Glacier Motion Estimation Using SAR Offset-Tracking Procedures

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Abstract—Two image-to-image patch offset techniques for estimating feature motion between satellite synthetic aperture radar (SAR) images are discussed. Intensity tracking, based on patch intensity cross-correlation optimization, and coherence tracking, based on patch coherence optimization, are used to estimate the movement of glacier surfaces between two SAR images in both slant-range and azimuth direction. The accuracy and application range of the two methods are examined in the case of the surge of Monacobreen in Northern Svalbard between 1992 and 1996. Offset-tracking procedures of SAR images are an alternative to differential SAR interferometry for the estimation of glacier motion when differential SAR interferometry is limited by loss of coherence, i.e., in the case of rapid and incoherent flow and of large acquisition time intervals between the two SAR images. In addition, an offset-tracking procedure in the azimuth direction may be combined with differential SAR interferometry in the slant-range direction in order to retrieve a two-dimensional displacement map when SAR data of only one orbit configuration are available.

Index Terms—Glacier-motion estimation, offset tracking, SAR, SAR interferometry, surge-type glacier.

I. INTRODUCTION

SATELLITE synthetic aperture radar (SAR) data have provided invaluable tools for the study of ice and glaciers. In particular, the potential of differential SAR interferometry to map displacements at centimeter resolution resulted in spectacular new results in glaciology [1]–[4]. In the interferometric approach, two complex SAR images acquired from slightly different orbit configurations and at different times are combined to exploit the phase difference of the signals [5]–[7]. The interferometric phase is sensitive to both surface topography and coherent displacement along the look vector occurring between the acquisitions of the interferometric image pair. The differential use of two interferograms with similar displacement allows the removal of the topographic-related phase from the interferogram to derive a displacement map [8]–[10].

Fig. 1. Flattened, filtered, 1×5 multilooking interferogram of Monacobreen for January 15 and 18, 1994. The interferogram was geocoded to UTM coordinates, and the look direction is approximately from the southeast. Rocky areas are masked out. The perpendicular component of the baseline is 84 m. The longitudinal profile is drawn along the flow direction. A coherence map is shown in the inset.

The successful use of differential SAR interferometry is limited by the phase noise, usually characterized by the coherence. Over glacier surfaces the coherence is affected by meteorological and flow conditions and generally diminishes with increasing time interval between the acquisitions of the two SAR images used in the interferogram. Meteorological sources of decorrelation include ice and snow surface melt [11] and possibly snowfall and wind through the redistribution of snow and ice. Decorrelation causes related to the motion of the glacier are incoherent displacements of adjacent scatterers and rapid flow if local deviations from the overall image registration function are not taken into account.

A typical interferogram for a fast-moving glacier is shown in Fig. 1. Monacobreen is a tidewater glacier in Northern Svalbard flowing north from the Isachsenfonna icecap into Liefdefjorden [12]. Monacobreen is known to exhibit surge-type behavior, which is characterized by long periods (20–200 years)

of slow flow punctuated by short periods (one to ten years) of fast flow during which substantial volumes of ice are transferred to lower altitudes causing a temporary increase in the overall melt rate [13]. The inaccessibility of most surge-type glaciers has made understanding the causes, mechanisms, and precise occurrence of surging difficult, and there is a need to acquire more information about this type of glacier. At the maximum of the surge phase in January 1994, large areas of Monacobreen were characterized by low coherence, and only the upper part, where the glacier started to flow from the ice cap, and disconnected areas in its central part were coherent. At the beginning and at the end of the surge, on the other hand, the complete upper and central parts of Monacobreen were coherent, but the front of the glacier has always been incoherent independently of the one- or three-day acquisition time-interval of the European Remote Sensing (ERS) SAR data.

In the case of decorrelation due to rapid and incoherent flow, offset-tracking procedures of SAR images are a welcome alternative to SAR interferometry for the estimation of glacier motion [14]–[19]. In this paper, two offset-tracking procedures based on satellite radar data—namely, intensity and coherence tracking—are discussed. With both techniques, 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. 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. The accuracy and application range of the two methods are examined with respect to the surge of Monacobreen using SAR data of the ERS-1 and ERS-2 satellites.

