Validation of Alpine Glacier Velocity Measurements Using ERS Tandem-Mission SAR Data

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***Abstract*— Five ascending and four descending ERS-1/2 tandem-mode synthetic aperture radar (SAR) interferometry (InSAR) data pairs with useful scene coherence are used to measure the surface flow field of an alpine glacier in the Canadian Rocky Mountains. The topographic component of the interferogram phase is calculated by using a digital elevation model (DEM) of the terrain and precise orbit data to reconstruct the ERS InSAR imaging geometry. The DEM is derived from the Canada Centre for Remote Sensing (CCRS) Convair-580 airborne SAR interferometer. As dual line-of-sight (LOS) measurements are not sufficient to completely resolve the three-dimensional (3-D) surface flow field, several different assumptions for determining the missing variables are considered, and the 3-D surface flow field is estimated by using single and dual LOS measurements. The InSAR results agree with historic and coincident displacement measurements made using traditional point surveying techniques.**

***Index Terms*—ERS, glacier, interferometry (InSAR), synthetic aperture radar (SAR).**

I. Introduction

It is important to take accurate measurements of the volume and motion of alpine glaciers for studies such as global climate change, modeling glacier dynamics, and determining freshwater storage capacity. Using traditional point surveying techniques, such measurements are very time consuming and can only be made in a limited number of locations. Remote-sensing techniques offer the possibility of making much quicker and more dense wide area measurements of glacier velocity.

Satellite synthetic aperture radar (SAR) used in repeat-pass interferometric mode, along with its associated signal processing, termed “InSAR”, has proven to be a suitable technique for estimating topography or displacements of the earth’s surface [1]. The concept of radar interferometry was first demonstrated by Graham [2]; repeat-pass airborne InSAR was demonstrated by Gray [3]; and repeat-pass satellite InSAR has been pioneered by groups at the Jet Propulsion Laboratory, Pasadena, CA, [4], [5], and the Politecnico di Milano [6], Milano, Italy. By measuring the phase differences between two coregistered SAR images, taken with a time lapse and/or a slightly different viewing angle of the sensor, repeat-pass InSAR has been used to make digital elevation models of limited areas of the earth’s surface, to make displacement maps of areas disturbed by seismic activity (see [7]), and to measure the velocity of ice sheet and glacier motion in Greenland and the Antarctic [8]–[12].

In this study, we focus on the Saskatchewan Glacier, an alpine glacier near the Columbia Icefields in the Canadian Rockies, a region that has been the focus of glaciologists for the past century [13]–[17] The Canada Centre for Remote Sensing (CCRS) CV-580 airborne SAR, operating in single-pass cross-track interferometer mode, acquired data sets in March and August 1995 over the test site for generation of a reference digital elevation model (DEM). At the time of the radar data takes, a science team was on the glacier measuring the positions and displacements of several benchmarks and deploying an active radar calibrator (ARC) as a reference point for DEM extraction. Shortly after that, Tandem Mission over-passes of ERS-1 and ERS-2 took place over the Athabasca and Saskatchewan glaciers of the Columbia Icefields in Alberta. In total, 12 ascending and six descending ERS-1/2 Tandem Mission data sets were collected and examined. Out of these, five ascending and four descending pairs had sufficient scene coherence over the Saskatchewan Glacier to be useful. Using these results, we assess the ability of repeat-pass satellite SAR interferometry to monitor alpine glaciers.

The Saskatchewan and Athabasca glaciers were the focus of a previous study [18], in which the glacier displacements were estimated using ascending ERS-1/2 passes only. In this paper, we expand the study of the Saskatchewan Glacier to include a more robust treatment of projection methodology, both the ascending and descending pass analysis, examination of three different assumptions for obtaining the missing parameter for estimation of the full three-dimensional (3-D) glacier flow from dual LOS measurements, and an error budget estimation.

After discussing the need for measuring the glacier flow in Section II, we summarize the various measurements made

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TABLE I
SUMMARY OF COHERENT ASCENDING PASS ERS-1/2 DATA OF THE SASKATCHEWAN GLACIER. THE DATA WERE ACQUIRED AT 5:00 GMT, 22:00 LOCAL TIME (MST). THE DATES LISTED ARE GMT DATES, ONE DAY LATER THAN THE LOCAL DATES

pass dates	orbits	RO	$B_n[m]$
2/3-Nov-95	22481/2808	449	94
21/22-Nov-95	22753/3080	220	17
5/6-Mar-96	24256/4583	220	245
21/22-Mar-96	24485/4812	449	297
25/26-Apr-96	24986/5313	449	34

TABLE II
SUMMARY OF COHERENT DESCENDING PASS ERS-1/2 DATA OF THE SASKATCHEWAN GLACIER. THE DATA WERE ACQUIRED AT 18:45 GMT, 11:45 LOCAL TIME (MST)

pass dates	orbits	RO	$B_n[m]$
26/27-Nov-95	22832/3159	299	115
31-Dec-95/1-Jan-96	23333/3660	299	175
10/11-Mar-96	24335/4662	299	27
29/30-Mar-96	24607/4934	70	97

by satellite SAR, airborne SAR, and ground surveys in Section III. We then discuss the assumptions that can be made about the glacier flow direction and evaluate how various assumptions are suited to resolve single and dual LOS radar measurements. Finally, the projected flow measurements are compared with ground surveys and their accuracy is discussed.

II. THE NEED FOR GLACIER MEASUREMENTS

Glaciers are indicators of the effects of climate and environmental change and are an important water resource for areas such as western and central Canada. For example, in the Columbia River drainage, approximately twice the water is stored in glaciers than is stored in manmade reservoirs. The runoff from glaciers dominates the flow of many western rivers during mid-to-late summer and provides an important buffering effect on the entire river system by providing more runoff during warm dry summers than wet cool summers.

For ice mechanics as well as glacier mass balance studies, the glacier *velocity* field is desired, and in most cases, only a few selected points can be measured with reasonable resources. The existing velocity measurement methods are accurate to a few centimeters per observation interval, but are very limited in that measurements can be made only at selected locations and times due to the cost of field logistics and personnel.

