Measuring the 3-D Flow of the Lowell Glacier with InSAR

Ian Cumming and Joe Zhang

Dept. of Electrical and Computer Engineering
The University of British Columbia, Vancouver, BC, Canada V6T 1Z4.
Email: ianc@ece.ubc.ca http://www.ece.ubc.ca/sar/

ABSTRACT:— In this paper, we use single and dual-pass satellite-based interferometric radar to measure the flow magnitude of a large alpine glacier. Since the radar measurements alone are not sufficient to resolve the 3-D flow direction of the glacier, several flow directions assumptions are made, and checked for mutual consistency. The assumptions that the horizontal component of flow is parallel to the medial moraine, and that the flow is parallel to the glacier surface give the best results over most of the glacier. With one or both of these assumptions, we are able to measure the glacier flow along its centreline to an accuracy of approximately ± 3 *cm/day*.[1]

1 Introduction

ERS Tandem Mission SAR data has been used to measure glacier surface displacement between 1-day observations. Previous studies have shown that relatively high coherence can be maintained over this short time interval on some glaciers, particularly under constant freezing conditions. Good results have been achieved in measuring the velocity field of ice sheets [1, 2, 3, 4], ice streams [5, 6] and alpine glaciers [7, 8, 9, 10, 11].

In order for interferometry to work effectively, the surface movement must have a reasonable degree of spatial cohesiveness over the 1-day observation interval. In radar terminology, this means that there should be a low degree of temporal decorrelation between the images. In the glacier context, this means that sections of the surface of the size of a pixel area (25m x 25m) or greater should move as a whole rather than in random parts, so that the scattering phase center is stationary (*i.e.* coherent) and representative of the time-averaged surface movement of the glacier. For at least part of the year, this assumption seems to be sufficiently valid for interferometry to work well. This makes it practical to use the phase of the interferogram to measure the surface motion pattern of the glacier.

In this paper, we describe how InSAR is used to estimate glacier surface displacement using different flow assumptions. The location of our study area and the radar data sets are described in Section 2. After the radar data is processed to form interferograms (Section 3), the motion of the glacier is estimated along the direction of the radar beam (Section 4). This direction is referred to as the radar line-of-sight or LOS.

Two different approaches are used to convert the radar LOS displacements into the glacier surface 3-D velocity field. The first approach uses only a single radar measurement together with two assumptions pertaining to the glacier flow direction (Section 6). The second approach combines radar measurements taken from two directions with only one flow assumption to resolve the 3-D velocity vector (Section 7). This is followed by a discussion on which approach and assumptions are most suitable for estimating the glacier surface velocity (Section 8).

2 The Study Area

Our study site is on the Lowell Glacier centred at 60.3^o N, 138.3^o W (see Figure 1). Compared to other glaciers studied by radar, the Lowell Glacier is very large, has a history of surging, and has created devastating floods by blocking the Alsek River.

Figures 2(a) and 3(a) show the radar images of the glacier taken with descending and ascending passes respectively. Approximately 15 by 30 Km of the lower part of the long glacier is shown. On the left side of the image, the Lowell Glacier flows towards the north-east

Figure 1: Terminus of Lowell Glacier as seen from across the Alsek River (looking west).

[1]Presented at the FRINGE'99 SAR Workshop, Liege, Belgium, November 10-12, 1999. The authors would like to thank MacDonald Dettwiler, NSERC, BCASI and BCSC for funding this work. Dr. Cumming is currently on sabbatical at DLR/DFD, Oberpfaffenhofen, Germany.

at a heading of around 20°. It then bends right where it briefly joins the Dusty Glacier on its left. After the bend, the glacier flows eastward, with an average heading of 100°. On the right of the scene, the glacier flows into a terminal moraine and lake, and then into the Alsek Lake and River, as seen in Figure 1.

The orientation of the glacier is different between the two passes due to the different look angles of the radar sensor. At $60^o N$, the ascending satellite track is oriented 344^o, while the descending pass track is oriented 196^o.

The upper portion of the glacier is almost perpendicular to the radar viewing direction for both descending and ascending passes, which unfortunately yields poor measurement accuracy for the ERS viewing geometry. However, both passes have relatively good viewing directions on the lower part of the glacier. So in this study, we will only investigate the feasibility of our approach along the lower portion of the glacier, east of the sharp bend.

Date of Passes	*Pass*	*RO*	B_n	*Coh*
17/18 Sep 95	Des	300	–82	0.18
22/23 Oct 95	Des	300	–87	**0.73**
31/01 Dec 95	Des	300	135	**0.54**
04/05 Feb 96	Des	300	-185	**0.51**
29/30 Sep 1995	Asc	464	218	0.21
08/09 Dec 95	Asc	464	–80	**0.47**
12/13 Jan 96	Asc	464	–113	**0.68**
16/17 Feb 96	Asc	464	–169	**0.62**
22/23 Mar 96	Asc	464	–108	0.40
26/27 Apr 96	Asc	464	–14	0.27

Table 1: Parameters of ERS-1/2 passes over the Lowell Glacier. RO is relative orbit and B_n is the normal baseline in meters.