II. ESTIMATION OF GLACIER MOTION USING OFFSET-TRACKING PROCEDURES

A. Introduction

In this section, the methodology to estimate glacier motion using SAR offset-tracking procedures is discussed, and the application range of these procedures is evaluated. First, two different techniques to compute the SAR image offsets, i.e., intensity and coherence tracking, are introduced. Then, the conversion of the offsets to motion values is presented. Accuracy, advantages, and disadvantages of the two different techniques are assessed and compared to those of differential SAR interferometry. Based on this discussion, conclusions concerning the methodology to apply on a specific case are drawn. The discussion also includes some specific implementations of our approach, which we consider of large interest because it is part of a commercial software package [20] and thus available to a wide user community.

B. Intensity Tracking

A first method to estimate the slant-range and azimuth registration offset fields of two SAR images is the intensity tracking, also known as cross-correlation optimization procedure [14]–[18]. The offset fields are generated with a normalized cross correlation of image patches of detected real-valued SAR intensity images. 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. When coherence is retained, the speckle pattern of the two images is correlated, and intensity tracking with small image patches can be performed to remarkable accuracy. Incoherent intensity tracking is also feasible but requires large image patches. In order to increase the estimation accuracy, oversampling rates are applied to the image patches, and a two-dimensional (2-D) regression fit to model the correlation function around the peak is determined with a four-point interpolation. The location of the peak of the 2-D cross-correlation function yields the image offset. Confidence in the offset estimate is measured by comparing the height of the correlation peak relative to the average level of the correlation function to supply a correlation signal-to-noise ratio (SNR). Coarse information on the slant-range and azimuth offsets is used to guide the search of the cross-correlation maximum. The image-patch size may be adapted to a specific case. For the present study with ERS SAR data, we systematically used patch sizes of 64×64 single-look pixels, which corresponds to around 1300 m in the ground-range direction and 250 m in the azimuth direction.

C. Coherence Tracking

A method of measuring the offsets between SAR images complementary to the intensity tracking is the coherence tracking, also known as the fringe visibility algorithm or coherence optimization procedure [19]. Throughout the single-look complex SAR images, small data patches are selected; a series of small interferograms with changing offset is constructed; and the coherence is estimated. The location of the coherence maximum is determined at subpixel accuracy by oversampling the single-look complex SAR image patches with zero-padding and by using a 2-D regression function to model the coherence peak with a four-point interpolator. The magnitude of the coherence maximum relative to the average level is used as a quality factor to help reject unsuitable patches. Coarse information on the slant-range and azimuth offsets is used to guide the search for the coherence maximum. Again, the image-patch size may be adapted to a specific case. For this study, with ERS SAR data patch sizes of 8×8 single-look pixels, corresponding to around 160 m in the ground-range direction and 30 m in the azimuth direction, were employed. Reliable offset estimates depend on a sufficiently high coherence level. For areas of insufficient coherence, such as observed for wet snow, no reliable offsets can be determined with this technique.

D. Estimation of the Glacier Motion

The image offsets in the slant-range and azimuth directions estimated with intensity and coherence tracking are related to the different satellite orbit configurations of the two SAR images and to the displacement occurring between the acquisition time interval of the image pair. The estimation of glacier motion, or surface deformation in general, requires therefore the separation of these two effects. The orbital offsets in the slant-range direction are related to the baseline, i.e., the separation in space of the antennas between the two SAR acquisitions. Orbital offsets in the azimuth direction are affected by the change of the baseline along the orbit. The estimation of the baseline from the

orbit parameters supplied by the space agencies is normally not precise enough either for the determination of the orbital offsets or in general for SAR image coregistration. It is, therefore, preferable to determine the orbital offsets from stable reference points. This is achieved, for instance, by fitting a bilinear polynomial function to offset fields determined globally from the SAR images if the assumption of no displacement for most parts of the image is satisfied. After subtraction of the orbital offsets, pixel shifts in slant-range and azimuth directions are related to glacier motion only and are transformed to displacements in meters with knowledge of the SAR image pixel spacing.

Slant-range and azimuth displacements provide only two components of the 3-D displacement vector. In order to obtain a 3-D displacement map, the slant-range and azimuth displacements can be combined with a digital elevation model (DEM) by assuming flow parallel to the surface of the glacier [4], [21]. If a DEM is not available, but it can reasonably be assumed that the surface is horizontal, then slant-range and azimuth displacements may provide a 2-D ground displacement field without using multiple image pairs from dual-azimuth angles (e.g., ascending and descending passes).