The Columbia Icefield was chosen for our experiments because of its ease of access for ground verification and the excellent quality of past glacier flow and runoff data. We were able to take advantage of the fact that this region has been one of the most intensely studied regions in North America during the past century (see Meier [13], Savage [14], Paterson [15], Luckman [16], and Raymond [17]). In addition, the Columbia Icefield was chosen because it is an excellent example of a large group of alpine glaciers that are impossible to measure by conventional ground-based methods and could benefit from the use of remote sensing for certain important measurements.

III. GLACIER MEASUREMENTS

In this section, we detail the ERS tandem mission data sets used in this experiment and outline the processing steps used to calculate the interferogram. Single-pass airborne InSAR measurements were used to derive the reference DEM needed for removal of the topography-induced phase term, and both historic and coincident ground measurements were used to estimate the accuracy of the InSAR measurements. We finally outline the processing of the data to give the displacement of the glacier along the line-of-sight (LOS) of the radar beam.

A. ERS-1/2 Tandem Interferograms of Glacier

All of the 18 available ERS-1/2 tandem mode data sets of the Saskatchewan Glacier site were examined. Out of these, only five ascending pairs and four descending pairs were found to have adequate scene coherence (roughly 0.5 or greater) over the entire length of the glacier for differential InSAR-based displacement measurement. The relevant data sets for ascending and descending passes are summarized in Tables I and II, respectively.

Processing of the ERS-1/2 tandem single-look complex (SLC) data to the interferogram stage is detailed elsewhere [19]. Essentially, the SLC images are first coregistered to subpixel accuracy. To optimize coherence, the images are then filtered in range and azimuth. The range filtering selects only overlapping portions of the object spectrum, based on a spectral analysis of the fringe frequency of the interferogram. The azimuth filtering suppresses nonoverlapping portions of the azimuth Doppler spectra, resulting from processing with different Doppler centroid frequencies. The filtered images are then oversampled by a factor of two and the interferogram formed. The coherence is estimated using an averaging window size of 50 (azimuth)$\times$ 10 (range) samples and corrected for finite SNR. Since the azimuth and range filtering avoid decorrelation due to spectral misalignment and the measured coherence has been corrected for finite SNR, the resulting coherence estimate may be interpreted as the temporal scene coherence. The systematic geometry-dependent phase term can be removed from the interferogram phase, resulting in a "flat-earth" corrected phase. The resulting coherence maps have a resolution of roughly 50 m.

A representative ascending pass interferogram from the March 5–6, 1996, data pair of the Columbia Icefield area is shown in Fig. 1. The Saskatchewan, Athabasca, and Dome glaciers can be seen from bottom to top in the scene. A representative descending pass interferogram from the March 10–11, 1996, data pair of the Saskatchewan Glacier is shown in Fig. 2. The Athabasca and Dome glaciers cannot be seen in the descending passes because of layover. In both figures, the upper panels show the image magnitude and scene coherence. The lower panels show the raw interferogram phase and the flat-earth corrected phase, both wrapped in intervals of 2π rad. In both cases, the coherence on the glacier is very good (0.55–0.87), except at the steep regions near the top of the glacier and on portions of the icefield).

B. Convair-580 InSAR Measurements

The interferometric SAR mode of the CCRS C-band Convair-580 SAR [20] has been described by Gray *et al.* [21].

