INTERFEROMETRIC ESTIMATION OF ICE SHEET MOTION AND TOPOGRAPHY

Ian Joughin, Ron Kwok	Jet Propulsion Laboratory, California Institute of Technology 4800 Oak Grove Drive Pasadena, CA 91109, USA. ian@rgps1.jpl.nasa.gov Phone: 818-354-1587 Fax: 818-393-3077
Mark Fahnestock	JCESS, Dept. of Meteorology University of Maryland at College Park College Park, MD 20742, USA
Dale Winebrenner	Polar Science Center, Applied Physics Laboratory University of Washington 1013 NE 40th Street Seattle, WA 98105
Slawek Tulaczyk	Division of Geological and Planetary Sciences California Institute of Technology, MS170-25 Pasadena, CA 91125
Prasad Gogenini	Radar Systems and Remote Sensing Laboratory University of Kansas 2291 Irving Hill Road Lawrence, Kansas 66045-2969

ABSTRACT

With ERS-1/2 satellite radar interferometry, it is now possible to make measurements of glacier motion with high accuracy and fine spatial resolution. We have applied interferometric techniques to map velocity and topography for several outlet glaciers in Greenland. For the Humboldt and Petermann glaciers, we have combined data from several adjacent tracks to make a wide-area map that includes the enhanced flow regions of both glaciers. Using these data in combination with thickness data from the University of Kansas Coherent Radar Depth Sounder (CoRDS), we have estimated the discharge flux of the Petermann Glacier upstream of the grounding line, thereby establishing the potential use of ERS-1/2 interferometric data for monitoring ice-sheet discharge. Interferograms collected along a single track are sensitive to only one component of motion. By utilizing data from ascending and descending passes and by making a surface-parallel flow assumption, it is possible to measure the full three-dimensional vector flow field. We demonstrate the application of this technique for an area on the Ryder Glacier. Finally, we have used ERS-1/2 interferograms to observe a mini-surge on the Ryder Glacier that occurred in the Fall of 1995.

Keywords: Glaciology, Interferometry

1. INTRODUCTION

Outlet glaciers are important elements of the great ice sheets as their dynamics determine the rate of ice discharge and, thus, exert a strong influence on ice-sheet stability. Studies of flow dynamics have been hindered by a lack of data. Even with the advent of the global positioning system (GPS), ground-based surveys are expensive, logistically-difficult, and provide measurements at only a limited number of points. Feature tracking in pairs of optical or SAR images can be used to measure velocity, but this method does not work well for the large, featureless areas that comprise much of the ice sheets. Recent results indicate that satellite radar interferometry provides an important new means for measuring ice sheet velocity [Goldstein *et al.*, 1993] and topography [Kwok and Fahnestock, 1996; Joughin, 1995; Joughin *et al.*, 1996a].

2. WIDE-AREA VELOCITY MAPPING

Interferograms collected along a single track are sensitive to surface topography and motion in the radar line-of-sight direction. Pairs of interferograms can be differenced to cancel the effect of motion, which typically does not vary with time on the ice sheets, particularly in the winter. Such double-differenced interferograms can be used to derive maps of surface topography [Kwok and Fahnestock, 1996; Joughin, 1995; Joughin *et al.*, 1996a]. The derived DEMs then can be used to cancel the effect of topography in either of the original interferograms to obtain a map of line-of-sight displacement [Joughin *et al.*, 1996b]. By making a surface-parallel flow assumption and by using the interferometrically determined surface slopes, it is possible to cancel some of the effect of vertical displacement caused by flow over bumps [Joughin *et al.*, 1996b]. The remaining vertical displacement can be ignored to estimate the horizontal velocity in the across track direction. The magnitude of the error resulting from uncompensated vertical displacement is typically a few percent of the along-track (i.e., unknown) component of velocity.

We have applied this technique to measure ice velocity and topography at several sites in Greenland. An example of this work is illustrated in Figure 1 . This figure shows a map of the across-track component of absolute velocity for the Humboldt and Petermann glaciers in north-west Greenland. Tie points from adjacent ice-free areas were used to make the measurements absolute and to estimate the baselines accurately. The data from different swaths were processed independently and then mosaicked together without adjustment so the good agreement across swath boundaries indicates that we have achieved a low level of error. Because the across-track direction is nearly aligned with the flow direction, the error due to uncompensated vertical displacement is small.

