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Glacier Flow Measurements with ERS Tandem Mission Data

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Abstract

Glacier flow measurements have provided one of the more striking applications of differential satellite SAR interferometry. In this paper, we summarize some results we have obtained on the Saskatchewan Glacier in the Columbia Icefield in the Rocky Mountains of western Canada.
Glacier measurements are important for hydrological studies, but are difficult to measure from the ground. We show that dense, wide-area flow measurements can be made from ERS Tandem Mission data, as long as the surface of the glacier is stable. The necessary stability conditions occur when the temperature is below freezing and no precipitation or strong winds occur during the observation interval.

Differential interferometry requires that the phase due to topography be removed from the phase due to motion in the interferogram. We do this by using an accurate DEM obtained from the CCRS Convair-580 across-track interferometer, then using the ERS satellite geometry to derive the phase due to the topography and the viewing parallax (baseline). When this phase is subtracted, the motion fringes can be processed to obtain line-of-sight glacier flow. Then, by assuming a given glacier flow direction, the LOS motion can be projected to the proper flow direction.

We show results obtained from the Saskatchewan Glacier on November 2/3 1995. The measured flows range up to 30 cm/day. They have been verified to be accurate to within 10% by ground measurements, and later SAR observations taken in November 1995, March 1996 and April 1996 reveal that the fine-scale structure of the glacier flow patterns are very repeatable. Glaciological studies are now underway to understand the physics behind the detailed observed flows.

Keywords: Differential interferometry, Glacier flow measurements

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Glacier Flow Measurements with ERS Tandem Mission Data

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1. Introduction

In this paper, we show how differential interferometry from the ERS satellites operating in Tandem Mode can yield excellent measurements of the flow rates of Alpine Glaciers. As long as the surface conditions are stable during the observation interval, accuracies of a few cm/day can be obtained from the ERS data.

In the interferometric processing, a means must be available to separate the phase differences in the interferogram due to topography from those due to motion. In this work, we use a DEM and a model of the satellite geometry to subtract the topographic phase, leaving a clear picture of glacier surface motion.

Our main results are taken over the Saskatchewan Glacier in western Canada in November 1995. We show the topographically-corrected interferogram, and the velocity map derived from it.

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2. Glacier Measurements

Glaciers have been studied for a long time, including measuring their area, depth, accumulation, water runoff, snow line position and terminus extent. They are an important indicator of historical and present global climate, as their parameters are an integral of climate and environmental effects such as temperature, precipitation and pollution. By taking core samples and dimensional measurements, glaciologists can infer climate and make models of glacier dynamics. Now that water resources are in scarce supply in many parts of the world, it is all the more important to make accurate measurements and models of glacier mass balance to forecast the water available for future consumption and to predict floods and droughts.

Measurements have traditionally be made on glaciers by ground-based crews, and sometimes by helicopters. These measurements are difficult and expensive to make, with the result that few glaciers are monitored, and even then, only a sparse set of readings can be taken. Many glaciers are relatively inaccessible and weather conditions often prevent operation by field crews.

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3. The Columbia Icefield

The Columbia Icefield in the Rocky Mountains of Western Canada was chosen as our study area because:

There are 7 glaciers flowing in all directions, so we can find one that is best for the ERS viewing directions, and can see the effects of other viewing directions.

The glaciers are relatively accessible for taking ground truth measurements, as a major highway and government interpretation centre are located there.

These glaciers have been studied for many years, go good-quality historical flow data is available.

These glaciers are typical of many inaccessible Alpine glaciers.

We will focus our attention on the Saskatchewan Glacier, located at 52^{o}8'N, 117^{o}11'W. It is the largest glacier in the Columbia Icefield, and has a favourable orientation for imaging with ERS ascending passes. The descending pass view direction is also reasonably good. The tongue of the glacier flows from west to east and is approximately 10 Km long and 1 Km wide. A 1:50,000 topographic map of the glacier is shown in Figure 1.

Click here to load map (350KB)

Figure 1: Topographic map of Saskatchewan Glacier.

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4. InSAR Processing

We will apply repeat-pass satellite interferometry processing to the 1-day repeat coverage ERS Tandem Mission data. Our data comes from frame 1035, with ERS-1 orbit 22481 on November 2, 1995 and ERS-2 orbit 2808 on November 3, 1995. The data is processed into SLC images with the MacDonald Dettwiler SAR processor, registered and an interferogram formed.

