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Scientific paper

Determination of ice flow velocity in Svalbard from ERS-1 interferometric observations

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Abstract: Based on ERS-1 data recorded in autumn 1991, differential interferogrammes have allowed the determination of the ice flow of north-west Spitsbergen glaciers.

The highest velocity of the d'Arodesbreen and the Fjortendejulibreen, observed in their equilibrium zone, was 3 cm and 6.6 cm per day, respectively. The large Kronebreen (700 km^2) is fed by two plateaux, Isachsenfonna and Holtedahlfonna. Along the longitudinal axis of Isachsenfonna, the velocity was near constant, around 20 cm per day over a distance of 20 km, while the velocity on Holtedahlfonna increased from near zero in the higher basin to 52 cm per day at 15 km to the calving front. The obtained velocities were in excess of 48% of the annual average velocity measured by GPS at three locations. Interferometric pairs were obtained at the end of the ablation period when the presence of subglacial meltwater can still lead a high velocity.

These relatively high rates of velocity indicate that the basal sliding of Isachsenfonna and Holtedahlfonna is important and that the glacier sole must be at the melting point down to the front. The present temperature distribution in the glacier is still possibly influenced by a surge, which occurred 130 years ago.

1. Introduction

After Goldstein *et al.* (1993) applications of INSAR techniques for glacier monitoring have been described and demonstrated in a number of papers. As examples, Rignot *et al.* (1996) who presented an overview of the literature have retrieved the surface topography and ice velocity over a large ice field from SIR-C data and, by using ERS-1 and ERS-2 tandem missions, determination of the ice velocity over an Alpine glacier has been obtained by Karim *et al.* (1998).

Sixty per cent of the Svalbard archipelago is covered by glaciers, which represent in total an area of about 40000 sq. km (Hagen *et al.*, 1993). For a high number of cirque glaciers, the ice flow fall in a range between zero and 30 m per year. Such velocities are also encountered in the accumulation area of ice caps, while their outlets can flow at several tens of centimetres per day in summer time. It could be estimated that 60 to 70% of the glacier surface in Svalbard is possibly subjected to such a velocity range, which is also the range of expected detection from INSAR techniques applied on ERS-1 data.

Based on data from ERS-1, clear fringes were firstly obtained over a high number of glaciers in Svalbard and an analysis of the images of coherence has made it possible to delimitate ice stream boundaries, to discriminate between slow and fast ice motion and to detect surging glaciers (Lefauconnier *et al.*, 1994a). By geodetic methods, a mean velocity of between 2 and 2.15 m per day with peak of 4.50 m per day at the beginning of July was measured at the calving front of Kronebreen by Voigt (1965) and Lefauconnier *et al.* (1994b). A similar result has recently been obtained by using the tandem ERS1–ERS2 (Eldhuset *et al.*, 2000). Also from tandem data, maximum velocities over three glaciers have been estimated by Wangensteen and Weydahl (1999).

From interferogrammes based on ERS-1 data obtained along a single track combined with the use of an accurate DEM and of an ice flow model, ice velocity fields have been obtained over three glaciers (Lefauconnier *et al.*, 1996a, b). The aim of the present paper is to present briefly this work, to validate the results by ground control and discuss the findings in a glaciological context.

2. Surveyed site

This area is one with a mostly alpine type relief comprised of terrain between 0 and 1400 m a.s.l. and numerous glaciers and ice fields from a few km^2 up to 1000 km^2 in extent, some of which have a calving front.

2.1. D'Arodesbreen and Fjortendejulibreen

The d'Arodesbreen (79°09′N and 12°04′E, Fig. 1) is a valley glacier, mainly facing the satellite look. The area of the glacier basin is of 16 km^2 and the length 10 km. This glacier is well individualised without any tributary. The glacier top reaches 750 m a.s.l, surrounding mountains culminate at 980 m a.s.l. The Fjortendejulibreen (79°07′N and 12°13′E, Fig. 1), is a calving glacier, which also mainly faces the satellite look. Its area is 81 km^2 and its length 18 km. Its head is partly fed by the Isachsenfonna around 900 m a.s.l. and surrounding mountains culminate at 1300 m a.s.l.