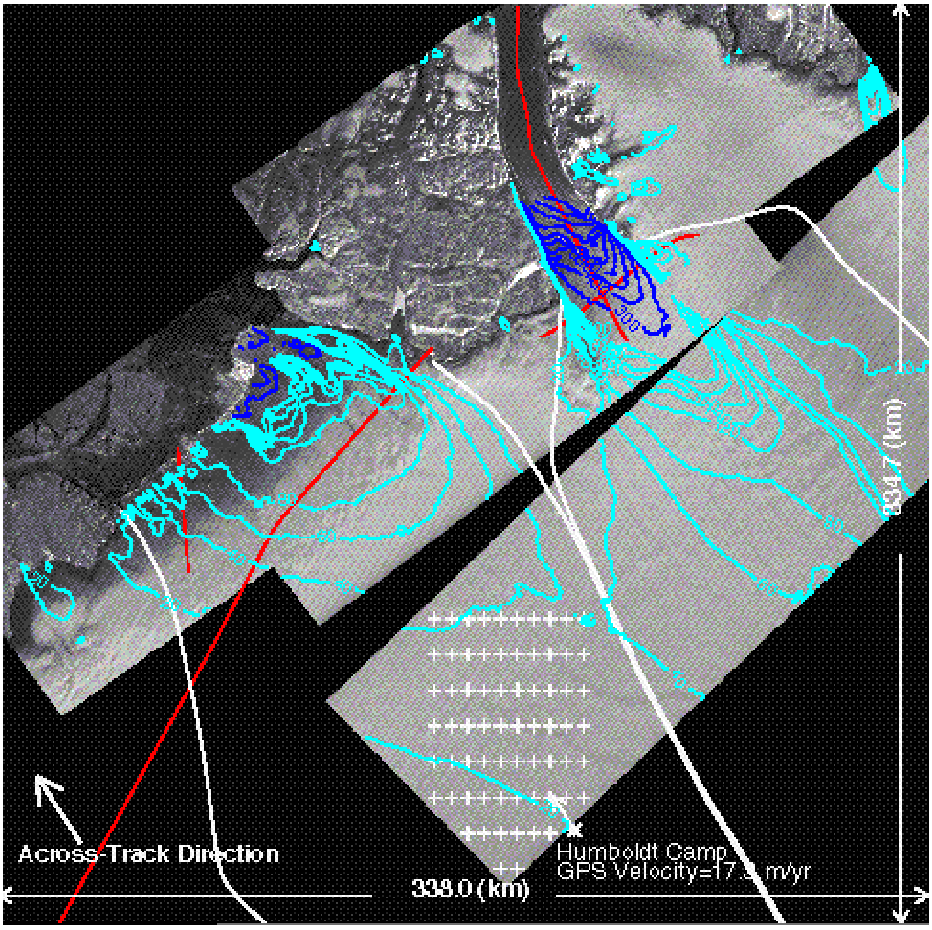


Figure 1. Contour map of the across-track component of velocity for the Petermann and Humboldt Glaciers. The across track direction is slightly different for each swath. The approximate across track direction is indicated by an arrow in the lower left corner. Contour interval is 20 m/yr for velocity less than 200 m/yr and is 100 m/yr for values greater than 200 m/yr. Red lines indicate locations of CoRDS profiles.

The velocity map was generated using data from both the tandem mission and 3-day pairs from the commissioning and first ice phases. We achieved good correlation for both data sets. Where we have the 3-day data and are able to unwrap it, errors are significantly lower with respect to tandem data, as we have the three times the sensitivity to motion. For the fast moving regions, however, the 3-day data were aliased and we could make measurements only using tandem data. To accurately measure the full range of ice velocities (i.e., 1 m/yr - 7000 m/yr) a range of temporal baselines is needed ranging from a few hours to tens of days.

The velocity maps indicate that although the Humboldt and Petermann are adjacent to each other, they have much different flow patterns. The Petermann is a fast-moving outlet glacier that is channelled by a well developed fiord extending back under the ice. The flow is strongly convergent with peak speeds of nearly 1200 m/yr near the grounding line. Using ice thickness data collected with University of Kansas CoRDS we were able to estimate the flux of the Petermann as 12.7 km^3/yr. The Humboldt discharges roughly half that volume across a much wider calving face, exhibiting weakly convergent flow with much slower flow speeds than the Petermann.