The magnitude and phase of the interferogram is given in Figure 2 and Figure 3 respectively, showing a 16 Km (range) by 5 Km (azimuth) portion of the scene. The left hand 1/5 of the scene shows the Columbia Icefield, which is the accumulation area of the glacier.The 10 Km long tongue of the Saskatchewan Glacier runs from left to right through the middle of the scene, ending in a terminal moraine at the right of the image. Note than the SAR images are rotated about 12^o with respect to the map, as they are in the slant range alignment given by the ascending pass viewing direction.

The interferogram shows reasonably good coherence on the ice surface (average coherence about 0.8). The areas where the phase noise is high are mountainous areas above and below the glacier, where layover is significant.

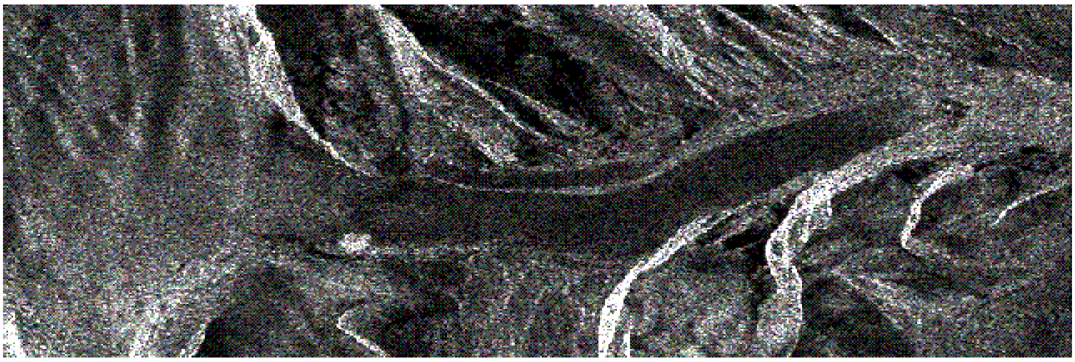

Figure 2: Magnitude of interferogram of Saskatchewan Glacier

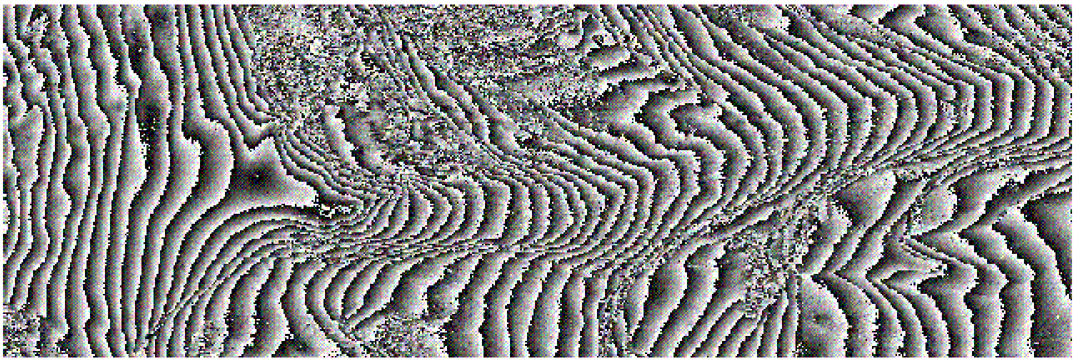

Figure 3: Phase of interferogram of Saskatchewan Glacier.

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4.1 Processing the Glacier Interferogram

In the interferogram, the differential phase is due to:

topographic effects, because of the different satellite beam incidence angles (cross-track parallax),

displacement effects, due to surface motion between the data takes, and

noise effects, from sources such as receiver noise and random scatterer motion.

As we are interested in extracting glacier motion, the topography phase must be removed from the interferogram. This can be done in at least two ways:

Predict the phase due to topography/parallax, and subtract it from the interferogram. If a DEM is available, it can be used with a satellite geometry model (knowing the baseline) to compute the topography phase.

If two interferograms are available with different baselines and/or different data take intervals, the interferogram phase can be solved using two independent equations for the two unknowns (topo and displacement phases). This requires the assumption that the glacier velocity is constant between the two pairs of data takes.

The second approach has been used successfully by Joughin on the Greenland Ice Sheet [Joughin, 1995]. In our case, an accurate DEM has been obtained by the CCRS Convair-580, and will be used with the first method above.

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4.2 The Convair-580 DEM

The Convair-580 SAR was flown over the test area in March and August 1995, with a viewing direction from the north-east (looking up the glacier). Figure 4 shows a SAR image taken from the August flight. Compared to the ERS images, the Convair image has a higher resolution, larger incidence angle and a higher SNR.