2.2. Kronebreen (Isachsenfonna and Holtedahlfonna)

The Kronebreen, (78°58′N, 13°11′E, Fig. 1) is the most active glacier in Svalbard. Its calving front is about 4 km wide and the central part, with many crevasses is moving close to 800 m per year (Lefauconnier *et al.*, 1994b). The main outlet is fed by two "fonna" (accumulation plateau): Isachsenfonna with a top above 900 m a.s.l. and Holtedahlfonna at 650 m but which is partly supplied by another fonna culminating at 1200 m. The total area is about 700 km^2, with a maximum length of 43 km. The net accumulation over the fonna together with the narrowing of the outlet and the buoyancy at the front causes an increase in velocity and high flow speed at the front, which will be discussed below. The flow of Holtedahlfonna is facing the satellite look while the flow of Isachsenfonna, which is also facing the satellite look in its higher basin, turn then to an angle of 30° toward the satellite sight. Over the two basins, the surveyed zone presents a slope average of less than 2°.

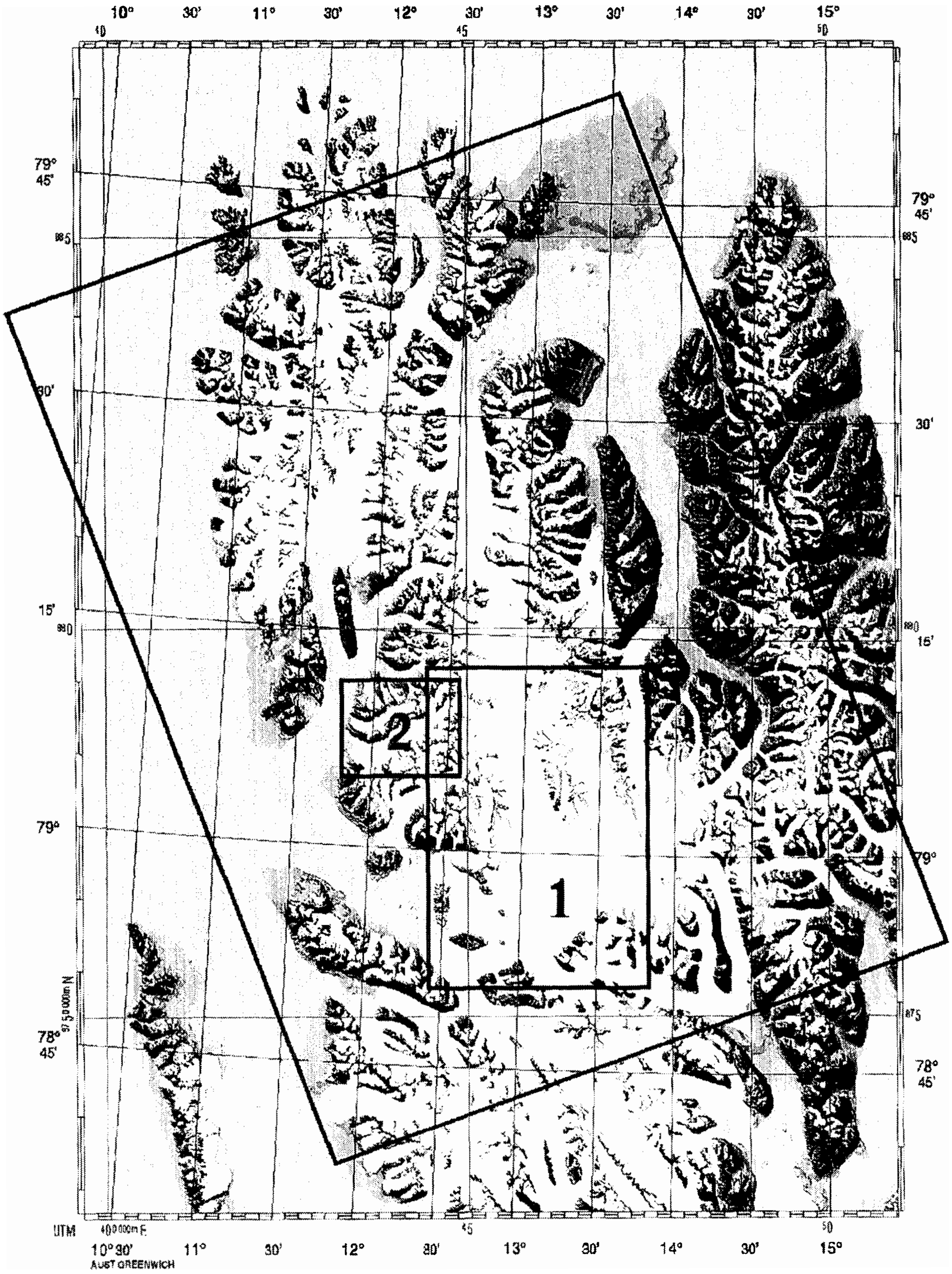

Fig. 1. *Map of the northwest Spitsbergen and location of the test sites; 1: Kronebreen; 2: D'Arodesbreen and Fjortendejulibreen.*

3. Method

3.1. ERS-1 data and DEM

Eleven ERS-1 scenes recorded at the summer-autumn transition were analysed. The

Fig. 2. Differential interferogramme over northwestern Spitsbergen from ERS-1 data recorded on ascending orbits the 17 and the 23 September 1991 (six days interval). The image is oriented to the North and covers the area of one complete ERS-1 scene (100 × 120 km). Despite of the scale, clear fringes are visible on several glaciers on the eastern part of the image while due to the meteorological condition the western part is characterised by a low coherence and lack of fringes. Inverse conditions as well as radar features were observed between the 23 September and the 3 October and on the nine days interval interferogramme not presented here.