E. Error Analysis

Error analysis is essential to demonstrate the applicability of offset-tracking procedures to surface movement and to support the selection of the methodology for a specific case. The theoretical part of the error analysis discusses the transformation of pixel registration accuracy for the ERS SAR configuration into displacement accuracy. This gives an indication of the relevance of the offset-tracking procedures in the estimation of glacier motions. In Section III, these indicative values are compared to the results obtained for Monacobreen using offset-tracking procedures and SAR interferometry as a reference.

The ERS SAR data used in this study were processed to a slant-range pixel spacing of 7.904 m and to an azimuth pixel spacing of 3.965 m. The expected accuracy of offset-tracking procedures can be estimated 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. Typical slant-range and azimuth offset estimation errors are of the order of 1/20th of a pixel for the image-patch sizes and oversampling factors considered in this study. The resulting accuracies in slant-range and azimuth direction are summarized in Table I. The relative errors are computed by dividing the absolute error by the observation period. Consequently, the slant-range and azimuth velocity errors are indirectly proportional to the observation period. The accuracy increases if only estimates with large SNR values are considered, but, if so, the number of estimates diminishes. The accuracy of the horizontal displacement vector (and similarly of the 3-D displacement vector if a DEM is used) is roughly estimated as the sum of the accuracies in ground-range and azimuth directions. However, the horizontal errors are strongly dependent on the glacier orientation relative to the SAR imaging geometry, because of the difference of the SAR imaging and glacier-centric coordinate systems. In addition to the statistical errors in the shift estimation of single-image patches, a systematic error may be introduced in the determination of the zero-velocity reference field.

TABLE I

EXPECTED ACCURACY OF ERS SAR OFFSET-TRACKING PROCEDURES (IN METERS PER DAY) ASSUMING AN ACCURACY OF THE SHIFT ESTIMATION OF 1/20TH OF A PIXEL IN SLANT-RANGE AND AZIMUTH DIRECTIONS. THE ERS SAR DATA OF THIS STUDY ARE PROCESSED TO A SLANT-RANGE PIXEL SPACING OF 7.904 m AND TO AN AZIMUTH PIXEL SPACING OF 3.965 m. THE EXPECTED ACCURACY FOR DIFFERENTIAL SAR INTERFEROMETRY (InSAR) IS COMPUTED ASSUMING AN ATMOSPHERIC DISTORTION OF $\pi/2$; NO OTHER ERRORS ARE CONSIDERED. ACCURACY OF DISPLACEMENT RATES ASSUMING FLOWING ON A HORIZONTAL PLAIN ARE COMPUTED 1) FOR OFFSET-TRACKING PROCEDURES IN SLANT-RANGE AND AZIMUTH DIRECTION, 2) FOR InSAR DATA IN SLANT-RANGE AND OFFSET TRACKING IN AZIMUTH DIRECTIONS, AND 3) FOR DUAL-TRACK InSAR DATA OF ASCENDING AND DESCENDING ORBITS (TANDEM PHASE)

ERS SAR	Tandem (m/day)	3-days (m/day)	INSAR (m/day)
slant-range	0.395	0.132	0.007
ground-range	1.011	0.337	0.018
azimuth	0.198	0.066	-
horizontal (1)	1.209	0.403	-
horizontal (2)	0.216	0.072	-
horizontal (3)	-	-	0.036

The accuracy of differential SAR interferometry is two orders of magnitude better than that expected from offset-tracking procedures. SAR interferometry is mainly limited by phase distortions caused by spatially heterogeneous atmospheric (in particular water vapor) and ionospheric conditions. For an evaluation of the error caused by atmospheric distortions, we consider a relative high phase error of $\pi/2$, which corresponds for the ERS SAR configurations to an error of approximately 0.7 cm in the estimation of the displacement in the slant-range direction. When Tandem data of ascending and descending orbits are combined to retrieve the magnitude of the displacement vector, we expect a total error on the order of the sum of the errors in the two ground-range directions, i.e., about 3.6 cm/day. Additional errors in SAR interferometry may arise in resolving the ambiguity in the phase signal through phase unwrapping.

A displacement vector can also be retrieved by combining differential SAR interferometry in the slant-range direction, offset tracking in the azimuth direction, and a DEM. This approach is less accurate than that based on differential SAR interferometry alone using dual-azimuth data, but can be applied using only one image pair. The accuracy of this approach is more than five times better than using offset tracking alone, because of the high ground-range resolution of the ERS SAR data.