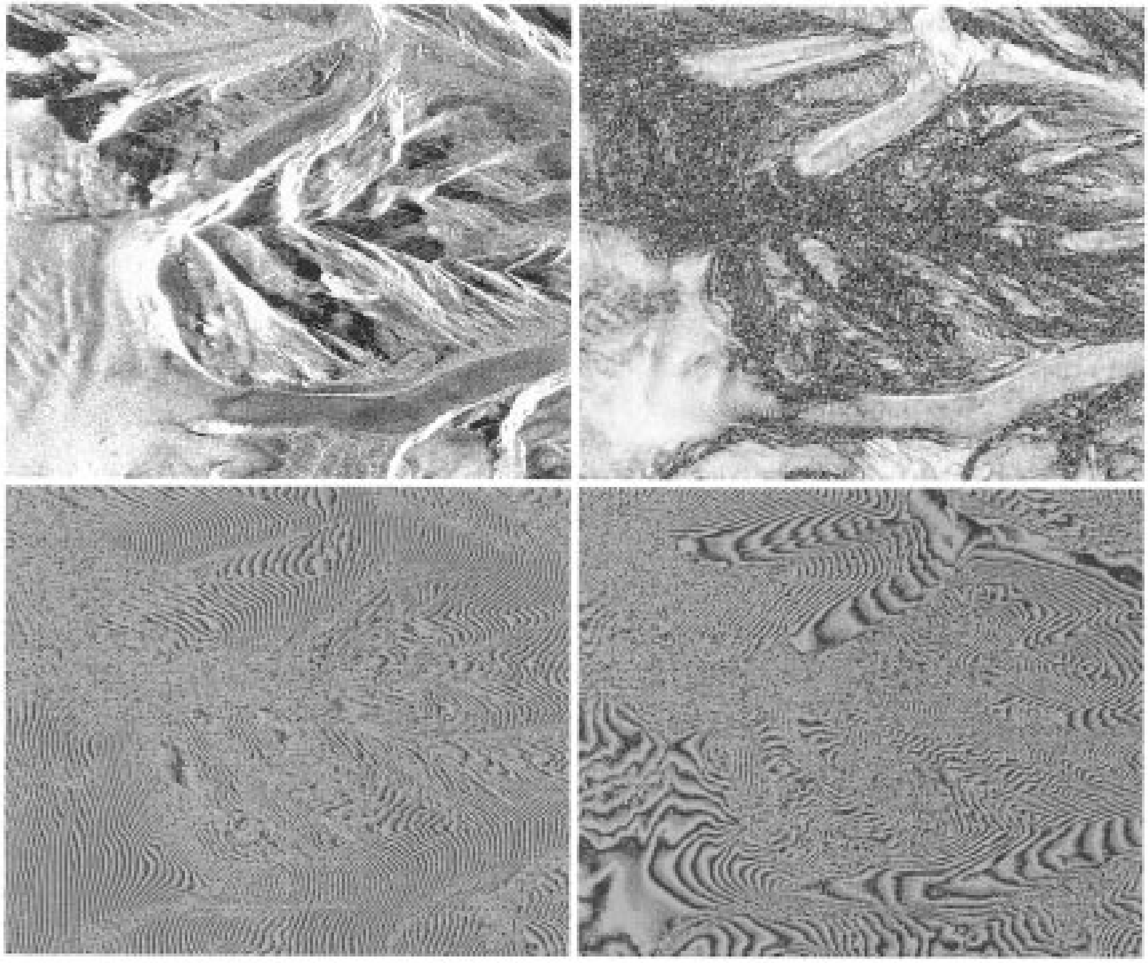

Fig. 1. Representative ascending pass interferogram from March 5–6, 1995, for the Columbia Icefield area and the Saskatchewan Glacier: image magnitude (upper-left); scene coherence (upper-right); raw interferogram phase (lower-left); flat-earth corrected phase (lower-right). Each color cycle in the lower panels represents a 2π phase change.

The cross-track mode was installed in 1991 and includes an auxiliary receive-only C-band H-polarization antenna mounted on the right-hand side of the fuselage. In contrast to satellite repeat-pass interferometry, radar pulses are transmitted by the main antenna and subsequently received by both antennas, having nominally identical channels. Consequently, high coherence is maintained and accurate topography can be obtained without being appreciably disturbed by scatterer motion.

All signal processing (including motion compensation, image compression, interferogram generation, phase unwrapping, phase-to-height conversion, and geocoding) is carried out in software after the flight and uses differential Global Positioning System (GPS) and Inertial Navigation System (INS) data for the reference track generation, motion compensation, phase calibration, and geocoding. The interferometer has a nominal baseline of 2.8 m at an off-vertical angle of 41°.

The airborne InSAR data used to generate the reference DEM for this study were obtained by the CV-580 InSAR system on March 25 and August 25, 1995, and mapped to a 5-m UTM grid referenced to the WGS-84 ellipsoidal model. An ARC, together with a P-code GPS receiver, was mounted near the toe of the Athabasca Glacier in the August data set and used in the processing and calibration of both data sets. The DEM of the Saskatchewan (lower) Glacier and surrounding area is shown in Fig. 3. The elevation portrayed in 50-m cycles was superimposed on the magnitude image. Typically, the accuracy of the derived DEM's are 1–5-m RMS error, with a height bias dependent on the control points, but typically less than 10 m [22].

C. On-Site Measurements

The Saskatchewan Glacier has been the site of extensive research by glaciologists over the past 100 years. Meier studied the glacier over several years in the early 1950's [13]. His survey results are included here for historical reference.

More recently, the National Hydrology Research Institute (NHRI) installed survey markers on the Saskatchewan Glacier in June 1995 to provide estimates of the glacier's surface flow field at three points on the lower glacier near its centerline. The marker positions were measured using laser ranging techniques in August, September, and December 1995. These point measurements form the basis for the validation of the differential InSAR flow measurements.

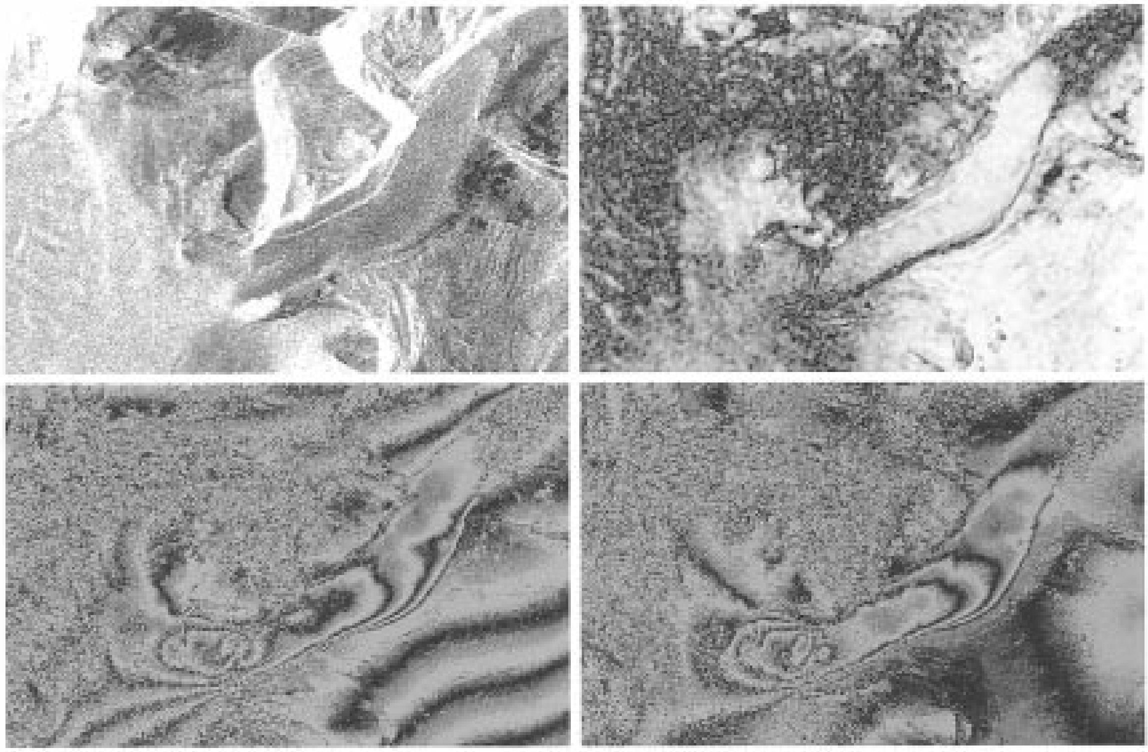

Fig. 2. Representative descending pass interferogram from March 10–11, 1995, for the Saskatchewan Glacier: image magnitude (upper-left); scene coherence (upper-right); raw interferogram phase (lower-left); flat-earth corrected phase (lower-right). Each color cycle in the lower panels represents a 2π phase change.