3 Processing to Interferograms

Ten ERS-1/2 data pairs were collected over the Lowell Glacier during the Tandem Mission. First, we processed the radar signal data to single-look complex (SLC) images using the MacDonald Dettwiler Desktop SAR processor. Then each data pair was co-registered to 1/10 of a pixel. The images were then filtered in the range and azimuth directions to optimize coherence. The filtered images are then oversampled by a factor of 2, and the interferogram formed. The coherence is estimated using an averaging window size of 3 (range) by 15 (azimuth) samples. The coherence is then corrected for finite signal-to-noise ratio [12], which means that the final coherence value is mainly a measure of the glacier's temporal decorrelation.

The measured coherence magnitudes of each data pair are listed in Table 1. In the sequel, we use only those interferometric pairs with coherence magnitudes greater than 0.45, which is sufficient to obtain useful phase estimates. Thus only three ascending pairs and three descending pairs are used, as shown in bold face in Table 1.

Representative **descending** and **ascending-pass** interferograms from October 22/23, 1995 and January 12/13, 1996 are shown in Figures 2 and 3 respectively. In both figures, the top panels show the interferogram magnitude and scene coherence magnitude; the bottom panels show the raw interferogram phase and flat-earth corrected phase.

The coherence magnitudes of these two interferograms are high (greater than 0.6) on most parts of the glacier except at the areas near the toe of the glacier, as well as in the water of the Alsek river. It is also noted that the coherence is a little lower at the upper portions of the glacier in the descending pass, indicating that the surface motion was more random or the surface conditions were less stable on those dates.

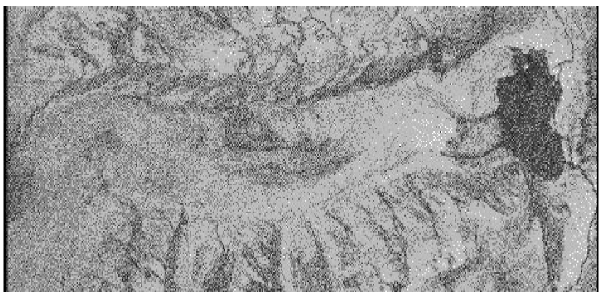
4 The Radar LOS Displacement

The interferograms shown in the previous section contain phase information due to topography and to glacier surface motion. In order to separate these phase components, three different approaches can be used:

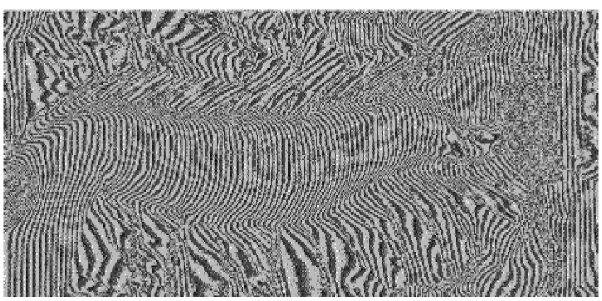
1. if the motion of the glacier is constant and the scene is quite coherent over 3 or more consecutive observations, we can estimate both the topography and the displacement of the observed area by combining the InSAR measurements with different baselines [2].
2. if the surface topography and the geometry of the satellite orbits are known, it is possible to convert the surface topography into phase, and subtract it from the interferogram to isolate the motion-induced phase.
3. obtain an InSAR pair with near-zero baseline, in which case the topography does not induce significant phase, as the parallax is small.

In our case, we chose the second approach, as neither zero-baseline data nor data with coherence over 3 passes was available. Then, we need topography information over the test area. But first, let's look at what the radar is measuring.

