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Estimation of Arctic glacier motion with satellite L-band SAR data

Tazio Strozzi [a,*], Alexei Kouraev [b], Andreas Wiesmann [a], Urs Wegmüller [a], Aleksey Sharov [c], Charles Werner [a]

[a] *Gamma Remote Sensing, Worbstrasse 225, 3073 Gümligen, Switzerland*
[b] *Laboratoire d'études en géophysique et océanographie spatiale (LEGOS), Observatoire Midi-Pyrenées (OMP), Avenue Edouard Belin 18, 31401 Toulouse cedex 9, France*
[c] *Joanneum Research, Wastiangasse 6, 8010 Graz, Austria*

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Abstract

Offset fields between pairs of JERS-1 satellite SAR data acquired in winter with 44 days time interval were employed for the estimation of Arctic glacier motion over Svalbard, Novaya Zemlya and Franz-Josef Land. The displacement maps show that the ice caps are divided into a number of clearly defined fast-flowing units with displacement larger than about 6 m in 44 days (i.e. 50 m/year). The estimated error of the JERS-1 offset tracking derived displacement is on the order of 20 m/year. Occasionally, azimuth streaks related to auroral zone ionospheric disturbances were detected and dedicated processing steps were applied to minimize their influence on the estimated motion pattern. Our analysis demonstrated that offset tracking of L-band SAR images is a robust and direct estimation technique of glacier motion. The method is particularly useful when differential SAR interferometry is limited by loss of coherence, i.e. for rapid and incoherent flow and large acquisition time intervals between the two SAR images. The JERS-1 results, obtained using SAR data acquired by a satellite operated until 1998, raise expectations of L-band SAR data from the ALOS satellite launched in early 2006.

Keywords: Glaciers; Satellite radar; Displacement map; Artic

1. Introduction

Glaciers and ice sheets are sensitive indicators of climate fluctuations. The effects of climate warming are for instance evident in the continuous retreat of glaciers. More specifically, changes in climate are affecting temperature and precipitation at the earth's surface and therefore the accumulation and melt along the surface of glaciers with a direct effect on the mass balance. Monitoring of ice sheet and glacier flow rates is also important in climate change studies, with accelerated or decreasing motion indicating an alteration of the equilibrium of ice masses. Recently, satellite Synthetic Aperture Radar (SAR) data enabled to derive ice-surface velocity fields without the expense of in-situ measurements by means of interferometry (Bamler & Hartl, 1998; Rosen et al., 2000) and offset tracking (Gray et al., 1998; Michel & Rignot, 1999; Strozzi et al., 2002).

Most of the SAR interferometry or offset-tracking studies used data from the European Remote-Sensing Satellites ERS-1 and ERS-2 and from Canada's Earth observation satellite RADARSAT-1 at C-band (5.6 cm wavelength λ) with 1, 3 or 24 days acquisition time intervals (Goldstein et al., 1993; Mohr et al., 1998; Rignot & Kanagaratnam, 2006). A limited number of glacier flow studies were performed at L-band (λ=24.3 cm), C-band (λ=5.7 cm) and X-band (λ=3.1 cm) with SAR acquisitions of the Shuttle Imaging Radar (SIR) during the flight of the Space Shuttle Endeavour in October 1994 (Forster et al., 1999; Rignot et al., 1996; Rott et al., 1998). The experience with L-band SAR data with longer acquisition time intervals is,

* Corresponding author.
E-mail address: strozzi@gamma-rs.ch (T. Strozzi).
URL's: http://www.gamma-rs.ch (T. Strozzi), http://www.gamma-rs.ch (A. Kouraev), http://www.gamma-rs.ch (A. Wiesmann), http://www.gamma-rs.ch (U. Wegmüller), http://www.gamma-rs.ch (A. Sharov), http://www.gamma-rs.ch (C. Werner).

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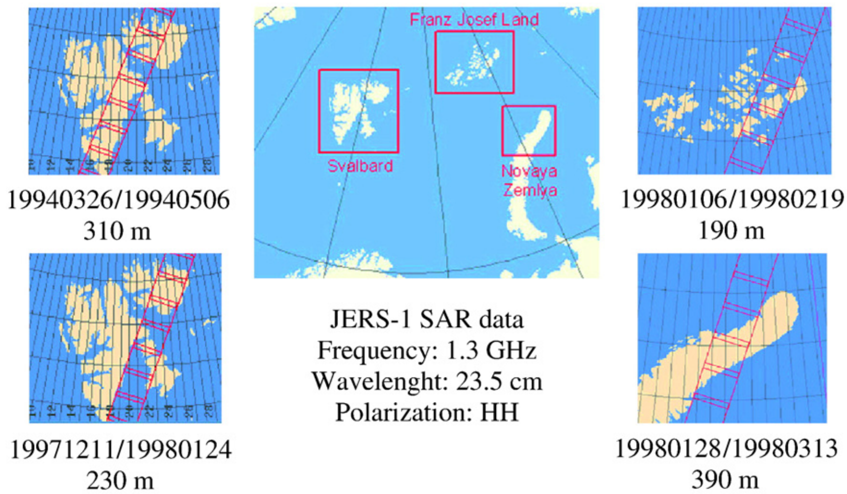

Fig. 1. JERS-1 SAR data considered in this study with indication of acquisition dates and perpendicular baseline.

however, limited (Kimura et al., 2004; Ozawa et al., 1999), in spite of the enormous amount of SAR data collected by the Japanese Earth Resources Satellite JERS-1 between 1992 and 1998 at $\lambda = 23.5$ cm and HH polarization.

As already demonstrated for the monitoring of land subsidence (Strozzi et al., 2003), landslides (Strozzi et al., 2005) and active rock glaciers (Strozzi et al., 2004), L-band SAR has the capability of complementing the existing applications based on C-band data. In the case of rapid displacements the larger wavelength reduces signal decorrelation and phase unwrapping problems. Furthermore, the greater penetration of the radar signals into the snow and firn at L-band compared to C-band (Rignot et al., 2001) results in a reduced temporal decorrelation. Here we discuss the motion of Arctic glaciers at Svalbard, Novaya Zemlya and Franz-Josef Land derived with offset tracking of L-band SAR data acquired by the JERS-1 satellite in winter with 44 days acquisition time interval.