D. Estimate of Line-of-Sight Displacement

The key to estimation of the LOS displacement of the glacier is to be able to separate the interferometric phase caused by surface displacement from that caused by topography. The following two approaches have been proposed to achieve this separation.

1) If the surface topography and the geometry of the satellite orbit is known, it is possible to estimate the InSAR phase due to the topography and to remove it [7].
2) If the motion of the glacier is assumed to be time-invariant and mutually coherent over three or more observations, it is possible to combine satellite InSAR measurements with different baselines to estimate both the topography and the motion of the observed area assuming steady-state flow [23].

Since we are relying on ERS-1/2 tandem-mode interferometry, in which only two tandem pairs are available and since an accurate reference DEM of the site was available from the CV-580 airborne InSAR system, and precise ERS-1/2 orbit data (PRC) was available from the German Processing and Archiving Facility (D-PAF) [7], we use the first of these approaches.

Using the PRC orbit data, the CV-580 magnitude image and DEM are mapped from UTM coordinates to the ERS-1 slant range geometry, creating a synthetic interferogram. The registration between the real and synthetic interferogram is optimized in azimuth and range to within a pixel. The differential interferogram is then created by multiplying the real interferogram by the complex conjugate of the synthetic interferogram. This removes the phase due to topography (including the synthetic phase due to the imaging geometry). This is followed by phase unwrapping and conversion of the phase to LOS displacement of the glacier. Finally, the drainage basin of the glacier is used as a zero motion reference to calibrate the LOS displacements. The LOS displacement for the five ascending pairs along the glacier centerline are shown in Fig. 4, and the displacement for the four descending pairs are shown in Fig. 5.

A previous study, focusing on ERS-1/2 interferometry in the Arctic, examined the nondeterministic components of the differential interferometric phase [22]. It was determined that, due in part to inaccurate PRC orbit data, the differential interferometric phase can have a linear trend of up to 1 rad or 0.5-cm LOS in range and azimuth over a 10-km scene. In addition, the differential interferometric phase can also have a component due to atmospheric inhomogeneities, typically on the order of 1–2 rad or 0.5–1.0-cm LOS. Others have observed similar orbit inaccuracies [24] and atmospheric effects [25]. These conclusions suggest that the differences observed between the various ascending or descending passes could be due to these artifacts, precluding any rigorous study of seasonal glacier flow variations. Nevertheless, the various LOS displacements agree very well with one another, relative to the maximum flow speed of 18-cm/day.

IV. Projection-to-Glacier Flow Direction

The InSAR data is processed to give the LOS displacement of the radar beam, as described in Section III-D. However, the