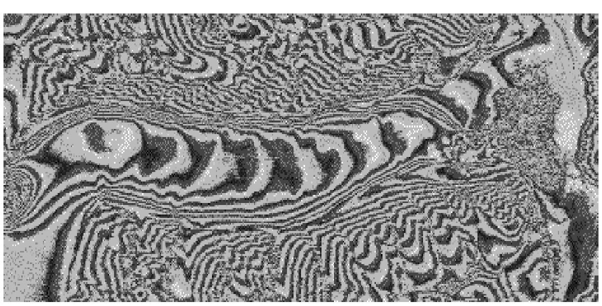
(a) interferogram magnitude



(b) coherence magnitude



(c) interferogram phase

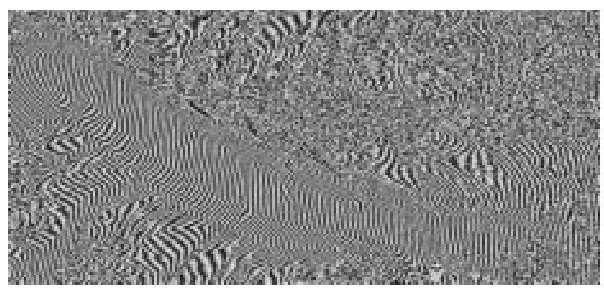


(d) phase after flat-earth fringes removed

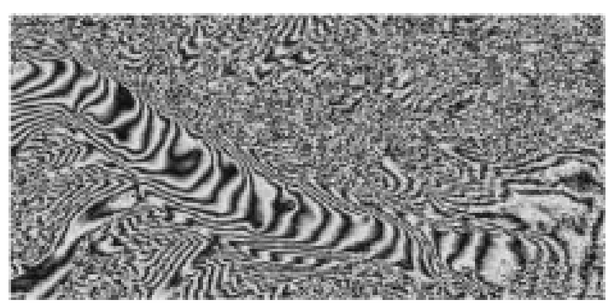
Figure 2: Representative descending-pass interferogram from October 22/23, 1995.

(a) interferogram magnitude

(b) coherence magnitude



(c) interferogram phase



(d) phase after flat-earth fringes are removed

Figure 3: Representative ascending-pass interferogram from January 12/13, 1996.

4.1 Measurement of LOS displacement

The flow regime along the centreline of a glacier is one of the most important components needed to model the mass balance of the glacier. So here we will concentrate on estimating the 3-D velocity along the centreline. Because accurate DEM data is not available for the Lowell Glacier, we use the 1:50,000 Canada topographic map (115B7-8/115C5) to estimate the centreline topography.

The elevation along the glacier centreline was read from this map and drawn in Figure 4. Because of the map's limitations, the time of the map survey (1974), our ability to locate the centreline and to extrapolate the contours, it is inevitable that the measured elevation information contains errors. But if the *relative* elevation read from the map is accurate to 10 m, a relative LOS displacement error of only $0.27cm$ is made when the normal baseline is 100 m. So we assume that the elevation accuracy read from the map is adequate for the present analysis.

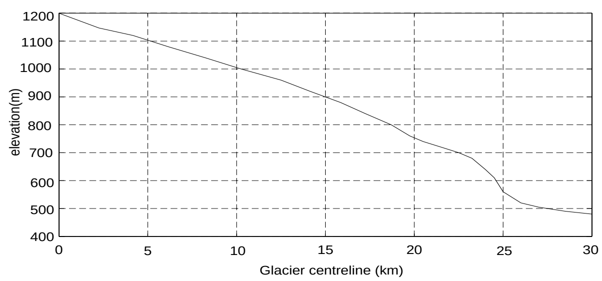


Figure 4: Elevation along the glacier centerline.

The flat-earth corrected phase was unwrapped using the region-growing phase unwrapping algorithm [13]. Then, the elevation along the glacier centreline was converted into topographic phase and registered to the interferogram using the precision orbit data (the precision orbit is accurate to 10 cm). The topographic phase was subtracted, and the remaining motion phase was converted to LOS displacement.

Figure 5 shows the LOS displacement R along the centreline of the glacier for the 3 descending and 3 ascending passes. The significant differences between these two passes are due to the different viewing directions (*i.e.* different LOS orientations).

Within each of the descending or ascending orbit data sets, there is a discrepancy of only ± 1 cm/day between the various LOS measurements. The observed velocity differences could be caused by several different factors:

1. monthly differences in flow speed or direction
2. atmospheric inhomogeneities which can create phase errors specific to the acquisition date
3. inaccurate image registration
4. inaccuracy of the precision orbit data
5. error in reading the elevations from the topo map
6. radar receiver noise

However, despite these sources of error, the overall agreement between the various LOS displacement measurements in Figure 5 is very encouraging. Because the radar measurements are most accurate in the differential sense, many real velocity changes can be observed *down the glacier centreline.* However, it is not known whether the observed changes from *month to month* are real changes in velocity, or due to measurement error.

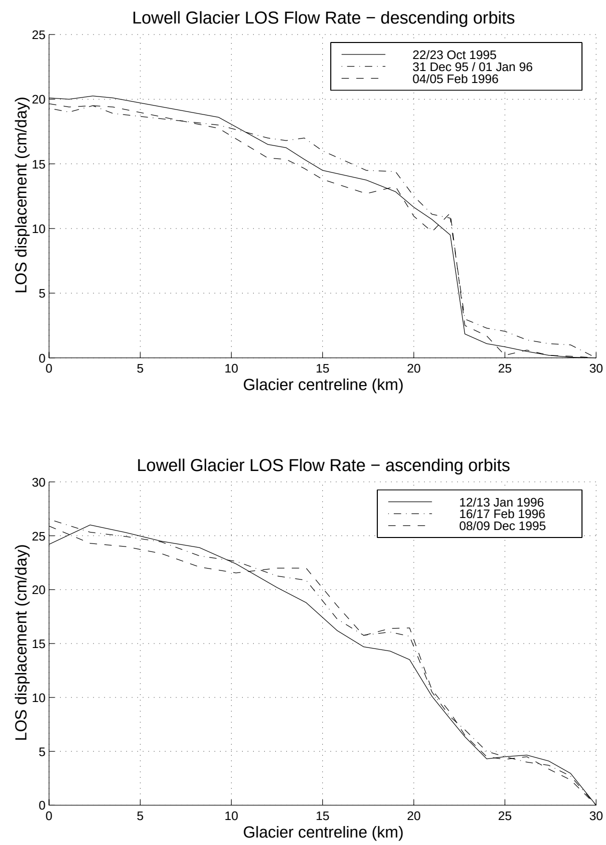


Figure 5: Lowell Glacier LOS flow rate from ascending and descending orbit data.