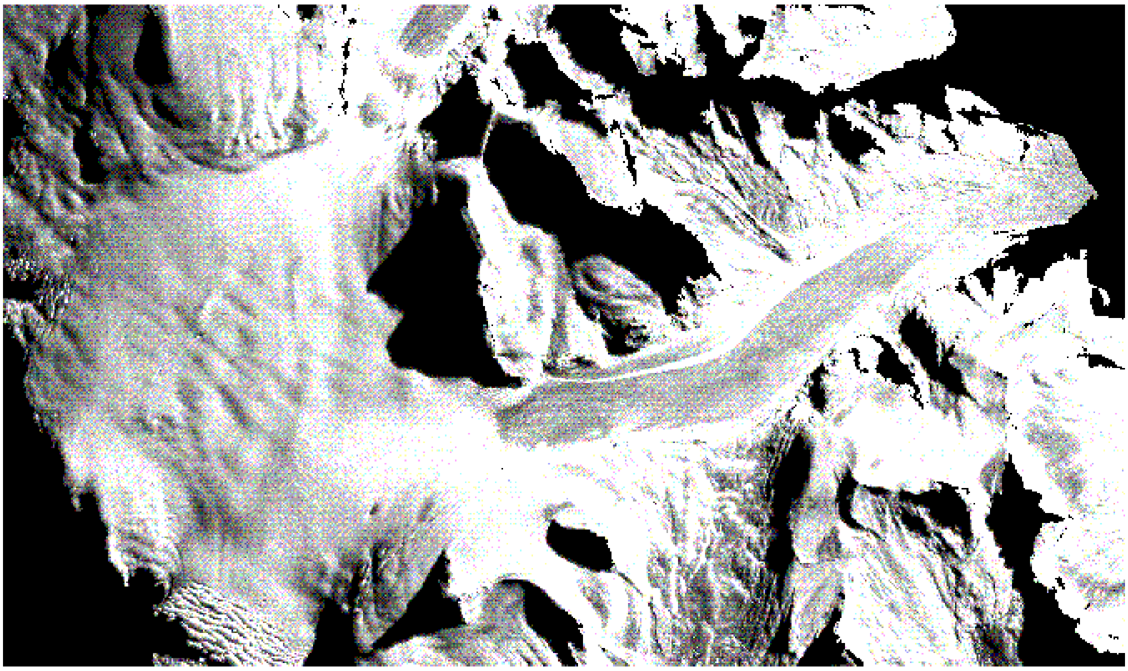

Figure 4: SAR magnitude image obtained by CCRS Convair-580

The Convair cross-track interferometric data was processed to a DEM using both the April and August data. They agreed to within 5 meters in most areas. The DEM is quite accurate because of the high SNR and resolution, and because the two interferometric channels are collected simultaneously. The DEM was produced in UTM coordinates, and can be used to create a perspective view of the SAR image, as shown in Figure 5.