Our velocity map indicates that wide-area mapping of ice sheets is possible without any limitation imposed by swath width and that such data can be used in combination with ice thickness data to measure ice discharge of individual drainage basins.

3. 3-D MEASUREMENT OF ICE FLOW

The ice velocity measurements described in the previous section are limited as they yield only a single component of motion, whereas we would like to measure the full three-component vector. Ideally, this requires observations from tracks with three different orientations. For ice, however, we can assume that flow is parallel to surface. This allows us to combine data from ascending and descending passes with our interferometrically determined knowledge of surface slope to measure the full velocity vector [Joughin *et al.*, 1996c]. An example of the application of this technique to the Ryder Glacier, Northern Greenland is shown in Figure 2.

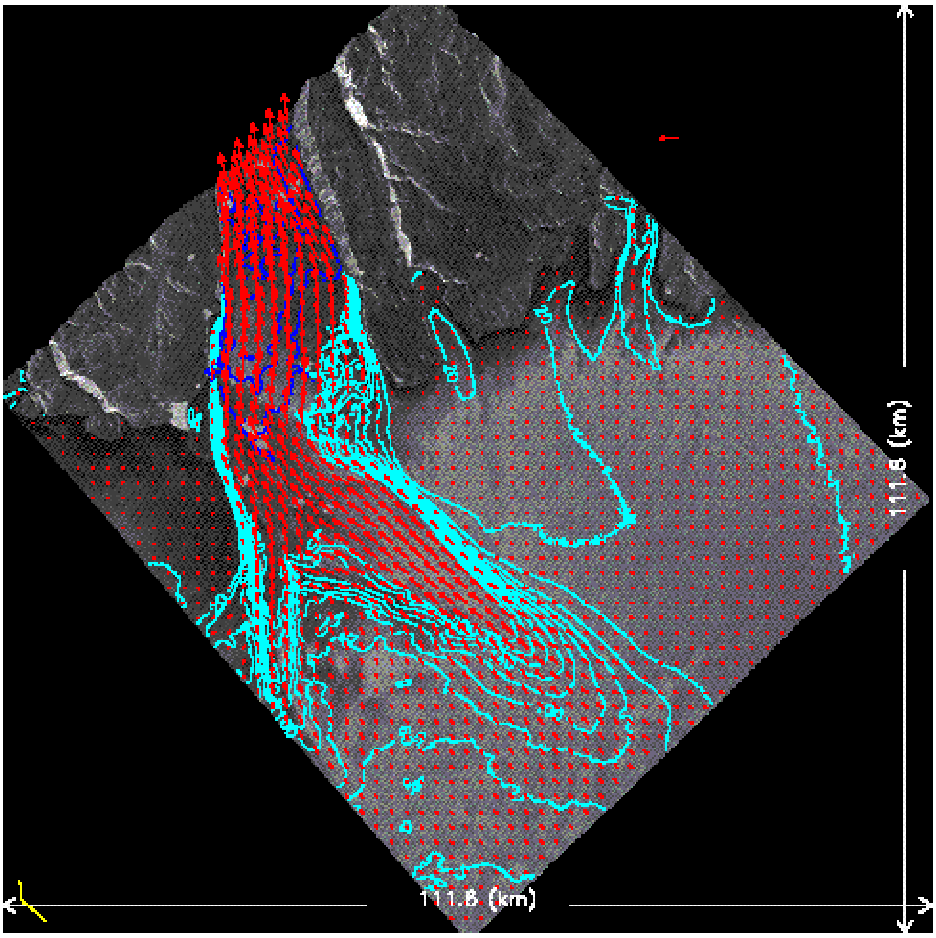


Figure 2. Horizontal velocity field plotted over the SAR amplitude image of the Ryder Glacier. Contour interval is 20 m/yr (cyan) for velocity less than 200 m/yr and is 100 m/yr (blue) for values greater than 200 m/yr. Red arrows indicate flow direction and have length proportional to speed.