5 Projection from LOS to Flow

The LOS displacement measurements must now be projected to an assumed glacier surface flow direction to get the absolute surface speed. The various angles involved in the projection are illustrated in Figure 6, whose axes are given by the satellite track vector x, the cross-track or ground range vector y and the local vertical z. The measured LOS displacement $\vec{R}$ is shown, aligned with the radar LOS. The LOS is assumed to lie in the y-z plane, and makes an angle θ with the vertical. The normal to the glacier surface $\vec{n}$ is μ radians from the vertical, and its horizontal projection is γ radians from the satellite track vector x.

To complete the projection, azimuth and elevation angles of the flow direction must be assumed. If, for example, the average flow is assumed to lie in the plane

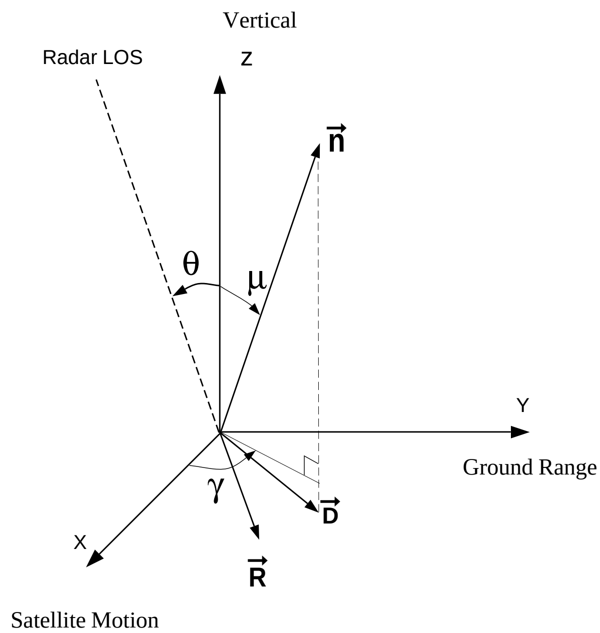


Figure 6: LOS projection geometry

of the glacier surface, the elevation angle of the flow is μ radians below the horizontal. The azimuth direction of the flow γ can be taken from either the moraine or down-slope directions. Then the surface displacement, D, can be derived from the LOS displacement R [7]:

$$|D| = \frac{|R|}{|\sin\mu\cos\theta + \sin\gamma\cos\mu\sin\theta|} \tag{1}$$

The azimuth flow direction γ can be obtained from:

$$\gamma = v + 2.2^\circ + track - 90^\circ \tag{2}$$

where v is the assumed flow direction measured from the map (clockwise from grid east) or from the moraine, 2.2° converts the UTM grid north to true north, and *track* is the platform track angle.

In addition to the unknown displacement, D, there are two unknowns on the right hand side of equation (1), the forementioned flow angles μ and γ. In order to solve for D, two possible approaches can be used. First, if only *one* InSAR LOS measurement is available, only one degree of freedom can be resolved in the estimated flow. Thus an assumption on the complete flow direction, *i.e.* both the angles μ and γ, must be made. Then the *magnitude* of the surface displacement D can be derived from equation (1), as done in Section 6.

Second, if *two* InSAR measurements along different LOS are available, two degrees of freedom can resolved in the estimated flow. Then, an assumption on only one of γ or μ is needed to determine the 3-D surface displacement vectors. Because the angle of the local surface normal μ can be obtained with reasonable accuracy from the map (as in Figure 4), this study focuses on examining different assumptions on the glacier horizontal flow direction, γ, as done in Section 7.

6 Single-LOS Measurements

In order to estimate the 3-D glacier displacement using a single LOS measurement, *two* assumptions have to be made about the direction of the flow. These two assumptions must provide *independent* flow information, *i.e.* they must provide information about the flow along orthogonal directions. The most convenient way of providing orthogonal information is to make one assumption about the glacier horizontal or azimuth flow direction, v, and another assumption about the vertical component of the flow direction.

In this study, all the selected interferometric pairs from both descending and ascending passes have quite high coherence magnitude along the whole glacier. Also, there appears to be remarkably little change in the measured LOS displacement from month-to-month during the winter (see Figure 5). Thus, it is reasonable to assume that neither accumulation nor ablation are significantly affecting the surface flow direction, and the glacier's flow direction is approximately parallel to its locally-averaged surface plane.