2. Data and methods

The JERS-1 SAR mission was operated between 1992 and 1998 collecting a considerable amount of SAR data at L-band (Nemoto et al., 1991). JERS-1 SAR data are archived both at Japan Aerospace Exploration Agency (JAXA) and at the European Space Research Institute (ESRIN), where there are more than 100,000 JERS-1 SAR frames over Europe acquired at the Tromsø and Fucino ground stations. For this study 8 winter JERS-1 SAR orbits covering Svalbard, Novaya Zemlya and Franz-Josef Land were exploited (see Fig. 1). The images were taken under favorable weather conditions and were selected in order to compute 4 interferograms with acquisition time intervals of 44 days and short baselines. The JERS-1 SAR data were obtained from the ESRIN archive as long stripes of Level-0 raw data. The raw data of complete orbits were then processed to full resolution Single-Look Complex (SLC) images over the islands of interest.

With offset tracking the registration offsets of two SAR images in both slant-range (i.e. in the line-of-sight of the satellite) and azimuth (i.e. along the orbit of the satellite) directions are generated and used to estimate the displacement of glaciers (Gray et al., 1998; Michel & Rignot, 1999; Pritchard et al., 2005; Strozzi et al., 2002). The estimated offsets are unambiguous values which means that there is no need for phase unwrapping, one of the most critical steps in SAR interferometry. In this study the offset fields are generated with a normalized cross-correlation of image patches of detected real-valued SAR intensity images (Werner et al., 2005). The location of the peak of the two-dimensional cross-correlation function yields the image offset. The successful estimation of the local image offsets depends on the presence of nearly identical features in the two SAR images at the scale of the employed patches. If the coherence is retained, the speckle pattern of the two images is correlated and tracking with image patches of about 1 km in size can be performed to remarkable accuracy. If the SAR image pair is interferometrically incoherent prominent surface features, such as crevasses, are tracked instead of speckle with reduced accuracy and spatial coverage. In order to increase the estimation accuracy, oversampling rates are applied to the image patches and a two-dimensional regression fit to model the correlation function around the peak is determined with interpolation. The confidence level of each offset is estimated by comparing the height of the correlation peak relative to the average level of the correlation function to determine an effective correlation Signal-to-Noise Ratio (SNR). Coarse information on the slant-range and azimuth offsets is used to efficiently guide the search of the cross-correlation maximum.

The image offsets in the slant-range and azimuth directions are related to stereo offsets, the different satellite orbit configurations of the two SAR images, the displacement occurring between the acquisition time interval of the image pair, and ionospheric effects. The estimation of glacier motion requires the separation of these effects. Stereo offsets are not

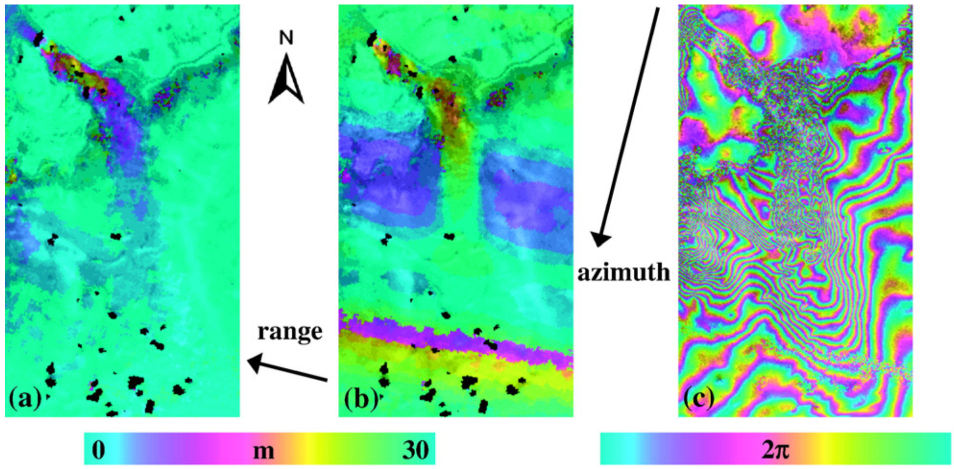

Fig. 2. Offset fields in slant-range (a) and azimuth (b) direction computed from the JERS-1 SAR images of December 11, 1997 and January 24, 1998 for Duvebreen (Austfonna, Svalbard). Incidence angle is ~35° and the perpendicular baseline is 230 m. JERS-1 interferogram is shown in (c). Image width is 20 km.

relevant for small orbit separations (e.g. baselines shorter than 300 m) and moderate topography (e.g. height differences up to 1000 masl) and can be ignored in our case. The orbital offsets are determined by fitting a bilinear polynomial function to offset fields computed globally from the SAR images assuming no displacement for most parts of the image. Ionospheric streaks occasionally detected on the azimuth offset maps are high-pass filtered along the range direction (Wegmüller et al., 2006).

An example for Duvebreen in Austfonna (Svalbard, for location see Figs. 5 and 6) is presented in Fig. 2. The offsets between the two SAR images in slant-range direction (Fig. 2(a)) adequately represent the displacement of the glacier, suggesting that the speckle of the JERS-1 image pair is still correlated after 44 days. This is confirmed by interferometric processing of the JERS-1 SAR pair done to 6 azimuth and 2 range looks with common-band filtering after co-registration of the SLC images. The interferogram of Fig. 2(c) indicates a very good coherence, with well preserved fringes over the slow moving parts of the glacier. Decorrelation is mainly observed over the areas with excessive strain rates, in particular along the margins of the glacier and at the front. On the other hand, the effects on the interferometric coherence of snow and ice melting, snow accumulation or wind drift, and microwave penetration in the dry snow cover and ice are limited.

