small phase disturbances may result in significant errors of the flow direction. Joughin *et al.* (1998) suggest to average over 10 to 20 ice thicknesses for estimating the flow direction from the downhill slope. On Hintereisferner (with average ice thickness of about 130 m) this would require averaging over more than 1 km, which is unfeasible because locally the flow direction changes significantly over smaller distances and because the width of the terminus is less than 1 km. For the velocity map in Fig. 4 the surface slope was averaged over 300 m distances. Therefore this motion map is noisier than the image of the motion component in range (Fig. 3).

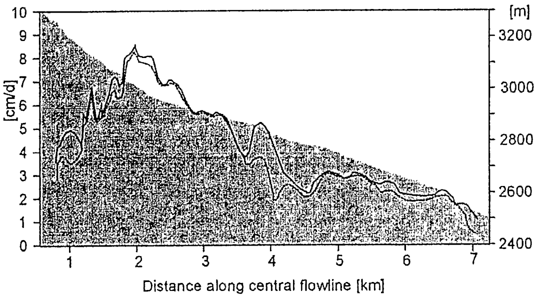

Figure 5: Ice velocity along the central flow line of Hintereisferner. Velocity component in range in cm/day projected to the surface (dashed line) and magnitude of the velocity vector assuming surface-parallel flow (full line). The boundary between the grey and white area corresponds to the elevation profile along the flowline.

Recent field data of motion for comparison are only available at a profile on the Hintereisferner terminus at 2600 m elevation. The interferometric motion in the center of this profile is 2.3 cm/d (corresponding to 8.4 m/year under the assumption of constant motion) which agrees within 20% with the mean annual motion measured in the field. The longitudinal profile along the central flowline (Fig. 5) shows the velocity maximum of 8 cm/d at an elevation of about 3000 m, which corresponds approximately to the boundary between the firn and ice area. Significant differences between the velocity in range and the velocity under the surface-parallel assumption are apparent at km 1 and km 4 downstream along the central flow line (Fig. 5). At km 1 is a steep crevasse zone, at km 4 the surface is quite flat and the flow deviates strongly from the across track direction. In nearly flat areas the estimation of the flow direction from the local slope is problematic and often noisy due to inaccuracies in the DEM. In this case the deviation between the flow and SAR look direction has been limited to 45°.

Among the tributary glaciers, Langtauferer-Joch-Ferner shows the highest velocity, with a pronounced maximum of 8 cm/d where the glacier becomes narrow about 200 m in elevation above the confluence with the Hintereisferner tongue. The side glaciers Vernaglwandferner and Stationsferner reach velocities up to 5 cm/d in their central parts.

MOTION ANALYSIS OF ROCK GLACIERS

In the multi-temporal SAR amplitude image (Fig. 6) the rock glaciers stand out from the surroundings due to the higher reflectivity of the very rough surfaces. For the motion analysis the two five-week interferograms from summer 1995 (Nr. 7 and 8 in Table 1) were used. Fig. 7 shows magnitude of the surface parallel displacement in slant range geometry from the image pair 20 July 1995 to 23 August 1995. This figure is less noisy than the previous interferometric analysis of the rock glaciers (Rott and Siegel, 1999) which did not apply the multi-baseline technique.

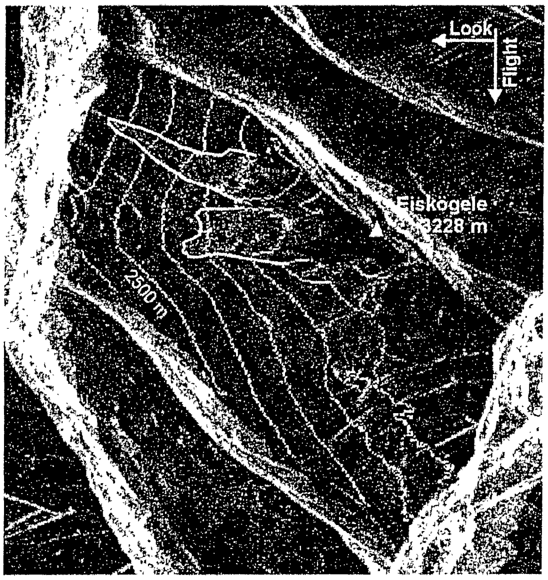

Figure 6: Section of multitemporal average ERS SAR amplitude image of Hochebenkar. White lines correspond to 100 m elevation contours from DINSAR analysis. The Inner and Outer Hochebenkar rock glaciers are outlined.

The interferometric analysis of the 35-day repeat pass data is suitable to derive the velocities of the moving parts of Inner Hochebenkar rock glacier (I-HEK) and of the upper part of Outer Hochebenkar (O-HEK) rock glacier. On the lower, narrow part of the terminus of O-HEK, however, the motion is too fast and the shear is too high to be resolved with 35-day interferograms.