images of phase and of coherence and obtained interferogrammes were analysed and the validity of the data to determine the ice movement from glaciers located in the area was assessed (Rossi, 1994). Three scenes recorded at the end of the ablation period were associated to the best coherence. The interferometric pairs used in this paper were based on the following combinations: scenes of the 17 September with the 23 September (six days interval, Fig. 2) and 23 September with 2 October (nine days interval). Due to the meteorological conditions during the period of the data takes (see Lefauconnier *et al.*, 1994a), clear fringes are present in the central and eastern part of the interferogramme with the six days interval, while the fringes are clear in the western part of the interferogramme with the nine days interval. The two interferogrammes were then used according to the location of the studied site.

Due to the tormented relief of the area (see Fig. 1), a DEM obtained from SAR interferogrammes was not accurate enough to be used. A DEM was then obtained from maps at the 1/100000 based on aerial stereo photogrametry. In Svalbard there are number of trigonometric reference points with an accuracy better than one meter in the three coordinates. The contour lines on rock sides are estimated to be associated to a possible error less than 5 m in height. On the other coordinates, the error depends of the slope and could be more than 10 m. The DEM that was used for the project is available on Arc-Info data, digitised from a scanning. Thus, due to the chain of treatment, errors in position are usually in the 20 m range.

The fringe pattern caused by the orbital trajectories and the elevation of the terrain (with one topographic fringe corresponding to 30 m in elevation) were simulated and removed to produce differential interferogrammes where the fringes are due to the ice movement.

3.2. Flow line model

The general behaviour of glaciers is known and over ideal, small glaciers with well-defined basins, the flow lines correspond to a description made by Reid (1896). It is therefore possible to roughly estimate the flow direction at the glacier surface. If the surface is taken as reference, the ice is submitted to a submergence velocity in accumulation area and an emergence velocity in ablation area (Paterson, 1994), which are not determined in the present work. We nevertheless propose a model of the flow direction and the results, as well as the possible influence of the vertical component of the movement, will be discussed for the studied glaciers.