A band of interferometric phase decorrelation can be observed to the south of Duvebreen. The azimuth offsets between the two SAR images (Fig. 2(b)) show a strong anomaly in this area related to auroral zone ionospheric disturbances (Gray et al., 2000; Meyer et al., 2006). The free electron density in the ionosphere varies with the activity of the Sun, the Earth magnetic field and atmospheric parameters, with higher concentrations and stronger spatial variations in polar regions. The free electrons interact with electromagnetic waves as a dispersive medium, with inverse effects on the phase and group velocities and stronger effects at lower frequencies. Electron density fluctuations result in variations in the interferometric

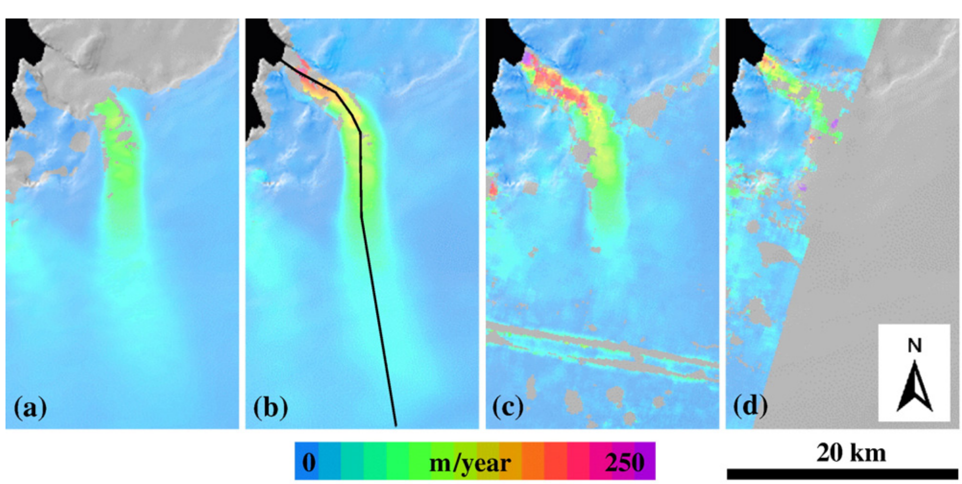

Fig. 3. Comparison between ice-surface velocities of Duvebreen (Austfonna, Svalbard) from ERS SAR interferometry in January 1994 (a) and January 1996 (b) and JERS-1 offset tracking in January 1998 (c) and April 1994 (d). The approximate main flow line of Duvebreen is shown in (b).

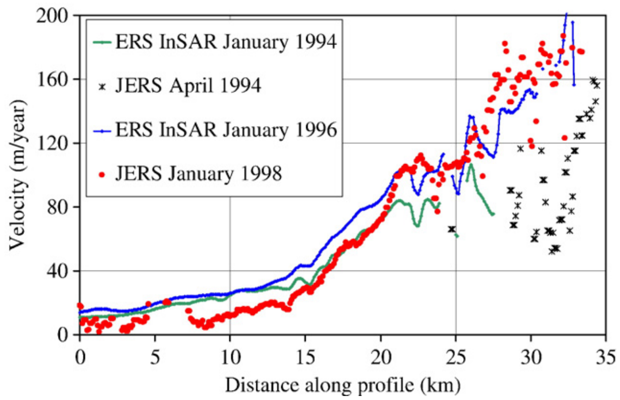

Fig. 4. Comparison between ice-surface velocities along the approximate main flow line of Duvebreen (Austfonna, Svalbard) from ERS SAR interferometry in January 1994 and January 1996 and JERS-1 offset tracking in April 1994 and January 1998.

range phase. Furthermore, delay phase ramps across the synthetic aperture cause the observed significant azimuth positional shifts ("azimuth streaking").

Differences between the characteristics of offsets related to glacier surface motion and ionospheric disturbances were used to separate the two effects (Wegmüller et al., 2006). Ionospheric anomalies are clearly visible in the azimuth offset field but hardly visible in the range offset field. Furthermore, the typical azimuth streaking geometry of ionospheric azimuth offsets differs from the more localized motion fields of glaciers. In order to estimate the ionospheric part of the azimuth offsets, we first rejected azimuth offset estimates for areas with significant (e.g.>0.2 pixel) range offsets. Furthermore, estimates over specific areas of interest (e.g. glaciers) were rejected. Then the remaining azimuth offset fields were filtered and interpolated taking into account the strong directionality of the azimuth streaks by using filters and interpolators that are significantly longer in the range direction than in the azimuth direction. Finally, this ionospheric azimuth offset estimate was subtracted from the initial offset field. The remaining offsets are interpreted as surface movements. Uncompensated ionospheric offsets can be identified by comparison with the ionospheric azimuth offset estimate. The final result for Duvebreen is shown in Fig. 3(c), where slant-range and azimuth displacements were combined to provide a two-dimensional ground displacement field.

3. Error analysis

Error analysis is essential to demonstrate the applicability of offset tracking to surface movement. In a first approach, the error is estimated by transformation of the offset estimation precision into a displacement precision. Then, the expected accuracy of JERS-1 offset tracking is assessed in stable zones