Further limitations of offset-tracking procedures are similar to those encountered in SAR interferometry: tidal motion of floating ice, limitation of the assumption of flow parallel to the ice surface, DEM errors, and errors arising from propagation effects in the ionosphere [17]. Most of these errors, as well as those introduced by the estimation of the shifts of single-image patches and by the determination of the zero-velocity reference field, tend to be random. Therefore, spatial averaging may reduce their contribution. In our examples, though, spatial filtering was not applied.

F. Application Strategy

Intensity tracking, coherence tracking, and SAR interferometry are complementary techniques for the study of glacier motion. The definition of a strategy for the mapping of a glacier flow depends on the size, orientation, and flow rate of

the glacier, the required spatial resolution and accuracy, the coherence, the computation time, and the availability of SAR data in the archive. Often, a combined approach is the most efficient way to determine the motion of a glacier.

SAR interferometry is by far the most accurate technique to measure the displacement component in the slant-range direction. Therefore, this method is used when applicable. The spatial resolution is also very high, typically 20 m × 20 m on the ground. The most important limiting factors of SAR interferometry are the coherence and the feasibility of phase unwrapping. Phase unwrapping is reliable only for areas of high coherence and low fringe rates. In some cases, disconnected areas of high coherence separated by areas of low coherence cannot be properly analyzed because information on a reference point is missing. Unlike offset-tracking procedures, SAR interferometry does not measure the displacement in the azimuth direction.

Coherence tracking is suitable for areas of high coherence, essentially where SAR interferometry is applied. In comparison to SAR interferometry, though, absolute estimates are obtained making it is also suitable for disconnected areas of high coherence and for very large displacements. In addition, coherence tracking provides information on the motion in two directions. However, the accuracy and resolution of coherence tracking are poorer than those of differential SAR interferometry. Finally, the computational efficiency is a limiting factor, and long processing times are required to track the motion of large areas at high spatial resolution.

The big advantage of intensity tracking is that it can be employed also where there is no coherence. In most areas, the successful analysis of SAR image pairs with large acquisition time intervals is restricted to intensity tracking because over glacier coherence is not retained for more than a few days. This is particularly important, since all the current and near-future planned SAR missions (ERS-2, RADARSAT, ENVISAT, and ALOS) have a revisiting time of 24 days or more. As coherence tracking, intensity tracking provides estimates of both slant-range and azimuth components of the displacement. Disadvantages are the very large image-patch sizes, reducing the spatial resolution, and the low accuracy, compared to the one of SAR interferometry. The computational efficiency is high and therefore hardly a limiting factor.

III. APPLICATION TO MONACOBREEN, SVALBARD

A. ERS SAR Data and Interferometric Analysis

A time series of ERS-1/2 SAR data from September 1991 to September 1998 was used to monitor the complete surge cycle of Monacobreen [22]. Sixteen scenes from March 1992 to February 1996 were chosen to investigate the use of offset-tracking procedures in glacier motion estimation. Table II shows dates and baselines for the image pairs selected.

For the differential SAR interferometric analysis, we applied the usual procedure [8]–[10]. The component of the interferometric phase related to the topography was removed by subtraction of two interferograms from which similar displacement could be assumed (i.e., a triplet of SAR scenes acquired with three days time interval or two Tandem pairs acquired a month apart). Where full differential data were not

TABLE II
IMAGE PAIR PARAMETERS FOR SAR ACQUISITIONS (NORMAL TEXT: DESCENDING MODE; *ITALIC: ASCENDING MODE*). TOPOGRAPHY BASELINE IS THE EQUIVALENT PERPENDICULAR BASELINE FOR THE TOPOGRAPHY COMPONENT OF THE DIFFERENTIAL COMBINATION OF INTERFEROGRAMS. ARROWS INDICATE FOR A PARTICULAR INTERFEROGRAM WHICH OTHER PAIR WAS USED TO REMOVE THE TOPOGRAPHIC SIGNAL