Both Isachsenfonna and Holtedahlfonna have a very weak slope (less than 2°). The laminar flow parallel to the surface and basal sliding dominate, and we are able to assume that, with the exception of a few areas, the real flow vectors follow the surface. Determination of the flow direction is made by taking into account information from air photos and satellite imagery. An important source of help in this determination is provided by the INSAR data themselves (see Lefauconnier *et al.*, 1994a). This is because the images of coherence show lack of coherence at the border of ice streams as well as at the confluence between two ice-streams. Hence, using Kronebreen as an example, especially on the Holtedahlfonna (Fig. 4), which is flowing toward the satellite look, the fringe morphology is used as the representation of real isotachytes. We therefore believe that the main central flow line is at least accurately detected.

3.3. Determination of the ice flow velocity

A grid of points is plotted every 500 m on the DEM and for each point, data on slope and aspect of the slope are extracted from the Arc-Info file. As the hypothesis is made on the flow direction we used then the relation (1):

$$\frac{2Vt}{\lambda}k \cdot s = n \qquad \text{as} \qquad V = \frac{n\lambda}{2tk \cdot s}, \tag{1}$$

where V is the velocity; t is the period between the data takes on which the interferogramme is based, λ is the wave length of the radar (56 mm); $k \cdot s$ is the scalar product of the coordinates in a cartographic system of the velocity vectors at each point of the grid (k) and the line-of-sight vector of the satellite (s); n is the number of fringes. The components of the line-of-sight vector are: 0.93; -0.21 and -0.32 for the vertical, North and East respectively and the coordinates of the vectors at each points of the grid (k) are obtained by using the following relation (2):

$$\begin{array}{ll} \text{Vertical:} & (\cos\,\theta), \\ \text{North} & (\cos\,\varphi.\ \sin\,\theta), \\ \text{East} & (\sin\,\varphi.\ \sin\,\theta), \end{array} \tag{2}$$

where θ, is the angle between the zenith and the flow direction and φ is the angle between the flow direction and North. The ellipsoidal shape of the Earth introduces negligible offset to θ, especially in Polar Regions.

On the interferogrammes, mountains and nunataks are all presented in black and the first fringe, which is clearly independent from these black zones, is counted as $n=1$. Due to the alpine relief the field of fringes is complex and the counting is then made manually. The counting is difficult or impossible on the western part of the Isachsenfonna and over the higher basin of Holtedahlfonna. In the lower part of the glacier where the velocity is too high and where there are many crevasses, no fringes were visible. Clear fringes are nevertheless seen over more than 50% of the glacier surface of Kronebreen, over about 80% of the Fjortendejulibreen and all over the d'Arodesbreen. The results are plotted on maps and due to the fact that the model cannot take into account small local topography, errors in the flow direction are detected and a few abnormal values, usually in the higher tributary basins, are eliminated.

4. Results

4.1. D'Arodesbreen and Fjortendejulibreen

For these glaciers, the interferogramme is shown in Fig. 3 and the obtained flow vectors in Fig. 5. The DEM is based on data (air photos and maps) from 1970. From this year to 1991 the slope over the main part of the basin may not have changed consistently except at the front where, due to high ablation, the elevation and dip of the slope may have changed drastically.

Over d'Arodesbreen, linear flow dominates and thus the results are accurate in the central basin, while they may be underestimated in the accumulation basin since a slight increase in the angle of the slope may have occurred. At the front, an important change of the surface topography through time due to the melting invalidates any possible result and the visible long vectors in the figure close to the front do not represent real values. The most accurate finding is then close to the equilibrium line where the velocity is 3 cm per day (a1 in Fig. 5).