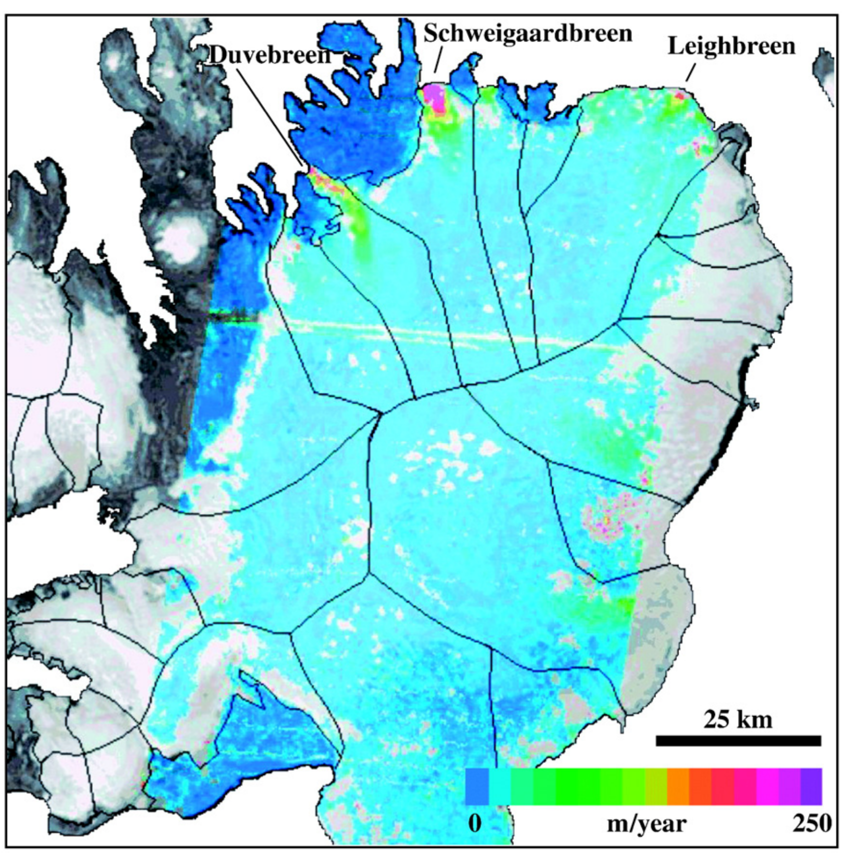

Fig. 5. Horizontal displacement for Austfonna (Svalbard) from JERS-1 offset tracking between SAR images of December 11, 1997 and January 24, 1998. Background is MODIS imagery from August 27, 2003. Ice divides and glacier names are after Hagen et al. (1993).

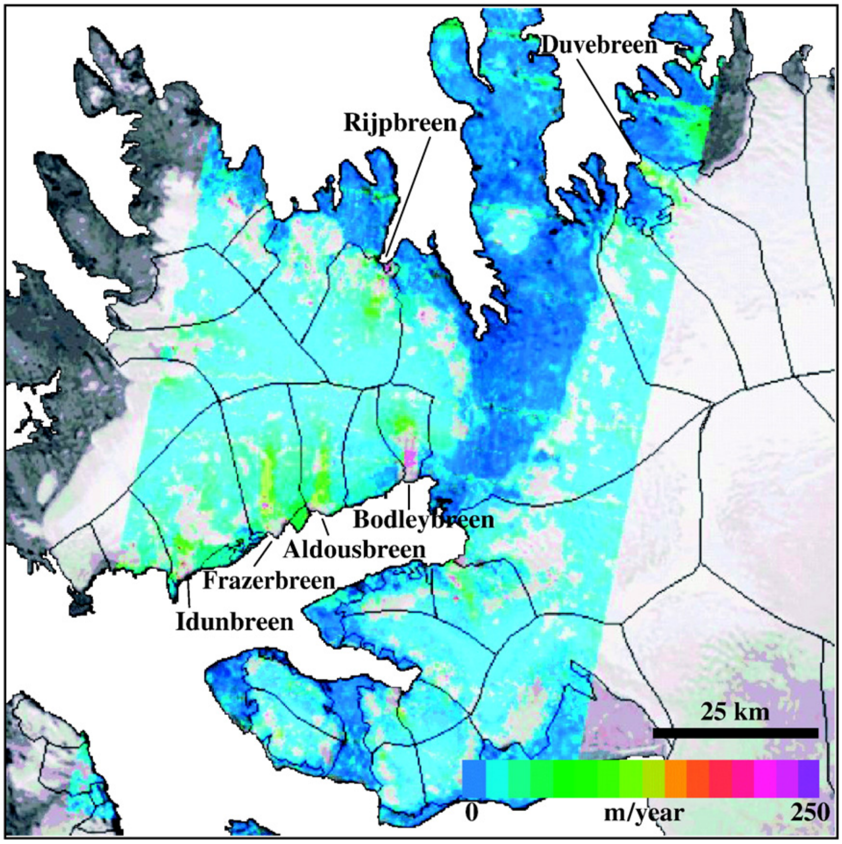

Fig. 6. Horizontal displacement for Vestfonna (Svalbard) from JERS-1 offset tracking between SAR images of March 23 and May 6, 1994. Background is MODIS imagery from August 27, 2003. Ice divides and glacier names are after Hagen et al. (1993).

and by comparison with ERS SAR interferometry. Finally, in the next section, the results found over Svalbard and Novaya Zemlya are compared with geodetic measurements.

Slant-range and azimuth offset estimation errors computed with window sizes of 64×256 pixels for JERS-1 SAR data with acquisition time intervals of 44 days are expected to be on the order of 1/5th of a pixel. This value has been determined in stable zones using the standard deviation between the values of individual estimates and those resulting from a regression function fitted globally to the SAR scene for a large number of JERS-1 images. The resulting precision of displacement for JERS-1 SAR data processed to a slant-range pixel spacing of 8.8 m and to an azimuth pixel spacing of 4.4 m is therefore on the order of 3.2 m, i.e. 26 m/year, assuming flowing in the horizontal plain with an incidence angle of 35°.

The magnitude of the errors in the flow rate can be assessed by the apparent displacement of rock areas. After masking areas of ice and water, mean displacement values for JERS-1 data where strong azimuth shift modulations were detected and filtered were 1.14±1.85 m or 9±15 m/year. Mean displacement values for 44 days JERS-1 data where azimuth shift modulations are very limited were 1.17±0.52 m, i.e. 10±4 m/year.