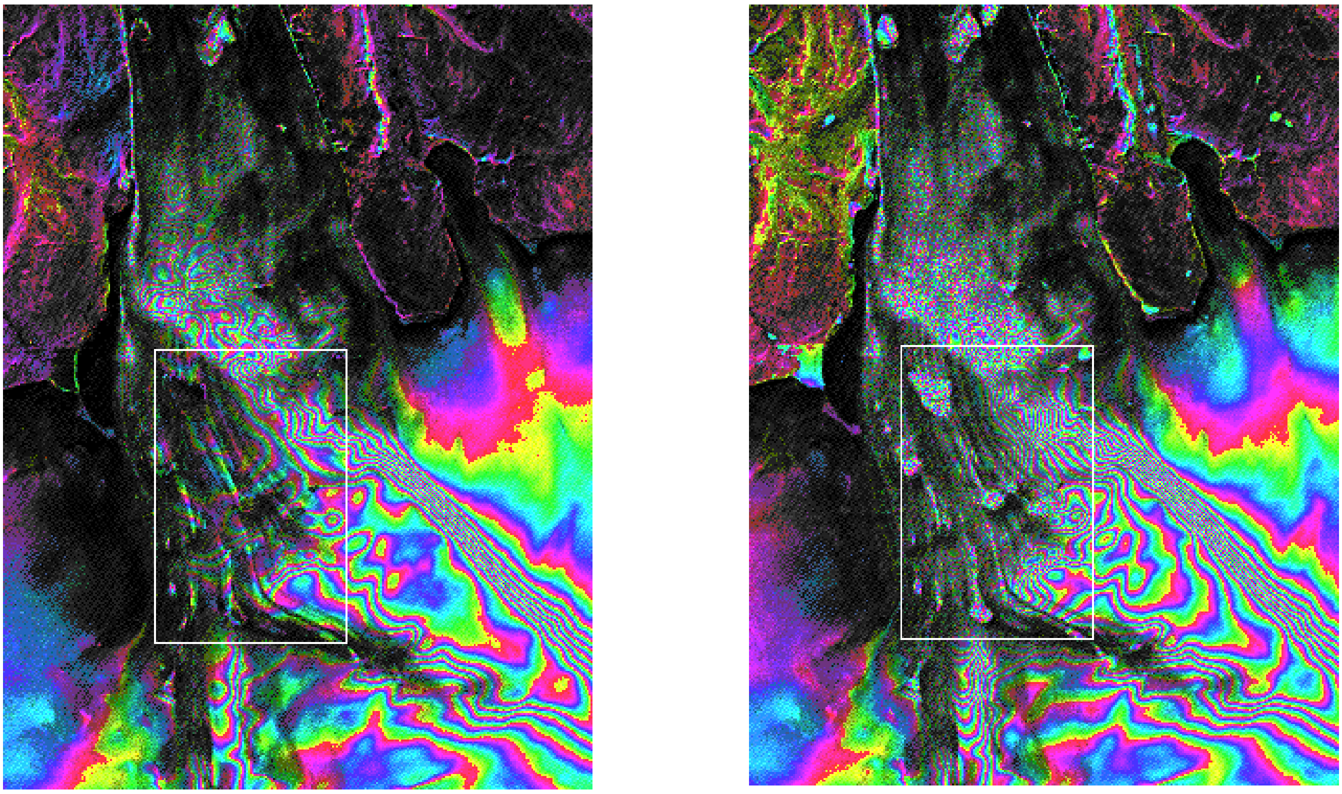
In making the surface-parallel flow assumption we have ignored small deviations from surface-parallel flow (i.e., the submergence and emergence velocity). The data provided with this method are extremely useful for most ice dynamics studies. With a SAR that can observe from both sides, however, it would be possible to collect data from three directions and measure ice flow without ignoring the submergence/emergence velocity. Such data would be extremely useful for making local ice-sheet thickening/thinning estimates, especially when combined with laser altimeter observations.

Although we do not have ground truth to fully validate our results, qualitatively we appear to have captured the main elements of the Ryder flow field. In places where there are flow stripes or other indicators of flow direction, we get good agreement with the measured flow direction. Thus, with ascending and descending data it is possible to map vector ice flow over large areas on the ice sheets. Although the mosaicking is slightly more complicated, when adequate ascending and descending data are acquired it will be possible to map vector velocity over entire ice sheets.

4. MINI-SURGE OBSERVATION

The ability to acquire frequent snap shots of ice velocity is important for monitoring seasonal or episodic changes in glacier velocity. We have used tandem ERS data to document a mini-surge on the Ryder Glacier, which occurred in the Fall of 1995 [Joughin *et al.*, 1996d].