Linear flow and basal sliding also dominate over the main basin of the Fjortendejuli-

Fig. 3. *Part of the differential interferogramme (16 × 13 km, 9 days interval) over the d'Arodesbreen and the Fjortendejulibreen (see location noted 2 on Fig. 1).*

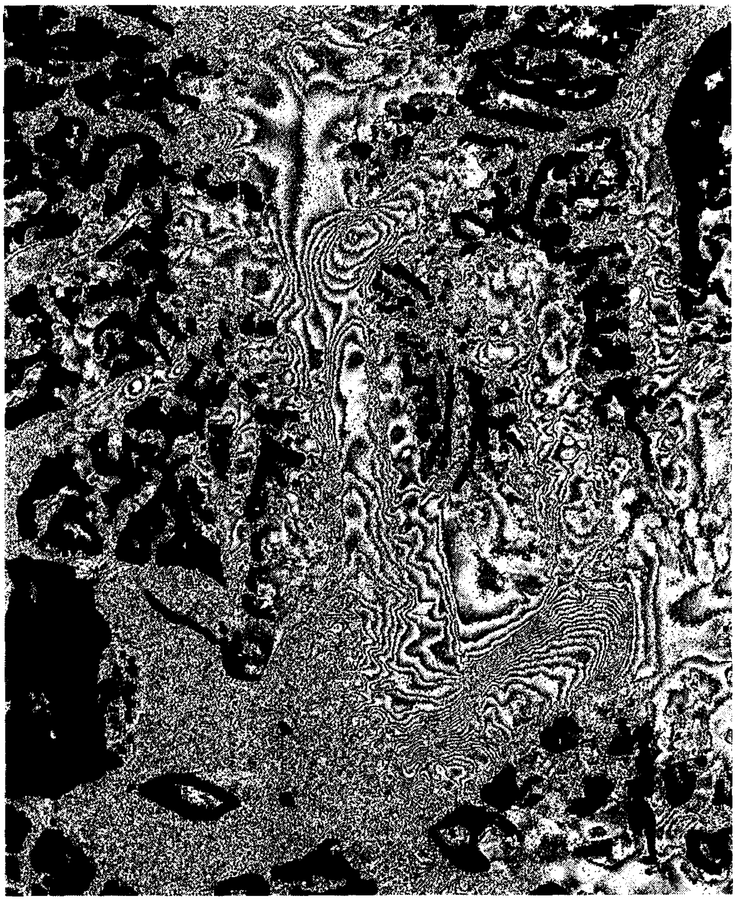

Fig. 4. *Part of the differential interferogramme (34 × 42 km, 6 days interval) over Kronebreen. There are no visible fringes in the lower basin of the glacier (to the west) due to high velocity of the termini and the high number of crevasses (see location noted 1 on Fig. 1).*