This surface-parallel assumption pertains to the <u>vertical</u> component of the flow direction, and we have no other plausible assumptions about the vertical flow direction. However, we can consider *two* possible assumptions concerning the azimuth or <u>horizontal</u> direction of the flow:

1. that the azimuth flow direction is indicated by the medial moraine line, or
2. that the azimuth flow direction is in the direction of the greatest surface slope.

In the next two subsections, we will consider each of these two horizontal flow direction assumptions in turn.

6.1 <u>Moraine-aligned</u> assumption

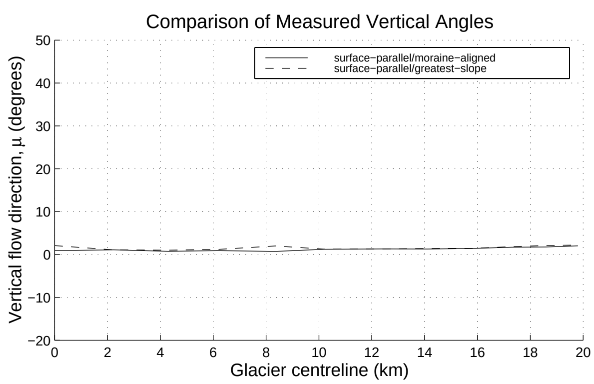
The longest, most prominent moraine line is close to the glacier centreline, as seen in Figure 2(a). We will consider the assumption that this line indicates the horizontal flow direction of the glacier in this region. This medial moraine line ends around 20 *km* from our starting point. In order to compare the results derived from different assumptions on the glacier horizontal flow direction, we further limit our attention to this 20 *km* centreline in the rest of this study.

After drawing the moraine line on the 1:50,000 topo map, the values of μ and v were read from the map. To reduce the root-mean-square (RMS) errors, five measurements near the medial-moraine line were made and then averaged to 2 km intervals. The measured values of μ and v are shown as the solid lines in Figure 7.

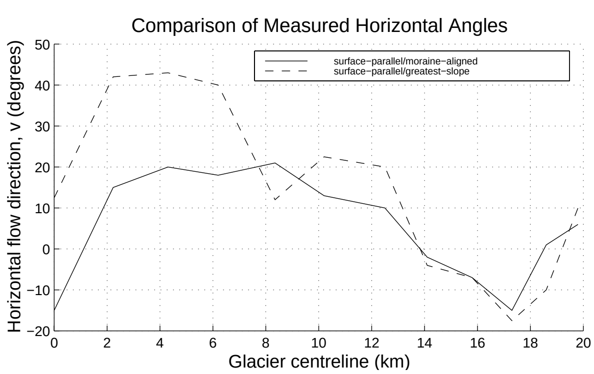
Using these values in equations (1) and (2), the surface displacement D is estimated using the descending and ascending LOS measurements R separately. Each set of descending and ascending LOS measurements is averaged first to get better accuracy. The derived surface displacements along the medial-moraine line over the 1-day interval are plotted in the top panel of Figure 8, where the descending pass data is shown as solid lines, and the ascending pass as dashed lines. It is seen that the glacier velocity is around 65 cm/day in the first 8 km, then decreases linearly to 35 cm/day at the 20 km point of the medial-moraine line.

6.2 Greatest-slope assumption

For surging type of glaciers, it may be reasonable to assume that the glacier flow direction is surface-parallel and along the greatest downhill slope. Based on these two assumptions, the vertical angle, μ, and horizontal angle, v, of the glacier flow direction can both be measured from the topo map, and are plotted with the dashed lines in Figure 7. The bottom panel of Figure 8 shows the glacier flows resulting from these assumptions.



(a) **vertical flow direction** (slope) measurement

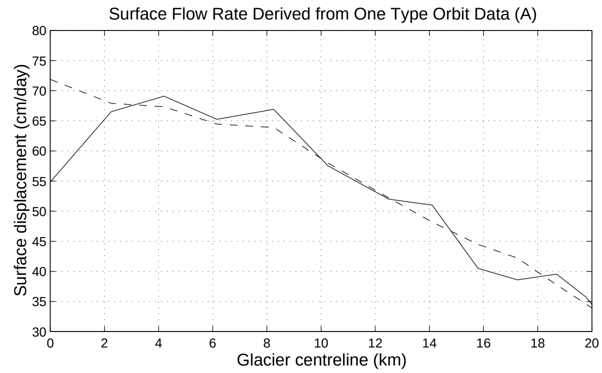


(b) **horizontal flow direction** measurement

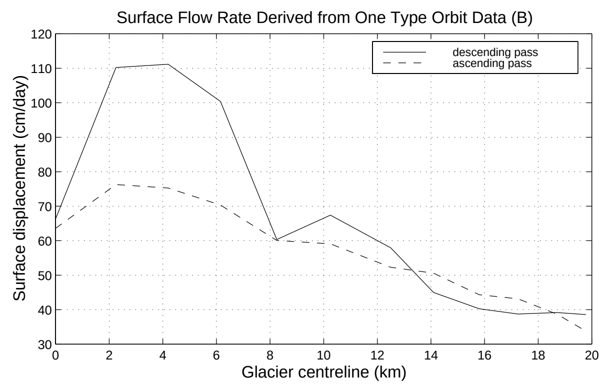
Figure 7: Glacier flow directions taken from the 1:50,000 topo map under two assumption sets.