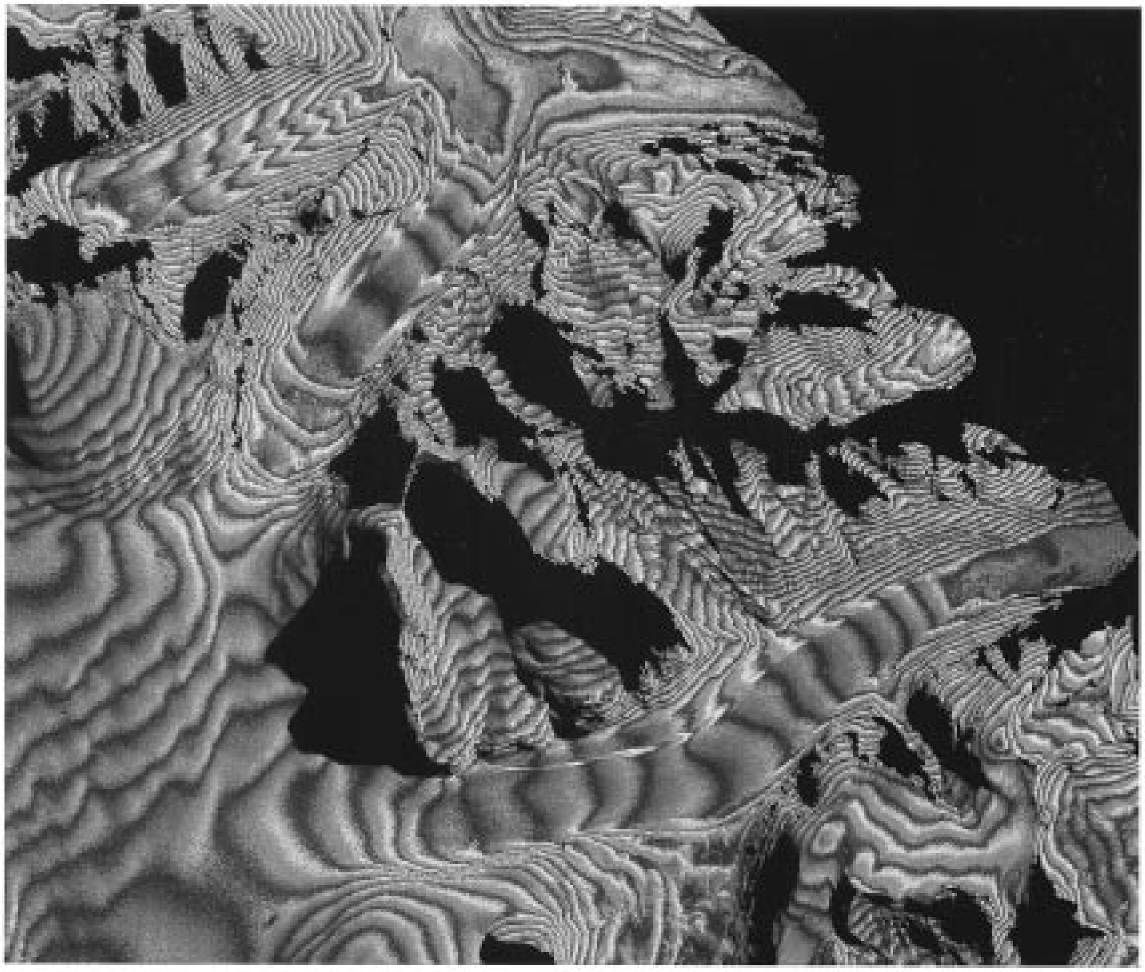

Fig. 3. DEM of the Columbia Icefield area and the Saskatchewan Glacier (bottom), obtained from the CV-580 cross-track InSAR system and mapped to UTM coordinates. The map covers 13.5-km easting by 14.5-km northing. Each color cycle represents a 50-m change in elevation. The data were acquired on March 25, 1995.

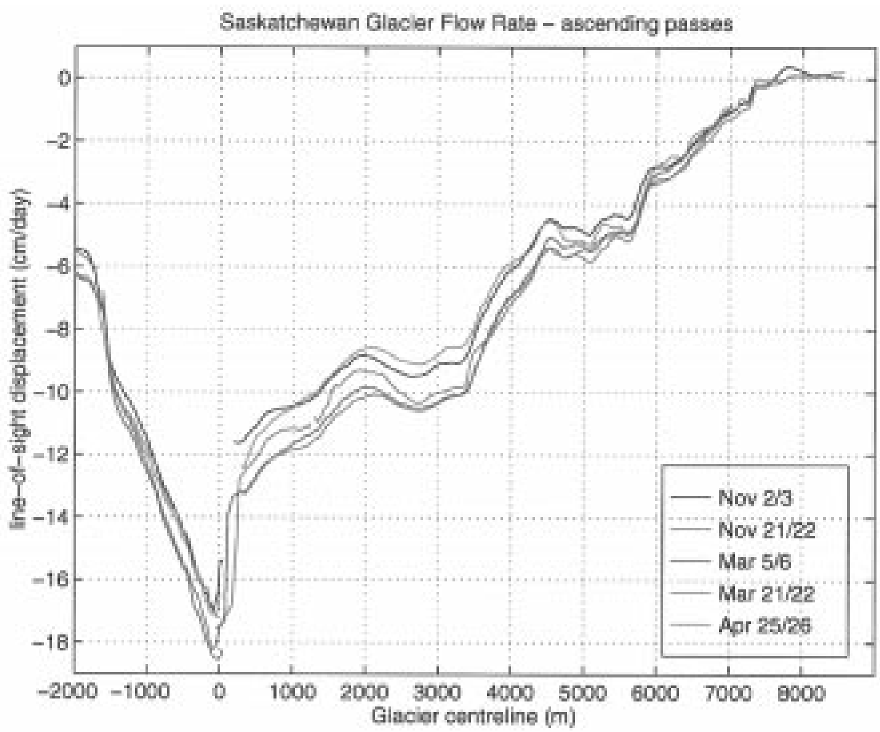

Fig. 4. Plot of the line-of-sight displacement for the five coherent ascending passes along the centerline of the Saskatchewan Glacier.

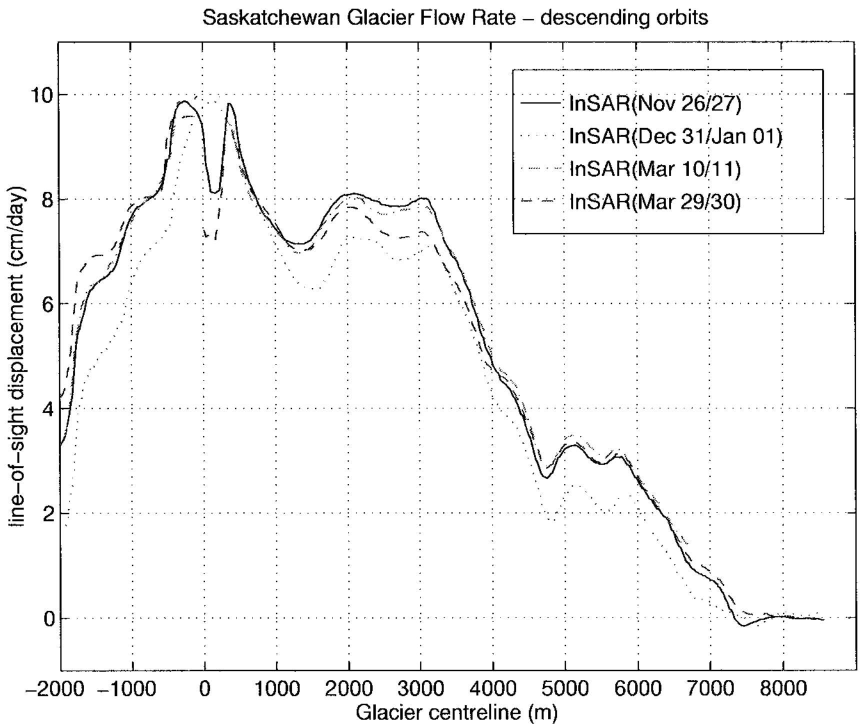

Fig. 5. Plot of the line-of-sight displacement for the four coherent descending passes along the centerline of the Saskatchewan Glacier.

true displacement may lie along a different direction, and more information is needed to resolve the measured displacement vector along the actual flow direction.

Three approaches can be taken to resolve the displacement vector. First, if we only have one InSAR measurement, only one degree of freedom can be resolved in the estimated flow. Specifically, if the 3-D direction of the true flow is assumed and if a direction of the LOS displacement, with respect to the surface displacement, is not perpendicular to the glacier flow direction, the magnitude of the flow along this direction may be estimated from the InSAR data. This approach is described in Section IV-A.