JERS-1 offset-tracking records of surface ice velocity are compared to ERS SAR interferometry results for Duvebreen. Fig. 3 presents velocity maps from dual-azimuth ERS SAR interferometry (Mohr et al., 1998) in January 1994 and January 1996 and from JERS-1 offset tracking in April 1994 and January 1998. Missing data in the lower part of Duvebreen in Fig. 3(a) are the result of phase decorrelation in ERS SAR interferometry. Low correlation SNR and ionospheric disturbances filtering in JERS-1 offset tracking are the reasons for partial information in Fig. 3(c). The JERS-1 SAR images of April 1994 cover only the front of Duvebreen (Fig. 3(d)). Although ice velocity results derived at four different dates, with different wavelengths and different intervals are hard to compare quantitatively and therefore the significance of this error assessment is little, this evaluation is important for a confirmation of the quality JERS offset-tracking for glacier motion estimation. A profile of ice-surface velocities along the approximate main flow line of the glacier (see Fig. 3(b) for line position) is shown in Fig. 4. The ERS SAR interferometry records indicate an increase of ice velocity from January 1994 to January 1996. The JERS-1 offset-tracking results in January 1998 are similar to the SAR interferometry outcomes of January 1996 determined with one day time interval, with differences within ±20 m/year. The surface ice velocities at the front of Duvebreen measured in April 1994 are smaller than in January 1998 but comparable with the SAR interferometry rates of January 1994. At the front of the glacier large variations of ice velocities are observed, also preventing from phase unwrapping of the ERS SAR interferometry images of January 1994 acquired with 3 days time interval.

In conclusion, our precision analysis, investigations and experience suggest that for the application of offset tracking using JERS-1 SAR data with 44 days acquisition time interval expected errors are about 20 m/year after filtering of azimuth streaks.

4. Results

4.1. Svalbard

Offset-tracking results are first discussed for Svalbard. For presentation and interpretation, slant-range and azimuth displacements were combined to provide a two-dimensional ground displacement field and these maps were superimposed to Moderate Resolution Imaging Spectroradiometer (MODIS) imagery and ice divides from Hagen et al. (1993) using a sea mask. The results of Figs. 5, 6 and 7 highlight the displacement of the fastest moving glaciers Duvebreen, Schweigaardbreen and Leighbreen over Austfonna (Fig. 5), Rijpbreen, Bodleybreen, Aldousbreen, Frazerbreen and Idunbreen over Vestfonna (Fig. 6) and Austre Torellbreen, Hansbreen, Paierlbreen, Hornbreen, Samarinbreen and Olsokbreen in South Spitsbergen (Fig. 7). Profiles of horizontal displacement along the approximate main flow lines of selected glaciers are presented in Fig. 10(a) and (b) for a more quantitative analysis.

The ice-surface velocity distribution throughout the ice caps of Austfonna and Vestfonna shows strong spatial variations, as previously observed with ERS SAR interferometry by Dowdeswell et al. (1999). Both ice caps are divided into a number of clearly defined fast-flowing units, evident also from JERS-1 offset tracking, associated with subglacial valleys mapped using 60 MHz airborne radar (Dowdeswell et al., 1986). Velocity mapping of the slower moving ice in the central regions of the ice caps and between the fast flow units is less accurate with JERS-1 offset tracking than with ERS SAR interferometry, because ice-surface velocity rapidly drops below 20 m/year. On the other hand, at the front of the fast flow units, in regions where JERS-1 offset-tracking works, rapid ice flow often cause phase decorrelation of ERS SAR interferograms. Insufficiently compensated ionospheric effects can be still observed in certain areas, e.g. to the north of Duvebreen in Fig. 6.

The flow behavior of Hansbreen, a 16 km long tidewater glacier in South Spitsbergen, was studied in detail during two field investigations performed in summer 1998 and 1999 by terrestrial survey and GPS (Vieli et al., 2004). The annual velocities between summer 1998 and 1999 at the front of the glacier were on the order of 100 m/year, in agreement with the values measured with JERS-1 offset tracking in winter (Fig. 10 (b)). During the melting season, short events with strongly

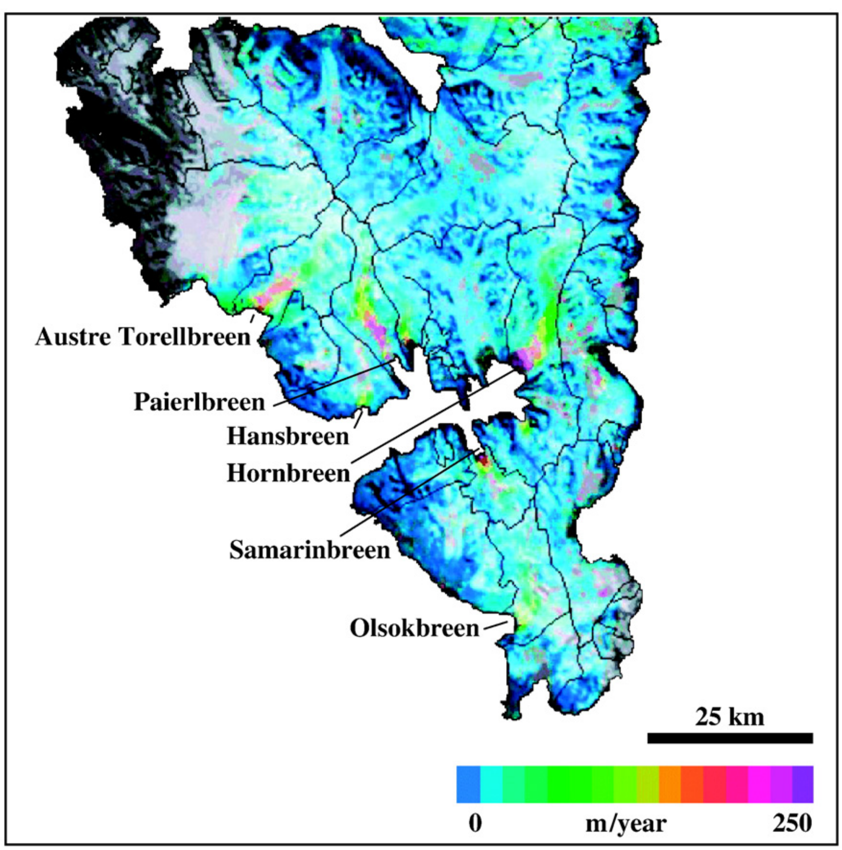

Fig. 7. Horizontal displacement for South Spitsbergen (Svalbard) from JERS-1 offset tracking between SAR images of March 23 and May 6, 1994. Background is MODIS imagery from August 27, 2003. Ice divides and glacier names are after Hagen et al. (1993).