1st image	2nd image	Delay	B$_{perp}$	B$_{perp}$ Topo.
23.3.1992	26.3.1992	3 days	74 m	137 m
26.3.1992	29.3.1992	3 days	-63 m	
12.1.1994	15.1.1994	3 days	177 m	93 m
15.1.1994	18.1.1994	3 days	84 m	
1.6.1995	2.6.1995	1 day	-2 m	↓
28.12.1995	29.12.1995	1 day	-38 m	-206 m
1.2.1996	2.2.1996	1 day	168 m	
26.12.1995	*27.12.1995*	*1 day*	*99 m*	*-33 m*
30.1.1996	*31.1.1996*	*1 day*	*132 m*	

available at a particular date, a DEM from the most recent pair was used to correct for topographic effects on phase. After subtraction of the topography-related phase, maps of the displacement in the line-of-sight direction were computed. The SAR data of December 1995 to February 1996 of ascending and descending orbits were combined with a DEM to obtain a 3-D displacement map by assuming flow parallel to the surface of the glacier [4], [21]. Unfortunately, data of ascending orbits are available only for the winter 1995/1996. In order to compute the 3-D displacement maps for the other dates, we assumed that the flow direction did not change. This hypothesis was confirmed by a careful analysis of the displacement direction over Monacobreen, which did not show any particular anomaly. However, areas with look and flow directions approaching perpendicular directions were masked out, because of the significantly increased uncertainty in displacement estimate.

B. Slant-Range Displacement Component From Coherence Tracking

As shown in Fig. 1, very low coherence was observed over large areas of Monacobreen in the January 1994 interferograms because of very rapid and incoherent flow at the maximum of the surge. However, the central part of the glacier showed sufficiently high coherence for phase interpretation. This area can be analyzed with SAR interferometry, but since the coherent part of Monacobreen is completely disconnected from static zones outside of the glacier, information on a reference point is missing, and SAR interferometry alone cannot be used to retrieve the absolute displacement. Coherence tracking was used to supply the missing information.

Coherence tracking was applied to both SAR pairs of the January 12 and 15 and of January 15 and 18, 1994. The displacement values retrieved with the offset-tracking procedure were used as a reference for the wrapped phase values derived for the same area from SAR interferometry. For the two datasets together (1053 patches of sufficient coherence), the standard deviation of the difference between the displacement values from coherence tracking and from SAR interferometry is 0.155 m/day. The shift accuracy of single-image patches in slant-range direction is therefore on the order of 1/20th of a pixel (see Table I). The mean error of the mean difference between the displacement values from coherence tracking and
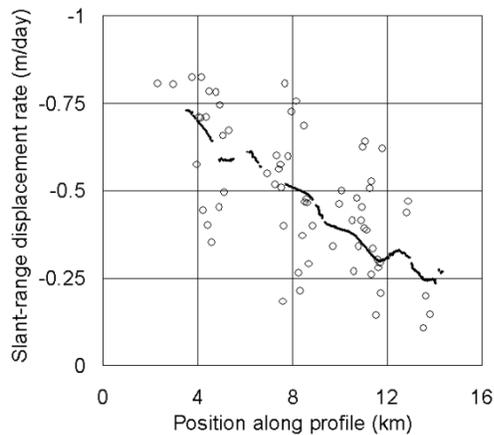
Fig. 2. Displacement rate in the slant-range direction from coherence tracking (circles) and SAR interferometry after correction for the reference velocity (line) along a longitudinal profile in the central part of Monacobreen in January 1994.

SAR interferometry is 0.155 m/day divided by the square root of 1053, i.e., 0.005 m/day. Fig. 2 complements the analysis by showing the displacement rates in slant-range direction from coherence tracking and SAR interferometry after correction for the reference velocity along a longitudinal profile of Monacobreen.

The combined use of coherence tracking and differential SAR interferometry allowed the complete and extensive measurement of surface flow over Monacobreen at the height of the surge and thus a better characterization of the spatial and temporal evolution of the entire surge phase of this glacier.

C. Combining Coherence Tracking in Azimuth Direction With SAR Interferometry

The data of December 1995 to February 1996 of ascending and descending orbits were used to investigate the accuracy of the novel approach based on the combination of offset tracking in the azimuth direction and differential SAR interferometry in the slant-range direction. Three sets of displacement maps were generated: the first one using full interferometric data of ascending and descending orbits (dual-track SAR interferometry), the second one by combining SAR interferometry in the slant-range direction with coherence tracking in the azimuth direction for data of the ascending orbit, and the third one by combining SAR interferometry in the slant-range direction with coherence tracking in the azimuth direction for data of the descending orbit. In all three cases, the same DEM of the descending mode was used because of its high accuracy resulting from a large baseline. Profiles of daily displacement were measured down the center line of the glacier and are shown in Figs. 3 and 4. The 3-D displacement vectors are characterized by their magnitude, elevation, and orientation angles.