Second, if two InSAR measurements are available that provide estimates of the displacement along two different lines-of-sight, only one assumption is needed to resolve the full 3-D glacier flow. This approach is discussed in Section IV-B, and three different assumptions for obtaining the missing parameter are considered.

If three noncoplanar lines-of-sight are available, no assumptions would need to be made about the glacier flow direction. This might be possible with an airborne SAR sensor, but it is not possible with ERS-1/2. In all cases, it is assumed that the glacier's flow direction and speed are constant for the interferometric pairs.

A. Estimate of the 3-D Glacier Displacement Using a Single LOS Measurement

The measured LOS displacement is the actual surface displacement projected onto the radar line of sight. From the geometry of Fig. 6, the surface displacement D can be given

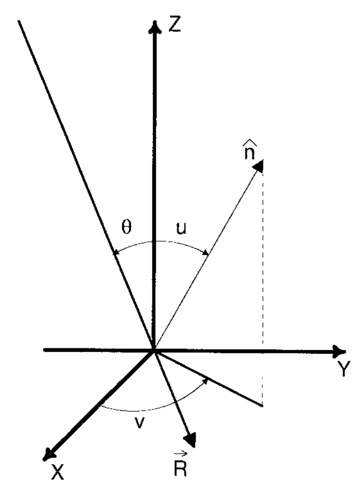

Fig. 6. Diagram showing the surface-normal geometry $\hat{n}$ and the angles u (surface slope) and v (direction of slope); $0 \leq u < 180°$; $-180° \leq v < 180°$. x is radar azimuth; y is ground range; and z is vertical. The measured differential displacement δR is in the direction of the radar LOS. The incidence angle θ is measured with respect to local vertical and is positive for left-looking and negative for right-looking radars. LOS is close to the y–z plane for SAR's, such as ERS, that are processed close to zero Doppler.

as [18]

$$D = \frac{\delta R}{|\cos u \, \sin v \, \sin\theta + \sin u \, \cos\theta|} \tag{1}$$

where θ is the radar incidence angle from the local vertical and is defined as negative for a right-looking radar, δR is the LOS displacement, u is the angle between the vertical and local surface normal, varying between 0° and 90°, v is the angle between the azimuth (or x-axis) and the projection of the local surface normal on to the horizontal and varies between $-180°$ and $180°$, and the y-axis is ground range, while the z-axis is vertical.

v can be given in terms of UTM map coordinates as

$$v = \nu + 0.2° + \text{track} - 90° \qquad (2)$$

where ν is the angle from grid east to the horizontal component of the displacement (measured CCW, the 0.2° converts the UTM grid north to true north for this location) and *track* is the platform track angle, $-16°$ for the ascending passes and $196°$ for the descending passes.

Using (2), the denominator of (1) can equal zero for certain critical values of u and ν, where the LOS displacement is perpendicular to the glacier displacement. Fig. 7 shows a plot of these critical angles for the ascending and descending ERS-1/2 passes used in this study. u is plotted along the ordinate, and the displacement direction with respect to the grid east ν, is plotted along the abscissa. The contour lines indicate the values of u and ν, obtained from the DEM of the main portion of the glacier within 50 m of the centerline.

Note that the derivative of D, with respect to both u and ν, varies inversely with the square of the denominator of (1). Thus, as u and ν near their critical values, the displacement D becomes increasingly sensitive to errors in u and ν. The RMS error of D becomes proportionately larger.

To estimate the displacement of the glacier from a single LOS measurement, we should ensure that the LOS direction, relative to displacement, is outside the critical range. Then, certain assumptions need to be made to enable the estimation of u and ν, the two unresolved parameters in (1). The first assumption pertains to the vertical orientation of the flow vector. Typically, the flow direction points slightly downward, with respect to the glacier surface in the accumulation zone, and slightly upwards in the ablation zone, assuming accumulation and ablation are small (see [13, Fig. 23]).

It is also expected that the coherence would suffer in regions of significant accumulation or ablation. Significant accumulation between the data sets that form the interferometric pair would result in a significant change in path length and a loss of coherence. Significant ablation between passes due to surface melting would significantly change the surface characteristics of the glacier and also result in a loss of coherence. Therefore, in regions of high coherence, accumulation or surface ablation are probably not a significant factor. Thus, we assume that the vertical flow direction is parallel to the glacier's surface.

The second assumption pertains to the flow direction. We again make use of the DEM and assume that the glacier flows down slope. The vectors u and ν are then obtained directly from the DEM, enabling the calculation of the displacement D. To reduce RMS errors, the displacement D is estimated along the glacier centerline and a 50-m wide swath around the centerline enables a degree of averaging for the calculation of u, ν and the LOS displacement.

Using these assumptions, together with (1) and (2), the displacement can be estimated using in turn the ascending and descending LOS measurements. For the ascending passes, u and ν are well outside the critical area. The calculated displacements over the 24-h interval that separate the tandem pair along the centerline of the glacier for the five available coherent ascending pass pairs are plotted in Fig. 8. The glacier velocity rises to a maximum of approximately 35-cm/day near the steep upper region. The velocities about the peak agree well with Meier's measurements [13]. Note that the foot of the glacier has receded around 1 km since Meier's measurements were made in the 1950's. Furthermore, the InSAR data agrees with the recent surveying measurements along the lower half of the glacier to within better than 5-cm/day.

Attempts to repeat the same calculation using the descending passes were not successful. In this case, as can be seen from Fig. 7, the LOS direction is perpendicular to the estimated surface flow direction at several locations along the glacier centerline; so the measure displacement cannot be resolved as a true displacement.

B. Estimate of the 3-D Glacier Displacement Using Two LOS Measurements

The 3-D glacier displacement can be estimated using both ascending and descending passes of the glacier if it is assumed that the flow rate was the same for both pairs. Equation (1) can be used twice, once for each LOS direction. However, with two equations and three unknowns, an assumption is still required for the remaining unknown. Here we take the flow direction v to be the remaining unknown. At least, the following three different assumptions can be considered.