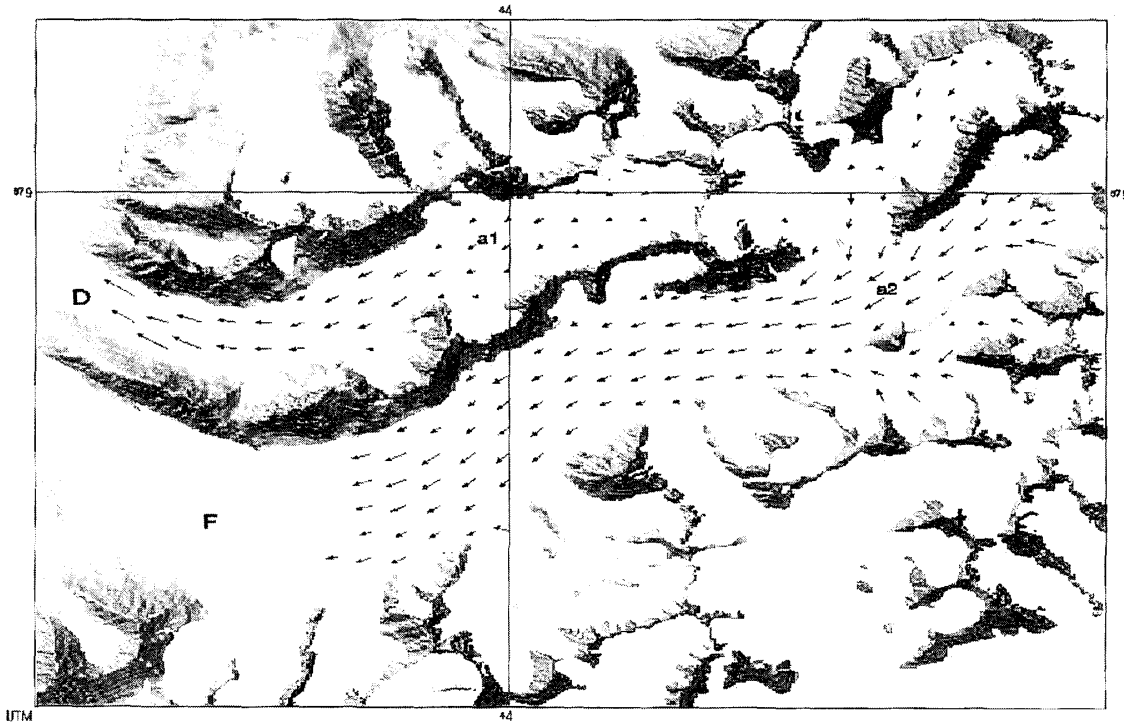

Fig. 5. *Ice velocity over d'Arodesbreen (D) and Fjortendejulibreen (F). The figure is oriented to the north and the glaciers are also noted on 2 in Fig. 1. There are no results at the front of Fjortendejulibreen due to a high number of crevasses. Over d'Arodesbreen, the velocities are slightly underestimated at the glacier head. Highly overestimated velocities at the front lead to unrealistic results. Daily velocities, around the equilibrium lines; a1: 3.0 cm; a2: 6.6 cm.*

breen. The results have the same source of error in the higher basin as for the d'Arodesbreen. At the front, higher velocities and the presence of crevasses cause a lack of coherence and no fringes are visible. A maximum velocity of 6.6 cm (a2 in Fig. 5) is found close to the equilibrium line, which is of the same order of magnitude that velocity measured geodetically in the same zone by Ahlmann (1948) between mid-June to mid-August 1934.

4.2. Kronebreen

The interferogramme is shown in Fig. 4 and the flow vectors in Fig. 6. The velocity is remarkably regular, around 20 cm per day over 20 km along the longitudinal axis of Isachsenfonna. The velocity over Holtedahlfonna increases from near zero to 52 cm per day along a transect terminating at 15 km to the calving front (c1 in Fig. 6). At the front, a mean annual value of between 200 to 215 cm per day was reported for 1964 (Voigt, 1965) as well as for 1986 (Lefauconnier *et al.*, 1994b) with in both cases, peaks of 450 cm per day at the beginning of July. Even if the data on which the DEM is based are from 1966, the slope of these wide basins did not appear to change significantly (the mean dip of the slope is less than 2°). The fringe morphology in this basin indicates a regular surface and possible variation in velocities due to local change in the slope are limited.

One source of error may come from the counting of the fringes. The determination of the first fringe which is sometimes largely spread and not clearly defined, is not easy in all