The results of Figs. 3 and 4 confirm the feasibility and potential of the approach based on SAR interferometry and coherence tracking for the retrieval of a 3-D displacement map. The standard deviation between the displacement rates determined with dual-track SAR interferometry and the combined interferometry and tracking approach is 0.233 m/day for the 383 patches of the two profiles with information available from both surveying procedures. The maximum difference is 0.757 m/day.
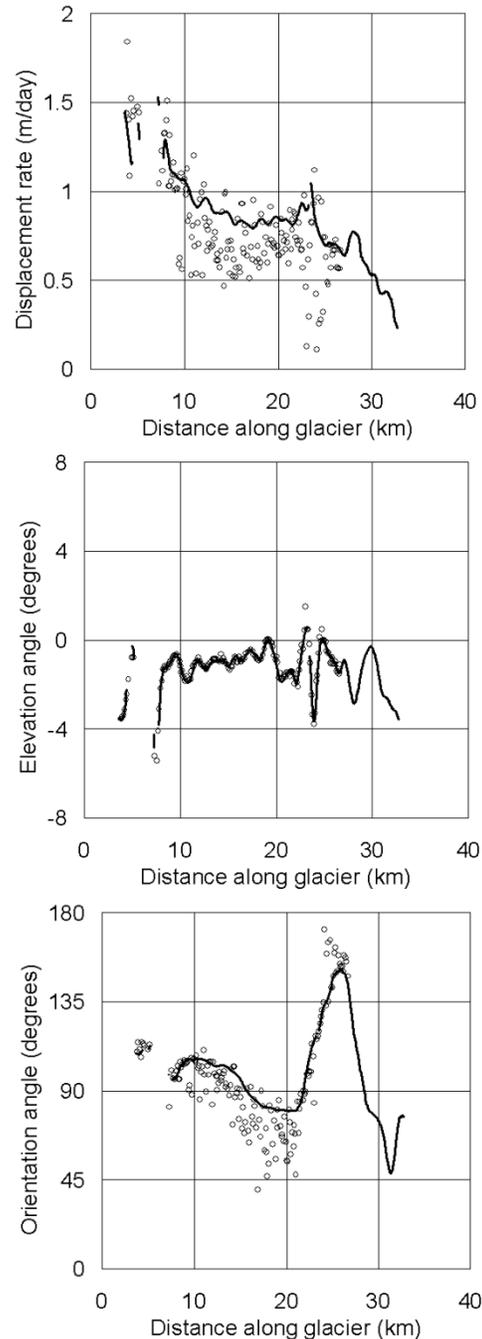
Fig. 3. Magnitude, elevation, and orientation angles of 3-D displacement vectors along a profile down the center line of Monacobreen derived with dual-track differential interferometry (line) and SAR interferometry combined with coherence tracking in azimuth direction for the data in ascending mode (circles). The orientation angle is 0° if flow is toward the east, 90° if it is toward the north, and 180° if it is toward the west. The position of the front of Monacobreen is 0 km.

The coherence-tracking accuracy in azimuth direction is, therefore, again on the order of 1/20th of a pixel (see Table I). For the orientation angle, the standard deviation between the two procedures is 10.3° with a maximum difference of 44.2°.