Figure 3 shows two interferograms that have been processed to remove topographic effects so that each fringe (yellow-red transition) represents 2.8 cm of displacement directed toward or away from the radar. The interferogram from the September observation (Figure 3a) agrees well with another interferogram from ERS-1 images acquired in March 1992 and appears to represent velocity in the normal flow mode of 100-500 m/yr for most of the glacier.



(a) (b)

Figure 3. Interferograms from the fast moving area of the Ryder Glacier (a) before (21-22 September 1995) and (b) during (26-27 October 1995) a mini surge. Each fringe is equivalent to 7.2 cm of horizontal displacement in the across track direction or 3.0 cm of vertical displacement. Both interferograms were acquired from data collected along the same descending track.

There are striking differences between the September and October observations over the fast-moving portion of the glacier. In areas where we could unwrap the phase, we measured differences of up to 150 m/yr representing a speed up of more than 50 percent. For a large part of the area where we could not unwrap the phase, the fringe density appears to have at least tripled, indicating increases in speed by a factor of three or more.

Analysis of an interferogram (not shown) formed from images acquired 8 and 9 November 1995 along an ascending track indicate that there was no significant enhanced flow at this time. Thus, the mini-surge appears to have started and ended sometime between 22 September and 8 November with enhanced flow observed over the interval from 26-27 October.

There is little information on the temporal variability of outlet glacier and ice stream flow in Greenland and Antarctica. Our results indicate that significant variation can occur and that such behavior can be observed via satellite radar interferometry. Thus, a program of regular observation of many outlet glaciers could help answer fundamental questions regarding the seasonal and episodic variability of ice flow.

5. CONCLUSIONS

Satellite radar interferometry provides an important tool for measuring the velocity and topography with unprecedented spatial detail and coverage. As the only existing data set with suitable temporal baselines for measuring ice motion, the ERS-1/2 and ERS-1 ice and commissioning phase data should be fully exploited to provide important new information for glaciological research.

6. ACKNOWLEDGEMENTS

I. Joughin and R. Kwok performed this work at the Jet Propulsion Laboratory, California Institute of Technology under contract with National Aeronautics and Space Administration (NASA). Mark Fahnestock was supported under NASA NMTPE grant NAGW4285. SAR data were provided by the European Space Agency.

We thank S. Ekholm of the National Survey and Cadastre, Copenhagen, Denmark for providing us with the DEM used to derive tie points. We also wish to thank C. Werner of the Jet Propulsion Laboratory for providing us with a SAR processor for the raw signal data.

7. REFERENCES

Goldstein R. M., H. Engelhardt, B. Kamb, and R.M. Frolich, 1993:
Satellite radar interferometry for monitoring ice sheet motion: application to an Antarctic ice stream, *Science*, vol. 262, pp. 1525-1530.

R. Kwok, M. A. Fahnestock,1996 :
Ice sheet motion and topography from radar interferometry, In: *IEEE Trans. Geosci. Rem. Sen.*, vol. 34, no. 1.

I. R. Joughin, 1995:
Estimation of Ice Sheet Topography and Motion Using Interferometric Synthetic Aperture Radar , Ph. D., Thesis, University of Washington.

I. Joughin, D. Winebrenner, M. Fahnestock, R. Kwok, and, W. Krabill, 1996a :
Measurement of ice-sheet topography using sateldlte radar interferometry, In: *Journal of Glaciology*, vol. 42, no. 140.

I. Joughin, R. Kwok, M. Fahnestock, 1996b:

Estimation of Ice Sheet Motion Using Satellite Radar Interferometry: Method and Error Analysis with Appdlcation to the Humboldt Glacier, Greenland,In: *Journal of Glaciolog*, vol. 42, no. 142.

I. Joughin, R. Kwok, M. Fahnestock, 1996c:
Interferometric estimation of the three-Dimensional Ice-Flow Velocity Vector Using Ascending and Descending Passes, Submitted to: *IEEE Trans. Geosci. Rem. Sen.*, October 1996.

I. Joughin, S. Tulaczyk, M. Fahnestock, R. Kwok, 1996d :
A Mini-Surge on the Ryder Glacier, Greenland Observed via Sateldlte Radar Interferometry, In: *Science*, vol. 274, pp. 228-230.

Last Modified: 17:41pm , March 17, 1997