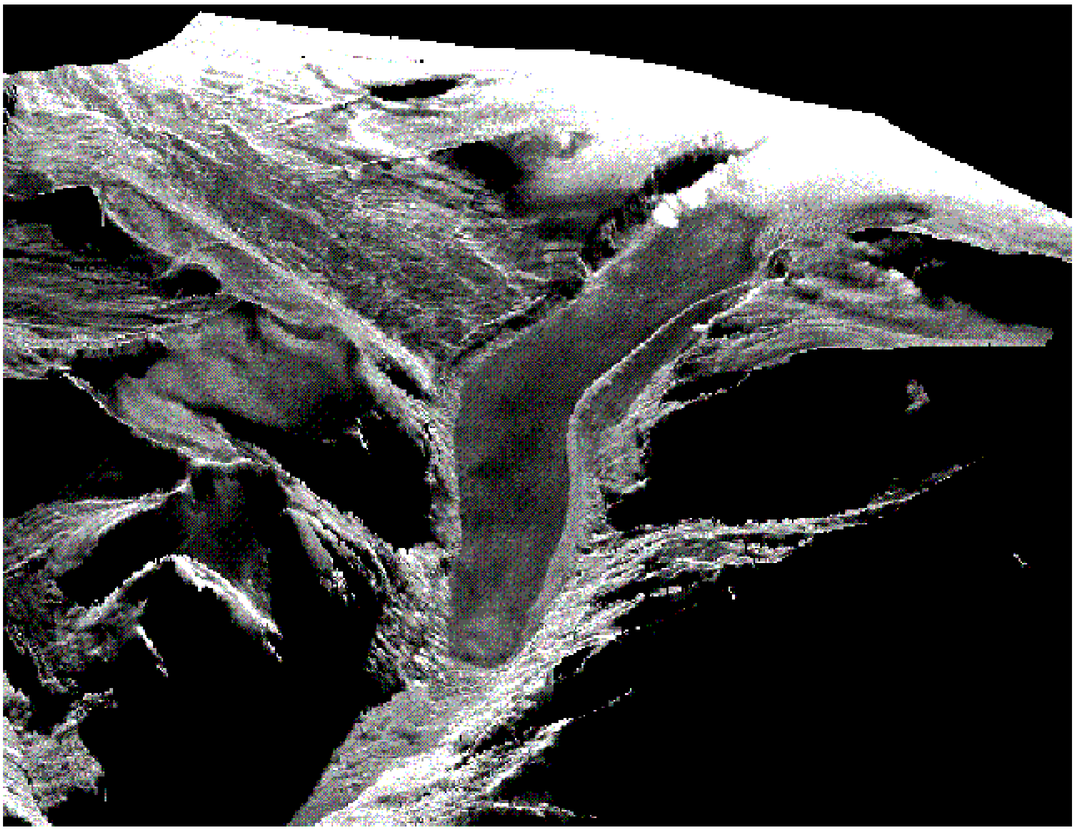

Figure 5: Perspective view of Saskatchewan Glacier from Convair DEM.

The DEM is mainly used to remove the topographic phase from the ERS interferogram. However, other parameters can be extracted from the DEM, which are subsequently used to project the ERS measured displacement along the glacier flow direction. These parameters include the height of the glacier, the surface slope and down-slope direction, all measured along the centreline. These parameters are shown in Figure 6.