The complex structure of the velocity field is evident in Fig. 8, based on aerial photogrammetric analysis and field measurements (Kaufmann and Ladstädter, 2000; Schneider, 1999). The largest displacement on O-HEK derived by interferometry amounts to 5 cm in 35 days (corresponding to 52 cm/a) if surface parallel flow is assumed and is located at an elevation of 2670 m . At this position Fig. 8 shows velocities between 20 and 60 cm/a for the 7-years period. This confirms that the interferometric analysis provides useful data, though spatially detailed information on the motion field cannot be obtained. On the lower part of O-HEK the 35 day image pairs are not coherent.

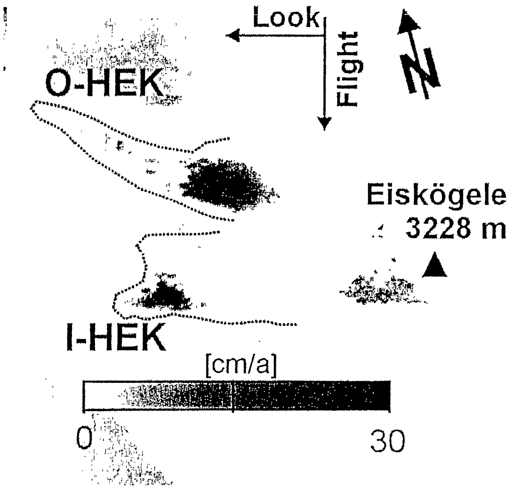

Figure 7: Surface displacement across track of the Hochebenkar rock glaciers (slant range geometry) derived by means of DINSAR from the ERS image pair Nr 9 (20 July 1995 – 23 August 1995).

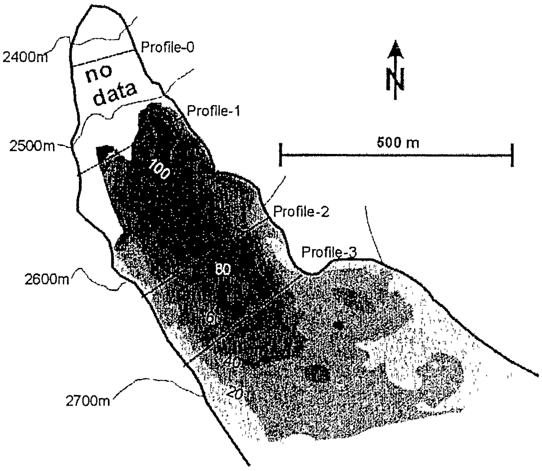

Figure 8: Sketch map of Outer Hochebenkar rock glacier with mean annual horizontal flow velocity of the period 1990-1997 (after Kaufmann and Ladstädter, 2000).

The interferometric analysis of I-HEK shows that two sections of the lower terminus, on the orographically left and right parts of the rock glacier, are in motion, and the main parts of the glacier are stagnant. This agrees with the photogrammetric velocity map of the period 1981-1997 of Kaufmann and Ladstädter (2000) which shows a moving section, about 400 m x 250 m in extent, on the left to central part of the terminus immediately above the front, with mean velocities between 2.5 cm/a and 40 cm/a. The moving section on the right (northern) side is only about 100 m wide and 500 m long, and only a small part of this section shows velocities above 20 cm/a (up to 30 cm/a). In the interferogram the moving section on the left side is clearly pronounced and shows velocities of up to 4 cm in 35 days (corresponding to 42 cm/a). This is in reasonable agreement with the airphoto analysis, in particular taking into account that the motion of the rock glaciers may change over the years. The section on the right side of I-HEK is not well resolved in the interferogram, because it is very narrow, but the interferogram provides at least a qualitative hint that this part is also moving.

CONCLUSIONS

The investigation confirm that interferometric ERS SAR images are very useful for mapping the motion of Alpine ice and rock glaciers. Though it is not possible to derive the spatial details of the small scale velocity fields, DINSAR is able to provide spatially averaged quantitative information on motion not only for large glaciers, but down to glaciers covering less than 1 km^2 in area. Of particular interest is the synoptic coverage by spaceborne SAR, which enables surveys and monitoring of many glaciers at low costs because a single scene covers a very large area compared to aerial surveys.

The multi-baseline technique (Ferretti *et al.*, 1999), using several one-day repeat pass interferograms, was applied for deriving the topographic phase in the differential analysis. For mapping the motion of the Alpine ice glaciers only one-day repeat pass SAR images from the ERS Tandem Mission, acquired during winter, were found to be useful. The 35-day repeat pass interferometric images were not coherent even in winter, due to temporal change of propagation in the snowpack. On rock glaciers the coherence is preserved over longer periods. Taking into account that 0.1 m/a to 1m /a is the typical range of velocities on the investigated rock glaciers, 35-day repeat pass interferograms from ERS SAR data from summer were used for motion analysis. The surface-parallel assumption was used for estimating the velocity vectors from single pass interferograms. This assumption provides accurate results from comparatively smooth motion fields only if accurate topographic data from INSAR or other sources are available. The comparison with field measurements and aerial photogrammetric analysis shows good accuracy of the interferometric velocity if areas with strong shear are avoided.

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