D. Results From Intensity Tracking

Intensity tracking was employed to retrieve displacement values at the front of Monacobreen where surge velocities exceed the range within which the interferometric phase could
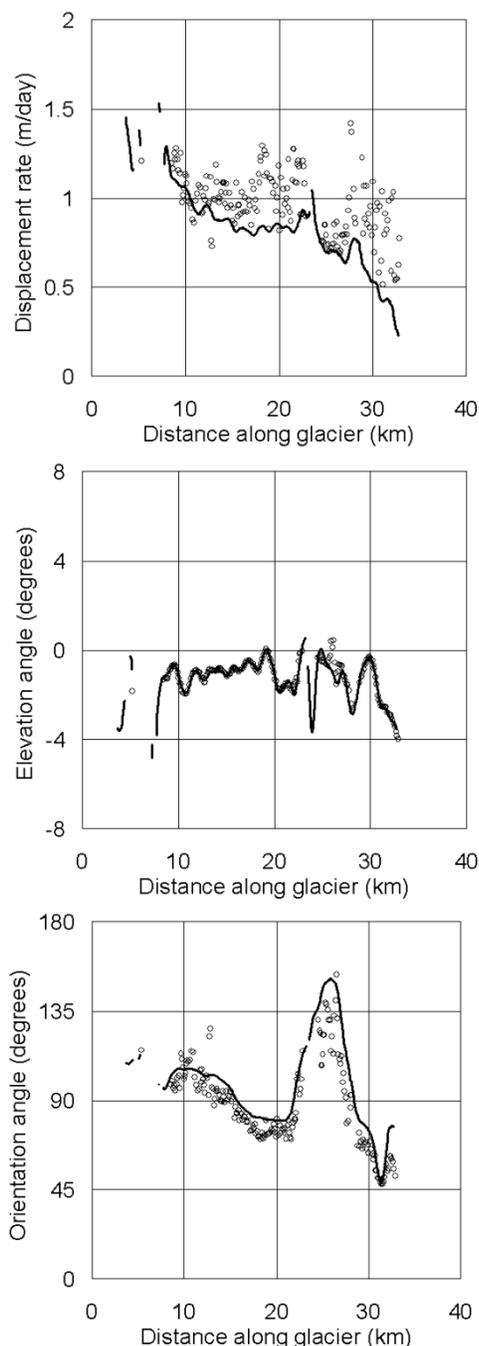
Fig. 4. Same as Fig. 3, but the circles are for SAR data in descending mode.

be successfully interpreted. Profiles down the center line of the displacement rate are presented in Fig. 5 for the ERS SAR data of March 1992, January 1994, June 1995, and December 1995. The profiles derived from differential SAR interferometry are also shown for comparison. The results of the data for the three-day repeat orbits (March 1992 and January 1994) are more accurate than those of the Tandem phase (June 1995 and December 1995), because of the larger acquisition time intervals and thus the larger displacement. For the 413 patches of the profiles of Fig. 5(a) and (b) from SAR data of the three-days repeat orbits with values from both differential SAR interferometry and intensity tracking, the standard deviation between the two surveying techniques is 0.250 m/day. The

maximum difference is 1.025 m/day. The standard deviation of 0.250 m/day corresponds to a shift accuracy of less than 1/20th of a pixel in slant-range and azimuth directions (see Table I). For the 304 patches of the two profiles of Fig. 5(c) and (d) from SAR data of the Tandem phase with values from both differential SAR interferometry and intensity tracking, the standard deviation between the two surveying techniques is 0.455 m/day. The maximum difference is 2.694 m/day. In both Fig. 5(c) and (d), a bias of the intensity-tracking values appears for low displacement rates, limiting the use of the procedure to large displacements. The bias is a result of the large statistical errors of single estimates and of the systematic error introduced by the determination of the zero-velocity reference.

Intensity tracking is essential for the study of the surge of Monacobreen. Only this technique provides information down to the front of the glacier where it indicates a continuous increase of the displacement rate and a very large scatter of the values. In particular, in 1992, the phase noise in the front of Monacobreen is not related to large displacement rates, but rather to large inhomogeneity of the displacement of adjacent scatters. This was confirmed by the application of coherence tracking to the same datasets, which failed over the front of Monacobreen.

Intensity tracking was also tested with ERS SAR data acquired with a time interval of 35 days. The interferogram formed with the ERS-1 SAR scenes of December 28, 1995 and the February 1, 1996 (perpendicular baseline −482 m) showed complete decorrelation over Monacobreen. With intensity tracking, displacement values could be retrieved over most parts of the glacier, even if the number of reliable estimates was very low. For the whole glacier, the algorithm was applied to more than 6000 image patches, but only 307 gave confident results. For comparison, in the case of the Tandem data of December 1995, almost all image patches gave good results. On the other hand, the accuracy of the displacement rates estimated with 35 days acquisition time interval is high: for the 188 patches of Monacobreen with displacement values from both intensity tracking and differential SAR interferometry, the standard deviation between the two surveying techniques is 0.151 m/day with a maximum difference of 0.727 m/day.

IV. CONCLUSION

Two SAR-based offset-tracking procedures—intensity tracking and coherence tracking—were presented and used to estimate the motion of Monacobreen in Northern Svalbard where the application of SAR interferometry was limited by phase noise. The accuracy of the offset-tracking procedures was estimated by transformation of pixel shift accuracies for the ERS SAR configuration and by comparison with differential SAR interferometry over the coherent areas of the glacier. Table I summarizes the relevance of the offset-tracking procedures for surface motion mapping. The complementarity of intensity tracking, coherence tracking, and SAR interferometry, in particular with respect to error budgets and applicability, often makes a combined approach the most efficient way to determine the motion of a glacier.