7 Dual LOS Measurements

When using *both* descending and ascending LOS measurements together in the flow calculation, only *one* flow direction assumption is needed to resolve the 3-D



(a) **surface-parallel & moraine-parallel** assumption



(b) **surface-parallel & down-slope** assumption

Figure 8: The Lowell Glacier centreline surface velocity using **single LOS** measurements.

displacement if the glacier flow rate is constant over the period between the two LOS measurements. The following three different assumptions on the glacier flow direction are considered in turn:

1. flow is parallel to the *glacier surface*; the azimuth direction is unspecified
2. flow is azimuth-aligned with the *medial moraine* line; the vertical angle is unspecified
3. flow is down the direction of *greatest slope*; the vertical angle is unspecified.

Under the second or the third assumption, which defines the glacier horizontal or azimuth flow direction, the values of v can be measured from the topographic map as in Section 6. Then, we can use equation (1) twice to obtain the surface displacement magnitude and the value of the vertical angle μ.

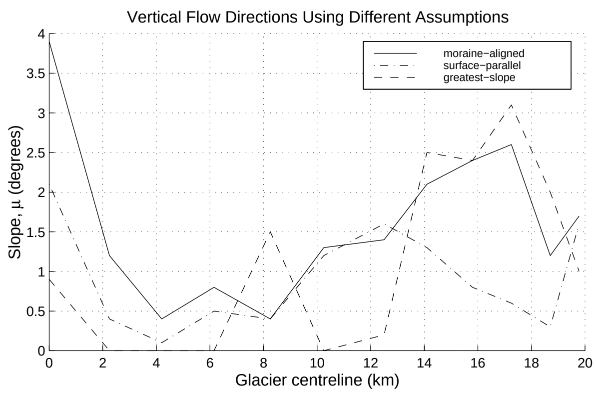
Under the surface-parallel assumption, where the glacier flow direction is assumed parallel to its surface $z_s(x,y)$, we can separate the surface velocity vector into three components:

$$V\,\vec{v} \;=\; V_x\,\vec{x} \;+\; V_y\,\vec{y} \;+\; V_z\,\vec{z}. \tag{3}$$

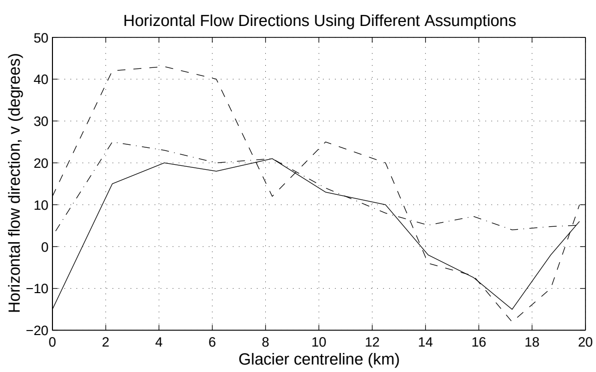
where $\vec{v}$, $\vec{x}$, $\vec{y}$ and $\vec{z}$ are unit vectors and the V's are magnitudes. Then the vertical velocity, V_z, can be related to the horizontal velocity, V_x and V_y by [11]:

$$V_z = V_x \frac{\partial}{\partial x} z_s(x,y) + V_y \frac{\partial}{\partial y} z_s(x,y) \qquad (4)$$

where the gradients are measured off the map. By using the above equation and the projection equation (1), the relationship of V_x and V_y with the LOS displacements from the descending passes, R_d, and the ascending passes, R_a, can be established [11]. After iterating the projection equation to make the assumption and the two LOS measurements agree, the values of v and μ (Figure 9) and the surface displacement magnitude (Figure 10) are obtained.



(a) **vertical flow direction** (slope) measurement



(b) **horizontal flow direction** measurement

Figure 9: Flow directions of the Lowell glacier derived from **dual LOS** measurements using various flow assumptions.

8 Discussion of Assumptions

8.1 Using single LOS data

In the attempt to resolve the glacier 3-D flow rate using only single LOS measurements, we examined two assumption combinations. Under the combination of surface-parallel and **moraine-aligned** flow assumptions, the results achieved from descending and ascending LOS displacements generally agree with each other quite well except for a significant discrepancy

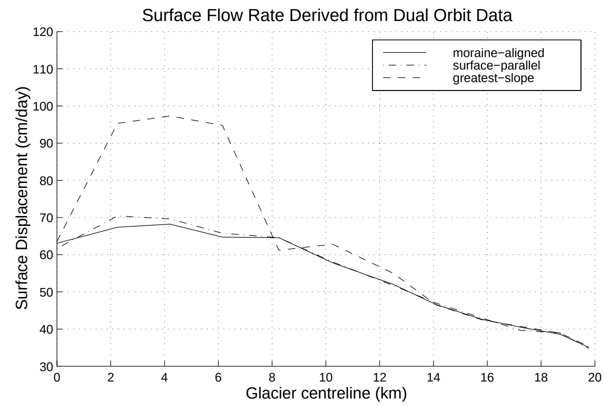


Figure 10: Lowell glacier 3-D flow rate derived from **dual LOS** measurements.

around the starting point (Figure 8(a)). This discrepancy suggests that at least one of the values of μ and v does not reflect the real flow direction of the glacier in this region.