1) If it is assumed that the glacier flows in the direction of greatest slope, ν and in turn v can be calculated from the DEM.
2) ν can be calculated assuming the flow is in the direction of the glacier centerline, i.e., parallel to the glacier margins.
3) Assuming the glacier flows parallel to the glacier surface $z_t(x, y)$, the vertical velocity v_z may be related to the horizontal velocity v_h by [26]

$$v_z = [\nabla_{xy} z_t(x, y)]^T v_h \qquad (3)$$

where ∇ is the del operator.

Equation (3) can then be used in combination with (1) to solve for the displacement. In this case, we used the ascending LOS displacement from March 5–6 and the descending LOS displacement from March 10–11. These measurements have the advantage of being close in time, and in addition, each measurement is close to the median of the LOS measurements from their respective pass directions. Fig. 9 is a plot of the displacement derived by using each of these three assumptions. Also included in the figure are the historic and recent NHRI glacier flow measurements.

All three assumptions agree in certain regions. However, there are also discrepancies. Each of the assumptions appear to have disadvantages. The downslope direction, assumption (1), appears to fail near the 4500-m mark. This coincides with the area near the bend in the glacier where the slope direction reaches nearly 70°, with respect to grid east. The

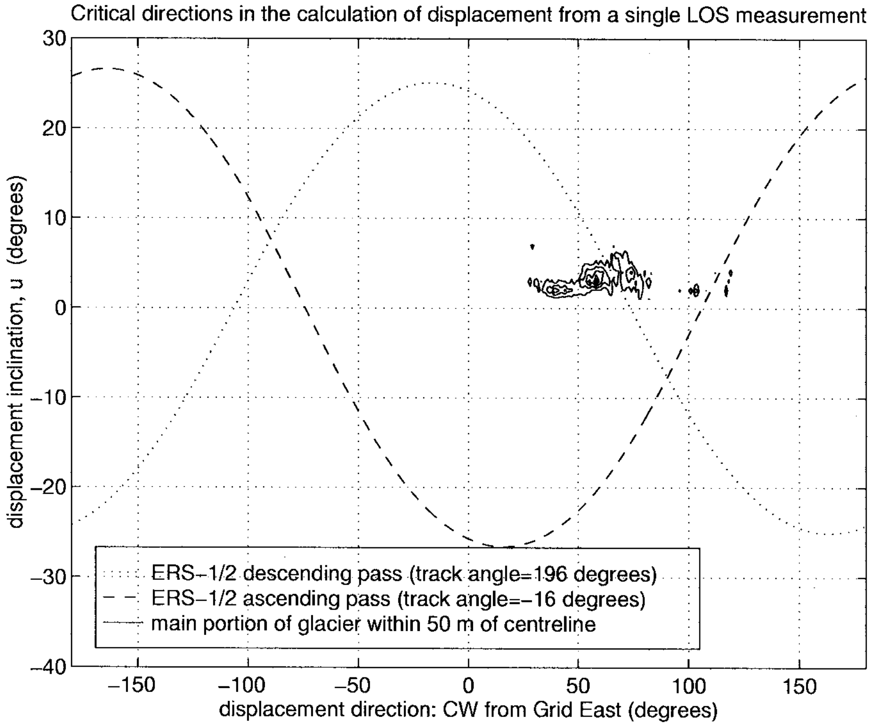

Fig. 7. Plot of the critical angles in the calculation of the surface displacement for the ascending and descending passes of ERS-1/2. For the cases considered here, the track angles are $-16°$ and 196°, respectively, and the incidence angles are 26.6° and 25.1°, respectively. The contour lines indicate the values of u and ν, obtained from the DEM, of the main portion of the glacier within 50 m of the centerline.

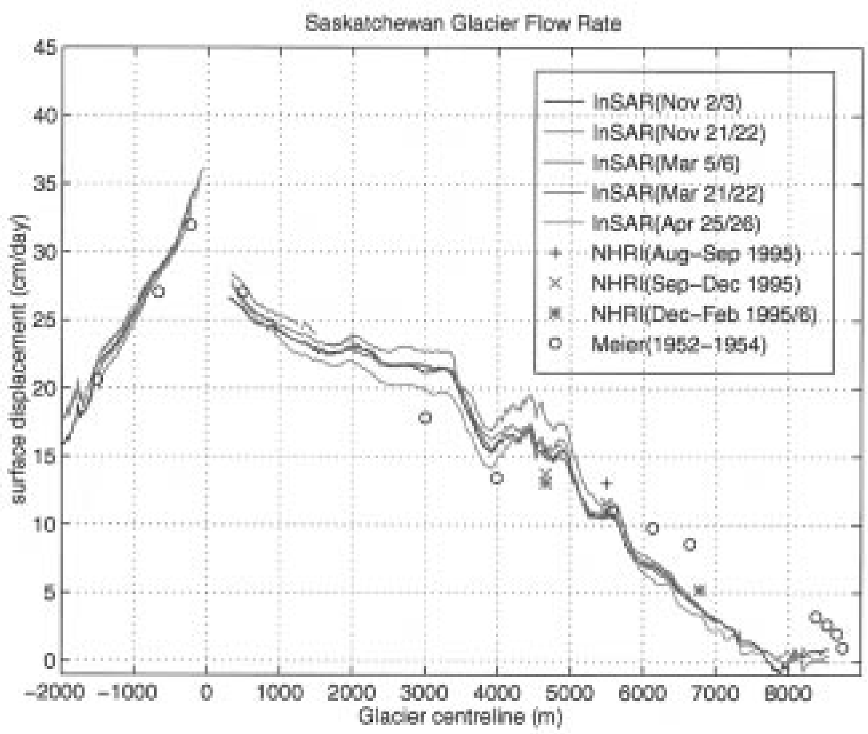

Fig. 8. Plots of the downslope velocity using the available coherent ascending line-of-site displacement measurements along the centerline of the Saskatchewan Glacier. Historic and recent surveying measurements are included.