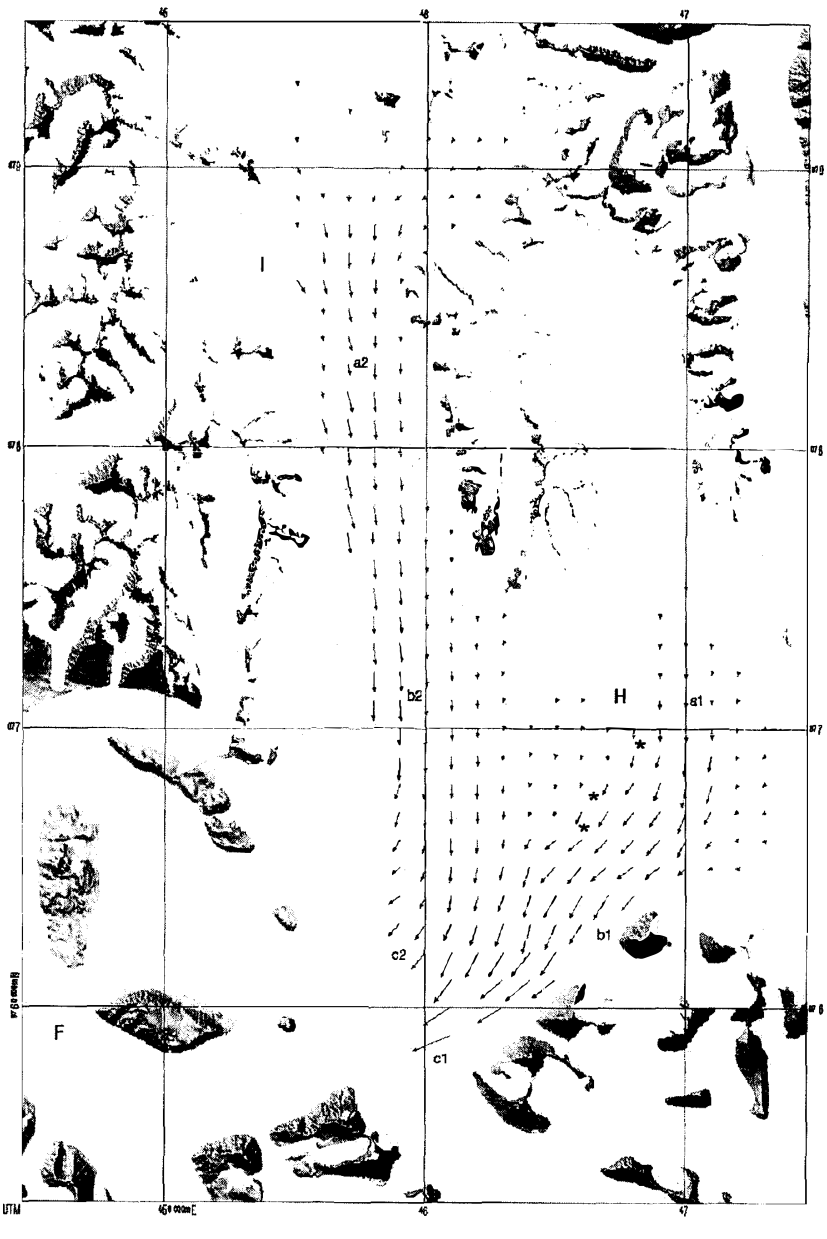

Fig. 6. *Ice velocity over Kronebren: I: Isachsenfonna; H: Holtedahlfonna; F: calving front. The figure is oriented to the north and the glacier is also noted on I in Fig. 1. Interpretation of fringes is not possible in the western part of the Isachsenfonna and the relief influences the fringe morphology on its eastern part. The lack of vectors over the terminal tongue of the glacier is due to a lack of fringes (corresponding to a high velocity and presence of many crevasses). The dots indicate the location of the stakes used as ground control and noted S10, S05, S11 from the East to the West (see also Table 1).*
Velocities per day; a1: 7.5 cm; b1: 32.0 cm; c1: 52.0 cm; a2: 20.0 cm; b2: 22.0 cm; c2: 21.0 cm.

parts of the scenes. Repeated independent counting from diverse locations always gave the same number of fringes over Isachsenfonna and an uncertainty of one fringe on Holtedahlfonna. In the later case, this uncertainty leads a possible error relatively important in the higher basin but of only 2% at point c1 (*e.g.* that the velocity is 51 or 52 cm per day). The atmospheric component of the interferometric measurement, the most common artefact to the technique, is not likely to significantly bias measurements with such high amplitudes.

4.3. Ground control

Three aluminium stakes (S11; S05 and S10 in Fig. 6) were settled in May 1996 on Holtedahlfonna for geodetic control by GPS. Their position was recorded again in May 1997, after 366 days. Table 1 presents the results of both interferometric and ground control measurements. The recorded movement of the stakes allows the validity of the flow model to be assessed at the three points. There was an error of 5° in the flow direction at stake S10 (see Table 1). This stake was settled on a gentle bump and the local aspect of the slope is not taken into account by the flow model. The accuracy of the model is confirmed at the two other points (with an error of only 1° in the flow direction and an error of 1% in the velocity (see Table 1). The velocities obtained from the fringes exceed the result from ground measurements by 48%. This discrepancy may be due to the fact that the velocity determination was made over 6 days just at the end of the ablation period, when the subglacial water pressure can still lead to high velocity rates. During the ablation period, velocities twice the mean annual value have been recorded at the front of this glacier in 1964 (Voigt, 1965) and 1986 (Lefauconnier *et al*., 1994b).