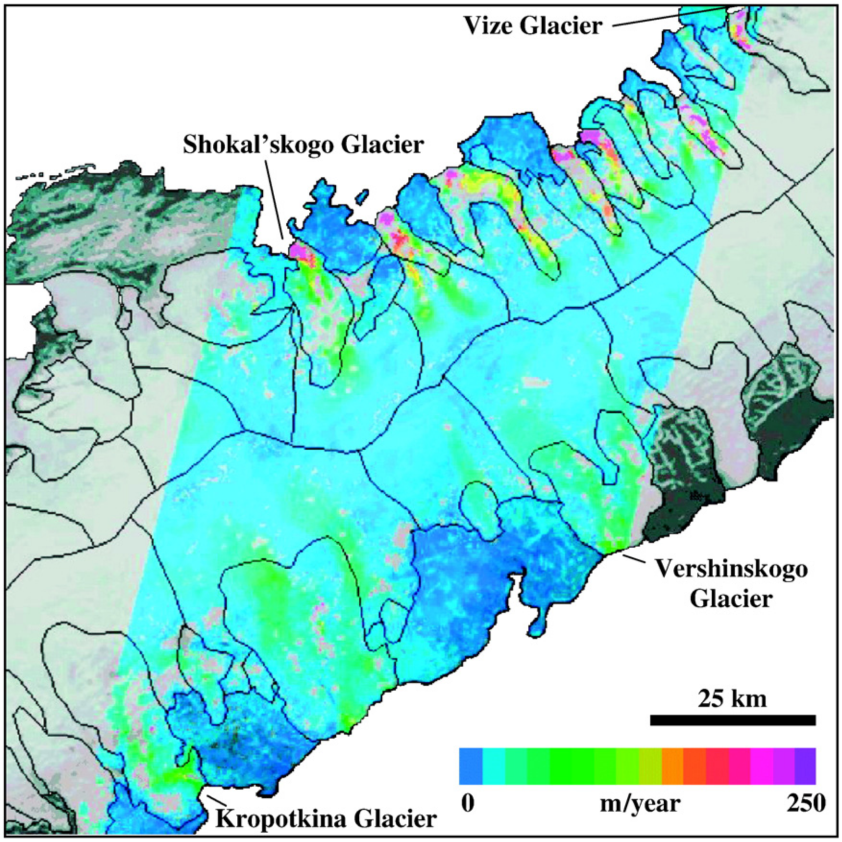

Fig. 8. Horizontal displacement for Novaya Zemlya from JERS-1 offset tracking between SAR images of January 28 and March 13, 1998. Background is MODIS imagery from July 29, 2003. Ice divides and outlet glaciers boundaries are after Varnakova and Koryakin (1978). Glacier names are after World Glacier Inventory (National Snow and Ice Data Center, 1999).

increased surface velocities and a typical duration of 1 to 2 days were observed, related to periods of strongly increased water input to the glacier due to rainfall or enhanced surface melt during warm wind conditions. However, during winter no significant increase of the flow occurs and the surface motion is in the range of the slow flow observed during summer. The ice-surface displacement of Austre Torellbreen, Paierlbreen, and Hornbreen measured with JERS-1 offset tracking in winter is larger than that of Hansbreen.

4.2. Novaya Zemlya

Offset tracking was subsequently applied to the pair of JERS-1 SAR images covering Novaya Zemlya. For this image pair the azimuth streaks were very limited. The displacement map was superimposed to MODIS imagery and a schematic map of ice divides and outlet glaciers from the catalogue of the glaciers of the USSR (Varnakova & Koryakin, 1978). In Figs. 8 and 10(c) it can be observed that the outlet glaciers between Shokal'skogo and Vize that drain the Novaya Zemlya ice cap to the north are flowing faster than those between Kropotkina and Vershinskogo that drain the ice cap to the south. The boundaries of outlet glaciers from the catalogue are generally consistent with JERS-1 offset-tracking results in the lower parts, but the JERS-1 based ice-surface motion map for 1998 shows a significantly larger glacier feeding zone in the upper parts. Thus, we expect that the mapping of glaciers with ice-surface velocities larger than 20 m/year can significantly benefit from JERS-1 offset tracking.

Ice-surface velocities in the marginal parts of tidewater glaciers in Novaya Zemlya were measured by Sharov (2005) using the conventional geodetic technique of forward intersection and a non-traditional "touch-and-go" technique during an expedition in September 2001. The frontal glacier velocities determined for three glaciers between Shokal'skogo and Vize were between 60 and 90 cm/day (i.e. about 220 to 330 m/year). The ice-surface velocities at the front of the outlet glaciers between Shokal'skogo and Vize measured with JERS-1 offset tracking in winter 1998 are typically between 250 and 350 m/year, with only two glaciers showing lower frontal velocities of about 50 to 150 m/year, which is in agreement with the geodetic measurements.