Most likely the moraine-aligned assumption is invalid here, as the glacier is curving here and joining with the Dusty Glacier. An interchange of ice between the two glaciers can change the flow regime. In contrast, the surface slope is quite uniform in this area, so the surface-parallel assumption is likely more reliable. Also, the different scales of vertical and horizontal angles seen in Figure 7 indicate that there is more variability to be expected in measuring the horizontal angle.

The descending pass and ascending pass results derived from the surface-parallel and **greatest-slope** assumptions are significantly different in the first 8 *Km* of the study area (Figure 8(b)). It is partially because the derived values of μ and v in this region make the assumed surface displacement almost perpendicular to the radar LOS for the descending pass, increasing the measurement error sensitivity. In this case, we should mainly rely on the result derived from ascending pass data. However, even the ascending pass results seem to be exaggerated by around 7 cm/day in this region.

This again indicates that the flow assumptions are probably not correct for this region. We suspect that the greatest-slope assumption is weak, because the flow direction should be more affected by the unknown *basal* slope rather than the surface slope.

8.2 Using dual LOS data

In the dual-measurement/single-assumption approach, all three flow direction assumptions surprisingly give a very similar velocity at the starting point and for the last 6 *Km* of the study area (Figure 10).

From the coherence images in Figure 2 and 3, we see that the coherence magnitude is slightly lower near the starting point of our study area. This is possibly caused by a moderate accumulation process here because extra ice mass comes down from the Dusty

Glacier where it joins the Lowell Glacier. The glacier flow direction may be slightly downwards from its surface at this point. Thus the **surface-parallel** assumption may not hold here. Even though the measured surface displacements under the **moraine-aligned** assumption and the **greatest-slope** assumption are coincidentally close at the starting point, the estimated the flow directions are quite different. Notably, a significant disagreement (25°) exists for the horizontal flow direction. Hence, one of these two assumptions must be incorrect. If the Lowell Glacier did not surge during the investigation period, we suggest that the **moraine-aligned** assumption is the most suitable one in this region.

From Figure 10, we see that good overall flow agreement has been achieved between the moraine-aligned and surface-parallel assumptions along most of the glacier, but not so with the greatest-slope assumption. The greatest-slope assumption gives an exaggerated velocity magnitude at the region just below the starting point. This may be because the glacier is pushed by its momentum in a direction different from that of the greatest downslope gradient.

So each assumption has its advantages and disadvantages, but in general, the moraine-aligned assumption and the surface-parallel assumption appear to be best for the 20 km region studied. This conclusion is supported by the single LOS measurements.

8.3 Reconciliation of Assumptions

From the single LOS experiments, we concluded that the surface-parallel combined with the moraine-aligned assumptions gave the most plausible results. This is because the ascending and descending pass flow estimates agreed with each other reasonably well — see the top panel of Figure 8. This near-agreement suggests that the assumptions can be tested by seeing what changes are needed in the assumed flow directions to make the ascending and descending pass flow estimates agree with each other.

From Figure 7, we note that there is a much larger variation in horizontal angle than the vertical angle between the assumption combinations. Also, there is more error in measuring an azimuth angle off the map than in measuring an average slope angle. For these reasons, we take the approach of adjusting the medial moraine azimuth angle at each point on the graphs to reconcile the ascending and descending pass velocity measurements.

The result is shown in Figure 11 where the original moraine angle is shown as the solid line, and the adjusted angle shown as the dashed line. As expected, the largest adjustment was needed in the first two points, where the ascending and descending velocities disagreed the most.

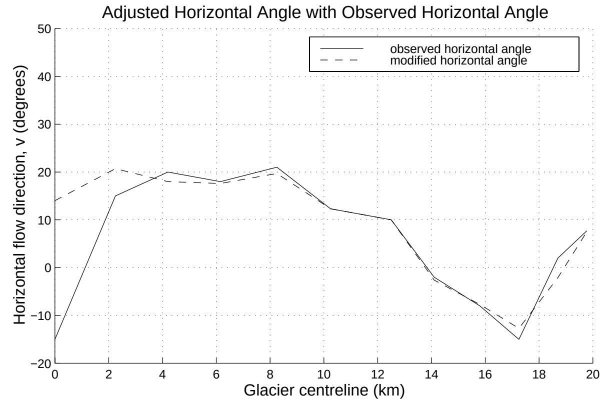


Figure 11: Adjustment the moraine azimuth angle to reconcile the ascending and descending pass measurements.