Table 1. Comparison of velocities obtained at three stake locations, by the INSAR method and by GPS. S10, S05 and S11 are three stakes settled over Holtedahlfonna (see Fig. 6).

N of days	Method	Ice flow (cm d^{-1})		
		S11	S05	S10
	INSAR			
6 days	A) Based on ice flow model	22.50	20.30	14.30
6 days	B) Based on the real flow line (from GPS)	22.80	20.10	14.60
366 days	GPS	15.20	13.00	10.40
	Difference in the flow line direction (A/B)	*1°7*	*0°7*	*4°57*
	Ratio INSAR/GPS values	*150%*	*155%*	*140%*

5. Discussion and conclusion

In this paper results have been based on data recorded along ascending orbits only. In order to estimates glacier velocities it was then necessary to propose an ice flow model for each surveyed glacier. Such models cannot be precise in all parts of the different glaciers. Moreover, The DEM is based on data recorded about twenty years before the records from the radar. If, in twenty years, the topography does not change consistently over the main areas of the glaciers, a small change occurs in the higher part of the accumulation area and an important change occurs at the front. Then, the findings must be considered as valid over the central basin only, and in particular close to the equilibrium line. In accumulation areas, where the vectors from the models cannot take into account the submergence velocity, the result provides only a fairly broad indication of the ice movement. At the fronts, changes in the glacier geometry and undetermined emergence velocities prohibit any realistic result. In order to improve the results over these two areas, the DEM would have to be based on data recorded as close as possible to the dates of the satellite passage and the results based on interferogrammes obtained from both ascending and descending orbits as demonstrated for example by Joughin *et al.* (1998) and Karim *et al.* (1998).

Historical data from one glacier (Fjortendejulibreen) and a ground control at three locations on the main glacier (Kronebreen) allow a rough validation of the results. The results have important glaciological implications. On Kronebreen, if a higher velocity at the end of the ablation period compared to the annual value is typical, our estimate of 48% in September–October is highly significant in a glaciological context. It would therefore be interesting to carry out more surveys of the glaciers behaviour during the rapid summer to the slow winter flow regime transition and to eventually detect shifts from extensive flow to less extensive flow and even possible local compressive flow. Further, since a large part of Isachsenfonna has been found to move almost as a single block over 20 km, it would also be of interest to examine up-glacier of the main zone with extensive flow.

Kronebreen like most Svalbard glaciers is a sub-polar or polythermal glacier with both cold and temperate ice volumes. The fairly high rate of movement, even if favoured by the buoyancy at the front, indicates that basal sliding is important and that the temperate ice layer which originates in the firn area of the accumulation zone must be continuous to the front and at least all over the glacier sole of Holtedahlfonna. Observation of sediments on an overturned iceberg by Glasser and Hambrey (2000) seems to support this suggestion and additionally indicates that the glacier slides over soft sediments. Such a basal sediment layer is also an index of a high rate of erosion and fresh water release into the fjord.

Since the Kronebreen has experienced a surge shortly before 1869 (Liestøl, 1988), the transfer of ice from the high basin to the ablation area may have facilitated the extension of the temperate layer toward the sea. A sustained high velocity together with a significant glacier thickness may have prevented a marked change in the distribution of cold and temperate ice layers until today.

An extension of the analysis of the interferometric ERS-1 data presented in this paper will, in a future work allow to obtain information on the flow regime of about 15 to 20 glaciers in the area and, for the Kronebreen, the main glacier presented here, to check for a possible detection of the change in ice velocity at the end of the ablation period.

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