Frontal velocity of tidewater glaciers in Novaya Zemlya were measured by Sharov (2005) also from interferometric ERS SAR data acquired in October 1995 and March 1996. The SAR interferometric measurements were based on the motion of the fast sea ice away from the shore as a result of the glacier flow (Sharov et al., 2003). In winter SAR interferograms acquired under steady and cold weather conditions without significant tidal effects, the local speed of the fast-ice drift was assumed to be equal to the frontal velocity of tidewater glaciers. Typical frontal velocity estimates for the outlet glaciers between

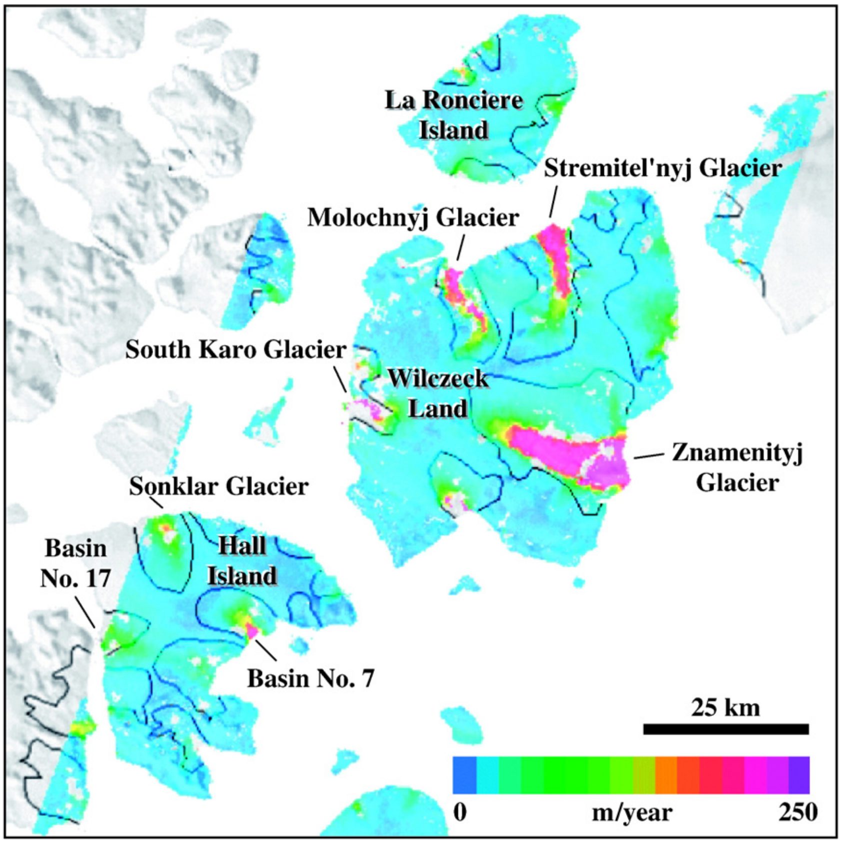

Fig. 9. Horizontal displacement for Franz-Josef Land from JERS-1 offset tracking between SAR images of January 6 and February 19, 1998. Background is MODIS imagery from April 2, 2002. Relevant outlet glaciers boundaries have been defined with the GisIce database (1998) and the MODIS image. Glacier and island names are after World Glacier Inventory (National Snow and Ice Data Center, 1999).

Shokal'skogo and Vize that drain the Novaya Zemlya ice cap to the north determined in March 1996 from the motion of the fast sea ice in ERS SAR interferograms were between 15 and 35 cm/day (about 50 to 125 m/year), i.e. lower than the values measured for the same glaciers in September 2001 using geodetic techniques. This difference was explained by Sharov (2005) by higher ice velocities in summer than in winter as a result of intense melting and precipitation. In contrast to a general increase of ice velocities during the entire melt season, observations on Hansbreen in South Spitsbergen (Vieli et al., 2004) show that there exist few but distinct short-term speed-up events lasting some days. The JERS-1 offset-tracking results with rates for the winter 1998 comparable to the geodetic measurements in September 2001 are an indication for rather similar mean summer and winter ice velocities. Offset tracking applied to other historical JERS-1 SAR images or to forthcoming ALOS PALSAR data will allow to specifically address questions related to the seasonality of the velocities of Arctic glaciers.

4.3. Franz-Josef Land

Horizontal surface-ice displacement from JERS-1 offset tracking for Franz-Josef Land is presented in Fig. 9. The displacement map is superimposed to MODIS imagery and relevant outlet glacier boundaries from the GisIce database (1998). Few clearly defined fast-flowing units characterize the ice caps on Wilczek Land, Hall and La-Ronciere islands. Between these fast flow units the ice-surface velocity is much smaller. The smooth results of Fig. 9 suggest that after 44 days the speckle at L-band is still retained. This was confirmed by SAR interferometric results, that indicated well preserved fringes over the ice caps. Also for the sea ice surrounding the islands the fringes in the 44 days JERS-1 interferogram were generally well preserved, suggesting little drift of sea ice in winter for this region.

Ice flow velocities at glacial fronts in Franz-Josef Land in the cold seasons 1994–1996 were determined from the motion of the fast sea ice in ERS SAR interferograms (Sharov, 2005). For La Ronciere Island typical frontal velocities of the outlet glaciers were between 8 and 44 cm/day (i.e. about 30 to 160 m/year). The maximum ice-surface velocities at the front of the outlet glaciers are in general agreement with the values measured with JERS-1 offset tracking, which are up to 150 m/year. The frontal velocities of the fastest moving glaciers Znamenityj, Stremitel'nyj, Molochnyj and South Karo on Wilczek Land and Sonklar, Basin No. 7 and Basin No. 17 on Hall Island determined by Sharov (2005) from the motion of the fast sea ice in ERS SAR interferograms were between 30 and 85 cm/day (i.e. about 110 to 310 m/year). These values are to some extent smaller than those determined with JERS-1 offset tracking (about