Coherence tracking was found to be particularly useful to support the SAR interferometric analysis of disconnected areas
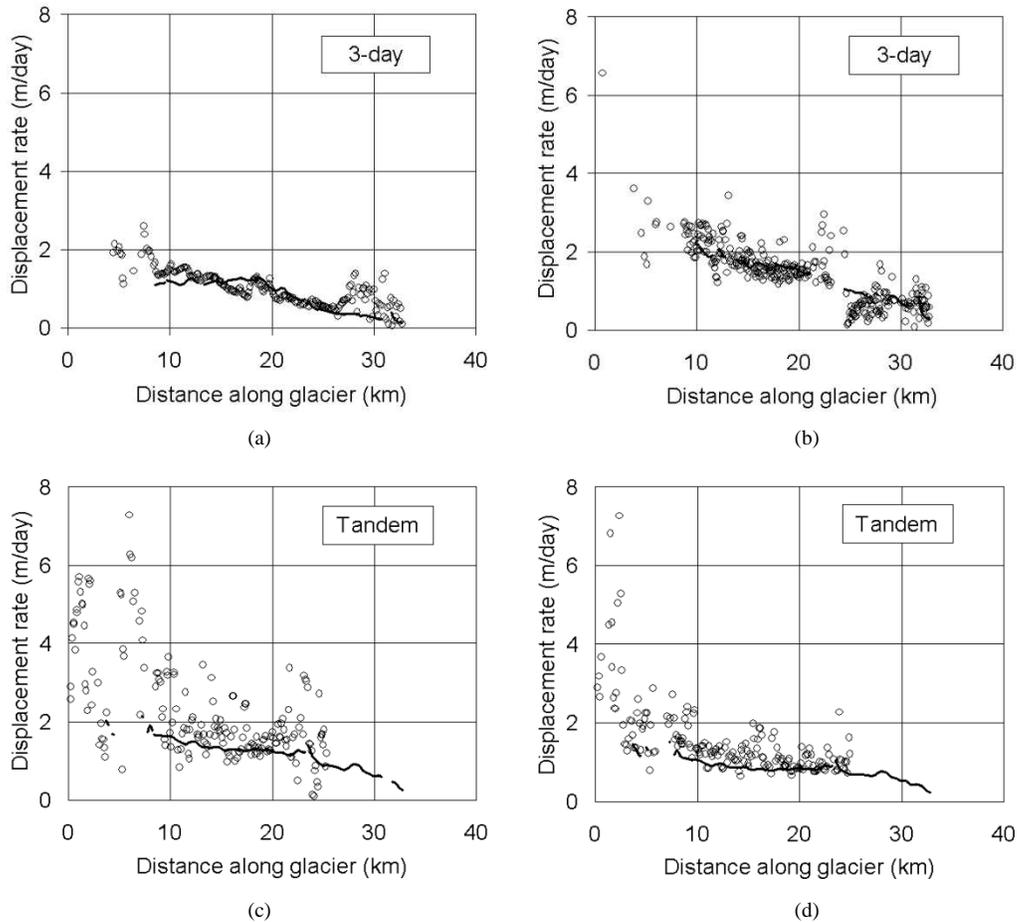
Fig. 5. Displacement rates from differential SAR interferometry (line) and intensity tracking (circles) along a profile down the center line of Monacobreen. The position of the front of Monacobreen at the end of December 1995 is 0 km. (a) March 1992; (b) January 1994; (c) June 1995; and (d) December 1995 in ascending mode.

of high coherence, i.e., as unambiguous reference information where phase unwrapping has failed to provide the link to a known reference. The combination of coherence tracking in azimuth direction and differential SAR interferometry in slant-range direction was found very useful for the estimation of displacement vectors with SAR data of a single orbit. This novel approach is applicable for areas where data of both ascending and descending modes are not available.

Intensity tracking is very useful to complement the other methods in areas concerned with very large and incoherent displacements as the result of fast flowing or of large acquisition time intervals between the two SAR images. Intensity tracking is an invaluable source of information for the study of fast-flowing glaciers and may be used in the analysis of large surging glaciers. In some cases, intensity tracking is the only technique that can be applied for SAR data acquired with more than a 24-day time interval, which is the case for all the current and in near-future planned SAR missions (RADARSAT, ERS-2, ENVISAT, ALOS).

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