glacier is apparently being pushed by its momentum along the direction of the glacier centerline rather than in the direction of greatest downslope gradient. The parallel centerline direction, assumption (2), appears to perform quite well, except near the region of maximum glacier flow, where the glacier merges with the icefield. In those areas, the glacier seems to be moving

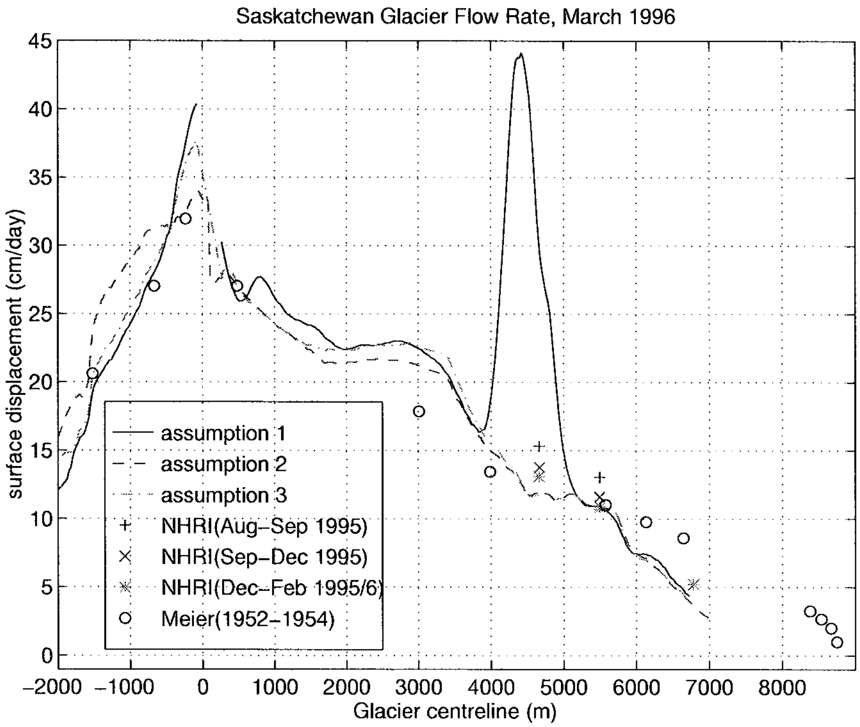

Fig. 9. Plot of the speed using both the ascending and descending line-of-sight displacement measurements along the Saskatchewan Glacier centerline, subject to the three assumptions. Historic and recent surveying measurements are included.

in a much more complex manner that was not well described by the chosen centerline. The surface-parallel direction, assumption (3), is valid for those regions of the glacier that are in steady state. It fails in regions of accumulation or ablation, where the flow is no longer parallel to the surface. As mentioned earlier, high coherence along the glacier implies minimal accumulation or ablation during the time interval that separate the tandem pairs. Therefore, assumption (3) appears, in general, to be a good assumption.

The flow speed derived from the ascending passes alone (see Fig. 4) compare very well with the flow derived from the two-pass direction using the third assumption. However, the flow is exaggerated at the 4500-m mark, where the DEM does not accurately reflect the glacier flow direction.

V. Summary and Conclusion

We have shown that ERS tandem-mode repeat-pass interferometry, separated by a 24-h interval, is a viable method for measuring the surface displacement of a typical midlatitude alpine glaciers. It offers the potential for relatively quick, dense, wide-area velocity measurements, as compared to the traditional and time-consuming point survey techniques. We made use of an accurate DEM of the region obtained by the CCRS CV-580 airborne single-pass interferometric SAR system. Accurate orbit data obtained from D-PAF were required to reconstruct the ERS imaging geometry and baseline, enabling the conversion of the DEM from meters in UTM to topographic phase in the ERS perspective and, subsequently, the removal of the topographic component from the interferogram phase. The reference DEM is expected to introduce an rms LOS flow rate error of less than the 0.4-cm/day. Orbit data inaccuracies are expected to introduce at most a 0.5–1-cm/day LOS flow error over the full length of the glacier. Inhomogeneous atmospheric effects could introduce a further 0.5–1-cm/day error. These accumulated errors limit our ability to detect subtle seasonal variations in the LOS displacement of the glacier.

Of the 12 ascending and six descending tandem ERS data pairs considered, data acquired from the beginning of August 1995 through the end of April 1996, only five ascending and four descending passes had suitable scene coherence over the full length of the glacier of interest to permit displacement measurements. Unfortunately, a complete set of weather data was not available. But it is known that the data sets acquired in August and September coincided with the above freezing temperatures and significant precipitation between the interferometric pairs. Both surface melting and precipitation obviously cause a loss of coherence.

We have shown that the magnitude of the 3-D flow field can be estimated from a single LOS measurement only if the LOS direction is appropriate, with respect to the surface flow direction, and with suitable assumptions concerning the direction of the flow. In this study, the ascending ERS passes were nearly ideally oriented for measuring the flow of the Saskatchewan Glacier, whereas the LOS direction of the descending pass was perpendicular to the estimated surface flow direction at several locations along the glacier centerline. Therefore, the 3-D flow field could not be derived from the descending pass data.

Examination of the three different assumptions for estimating the 3-D flow field using a combination of the ascending and descending pass LOS measurement has helped to address the problem of which assumption to make in converting a line-of-sight displacement to a 3-D glacier flow field. We measured a peak flow rate of around 35-cm/day at the steep and narrow upper portion of the glacier. The discrepancy between the various assumptions in the estimation of the flow field is most pronounced where the glacier merges with the icefield and at the bend near the middle portion of the glacier, reflecting the more complex flow patterns in those regions.

The peak flow rate is in good agreement with Meier's measurements made in the early 1950's. The discrepancy between our measurements and those of Meier's at the lower portions of the glacier reflect the fact that the terminus of the glacier has retreated by about 1 km over the 43 years that separate the two sets of measurements.

The displacement in the lower portion of the glacier is in agreement with near-coincident ground measurements made by NHRI using point survey techniques.

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