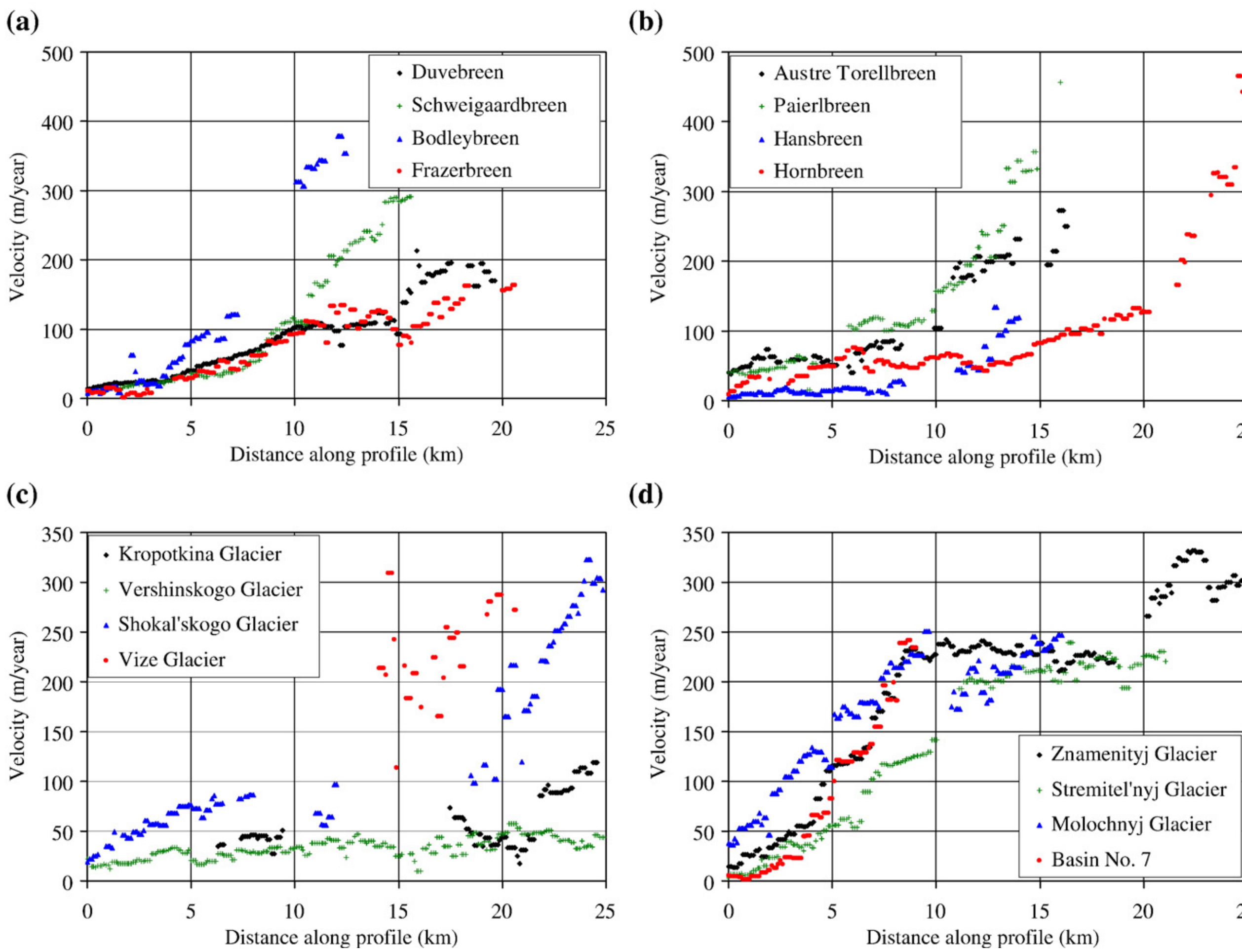

Fig. 10. Horizontal displacement along the approximate main flow lines of selected glaciers in (a) Austfonna and Vestfonna (Svalbard), (b) South Spitsbergen (Svalbard), (c) Novaya Zemlya, and (d) Franz-Josef Land from JERS-1 offset tracking. For acquisition dates of SAR data see Figs. 5–9.

200 to 400 m/year, see Fig. 10(d)), but overall the comparison between velocities of various glaciers is the same. The different years, seasons, and time spans of ERS and JERS-1 observations and the different rheological and deformation properties of glacier ice and sea ice could explain these differences.

5. Conclusions

SAR data acquired by the JERS-1 satellite between 1994 and 1998 over Franz-Josef Land, Novaya Zemlya and Svalbard were used for glacier motion studies with offset tracking. The displacement of the outlet glaciers around the ice caps was mapped with an estimated error of about 20 m/year. Azimuth streaks related to auroral zone ionospheric disturbances were detected and filtered. Our results demonstrate that offset tracking of L-band SAR images is a robust and direct estimation technique of glacier motion. The method is particularly useful when differential SAR interferometry is limited by loss of coherence, i.e. for rapid flow and large acquisition time intervals between the two SAR images. Offset tracking and differential SAR interferometry would compliment each other perfectly, but the latter is less straightforward requiring the removal of topographic phase, precise orbit estimation and phase unwrapping (Bamler & Hartl, 1998; Rosen et al., 2000).

The ice-surface displacement maps from JERS-1 offset tracking show that the ice caps of Svalbard, Novaya Zemlya and Franz-Josef Land are divided into a number of clearly defined fast-flowing units. Our results are in general agreement with previous studies performed with conventional ERS SAR interferometry over Austfonna and Vestfonna (Dowdeswell et al., 1999), terrestrial and GPS survey of Hansbreen in South Spitsbergen (Vieli et al., 2004), and geodetic techniques in Novaya Zemlya (Sharov, 2005).

The JERS-1 results presented here, obtained using SAR data acquired by a satellite operated until 1998, raise expectations of data from the PALSAR sensor onboard the Japanese Advanced Land Observing Satellite (ALOS) launched in early 2006. Estimation of Arctic glacier motion with offset-tracking satellite L-band PALSAR data is the subject of future activities. Further historical JERS-1 SAR data will support this effort for a better comparison of past and recent behavior of polar regions and possibly detect changes in the velocity of the glaciers. Questions related to the seasonality of the velocity of Arctic glaciers will be also addressed.

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