9 Conclusions

We have extended the previous radar glacier measurement work by studying a glacier with quite different size, location, climate and flow dynamics, and by resolving measurements taken from two different look directions. A 1:50,000 topo map and the medial moraine line were used to provide supplementary information needed to assume various flow directions.

Assumptions that the glacier flow was aligned with the medial moraine line, was parallel to the surface, and was in the direction of the steepest slope were tested and compared. In different glacier flow regimes, different assumptions can produce the best results, although in the present example, the moraine-aligned and surface-parallel assumptions were best over most of the glacier surface.

We conclude that to measure glacier flow rates and directions with a C-band satellite radar, the following conditions are recommended:

1. the radar data should be taken no longer than a day or two apart to obtain good coherence and to avoid phase aliasing
2. the glacier flow direction should not be close to parallel with the satellite track to avoid sensitive projection geometry — flow directions within $\pm 50^o$ of east-west provide the best results
3. more than one satellite look direction should be used if available
4. winter measurements provide better coherence, and heavy precipitation periods should be avoided
5. supplementary flow direction information improves the radar measurement accuracy

If these conditions are met, satellite radar can provide a useful measurement tool for obtaining surface velocities for a wide variety of glaciers. Unlike some other measurement techniques, the measurements are closely spaced and cover a wide area. Accuracies in the order of a few centimeters per day can be expected.

References

[1] E. Rignot, K. C. Jezek, and H. G. Sohn, "Ice flow dynamics of the Greenland ice sheet from SAR interferometry," *Geophysical Research Letters*, vol. 22, no. 5, p. 575, 1995.

[2] I. Joughin, D. Winebrenner, M. Fahnestock, R. Kwok, and W. Krabill, "Measurement of Ice Sheet Topography Using Satellite Radar Interferometry," *J. of Glaciology*, vol. 42, pp. 10–22, 1996.

[3] R. Kwok and M. A. Fahnestock, "Ice Sheet Motion and Topography from Radar Interferometry," *IEEE Trans. on Geoscience and Remote Sensing*, vol. 34, pp. 189–200, 1996.

[4] H. Vadon and F. Sigmundsson, "Crustal deformation from 1992 to 1995 at the Mid-Atlantic Ridge, southwest Iceland, mapped by satellite radar interferometry," *Science*, vol. 275, pp. 193–197, Jan. 1997.

[5] R. M. Goldstein, H. Engelhardt, B. Kamb, and R. M. Frolich, "Satellite Radar Interferometry for Monitoring Ice Sheet Motion: Application to an Antarctic Ice Stream," *Science*, vol. 262, pp. 1525–1530, Dec. 1993.

[6] E. J. Rignot, S. P. Gogineni, and W. B. Krabill, "North and northeast Greenland ice discharge from satellite radar interferometry," *Science*, vol. 276, pp. 934–937, May 1997.

[7] P. W. Vachon, D. Geudtner, K. Mattar, A. L. Gray, M. Brugman, and I. G. Cumming, "Differential SAR Interferometry Measurements of Athabasca and Saskatchewan Glacier Flow Rate," *Can. J. Remote Sensing*, vol. 22, pp. 287–296, Sept. 1996.

[8] K. E. Mattar, P. W. Vachon, D. Geudtner, A. L. Gray, I. G. Cumming, and M. Brugman, "Validation of ERS Tandem Mission SAR Measurements of Alpine Glacier Velocity," *IEEE Trans. on Geoscience and Remote Sensing*, vol. 36, pp. 974–984, May 1998.

[9] B. Unwin and D. Wingham, "Topography and dynamics of Austfonna, Nordaustlandet, Svalbard, from SAR interferometry," in *International Symposium on Changing Glaciers*, vol. 24, (Fjaerland; Norway), pp. 403–408, International Glaciological Society, Annals of Glaciology, June 1996.

[10] J. Mohr, N. Reeh, and S. Madsen, "Three-dimensional glacial flow and surface elevation measured with radar interferometry," *Nature*, vol. 391, pp. 273–276, January 15, 1998.

[11] I. Joughin, R. Kwok, and M. A. Fahnestock, "Interferometric Estimation of Three-Dimensional Ice-Flow Using Ascending and Descending Passes," *IEEE Trans. on Geosci. and Remote Sensing*, vol. 36, pp. 25–37, Jan. 1998.

[12] P. W. Vachon, D. Geudtner, A. L. Gray, and R. Touzi, "ERS-1 synthetic aperture radar repeat-pass interferometry studies: Implications for RADARSAT," *Can. J. Remote Sensing*, vol. 21, no. 4, pp. 441–454, 1995.

[13] W. Xu and I. G. Cumming, "A Region-Growing Phase Unwrapping Algorithm," *IEEE Trans. Geoscience and Remote Sensing*, Accepted for publication, January 1998.