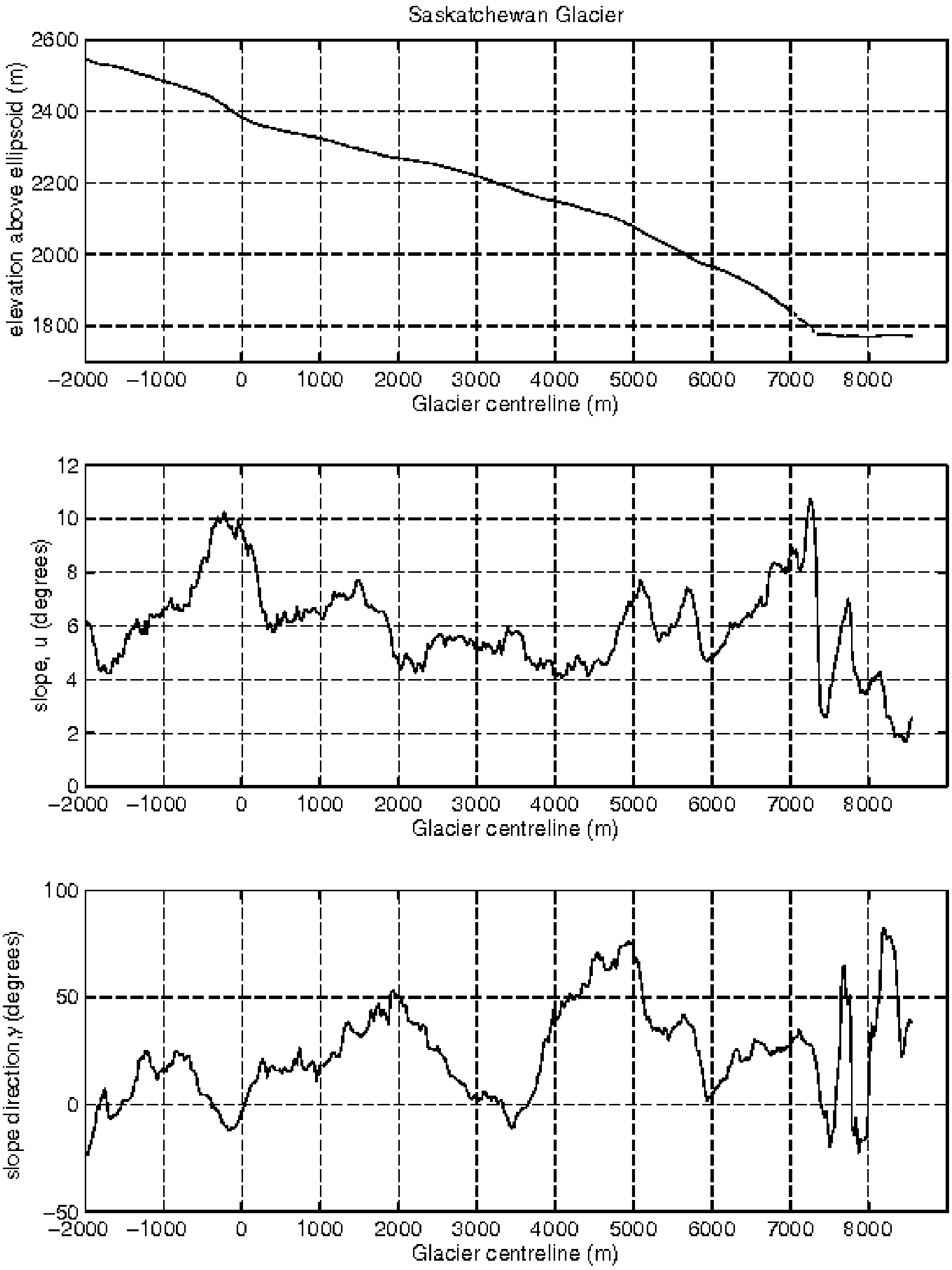

Figure 6: Glacier height, slope and flow direction from Convair data.

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4.3 Removing Topographic Phase from the Interferogram

The Convair-580 DEM was resampled to the ERS slant range/azimuth grid, and used to compute the topographic phase that would be expected with the 94 meter baseline. The result is shown in Figure 7, where fringes due to the change in line-of-sight velocity are clearly seen. Most of the rocky areas adjacent to the glacier have the same phase, which can be assigned a zero motion value.

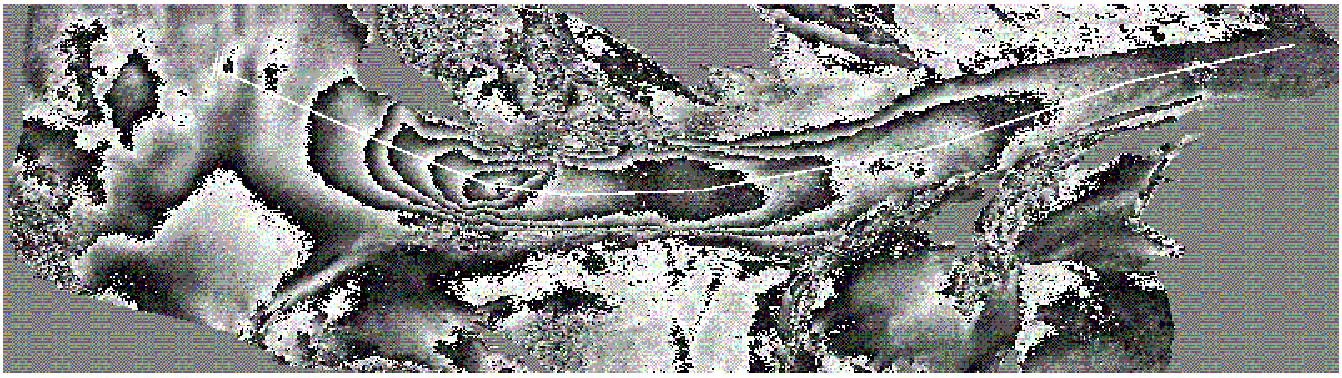

Figure 7: Interferogram phase after topographic phase removed.

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5. Glacier Flow Measurements

In this section, we extract the glacier flow from the ERS SAR data, and compare it to flow measurements taken from surface readings.

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5.1 InSAR Flow Measurements

A 200 meter strip of the ERS SAR data was chosen around the glacier centerline (the white line in Figure 7). The phase was smoothed in this region, then unwrapped. As each phase fringe represents 2.85 cm of motion parallel to the radar beam vector over the 1-day interval, a curve of line-of-sight (LOS) displacement could be plotted vs. the distance along the centreline.

However, our interest lies in measuring the surface velocity, so we must determine what surface velocity creates the measured LOS velocity. To do this, we make the assumption that the surface flow is parallel to the surface, in the direction of the maximum slope. Then, using a reverse projection, the LOS displacement values are converted into surface displacements.

To date, five Tandem Mission data pairs taken between November 1995 and April 1996 have been analyzed in this fashion, and the surface displacements in cm/day are plotted in Figure 8. Six other Tandem Mission data pairs taken during this interval had too low a coherence to give useful results [Vachon, 1996].

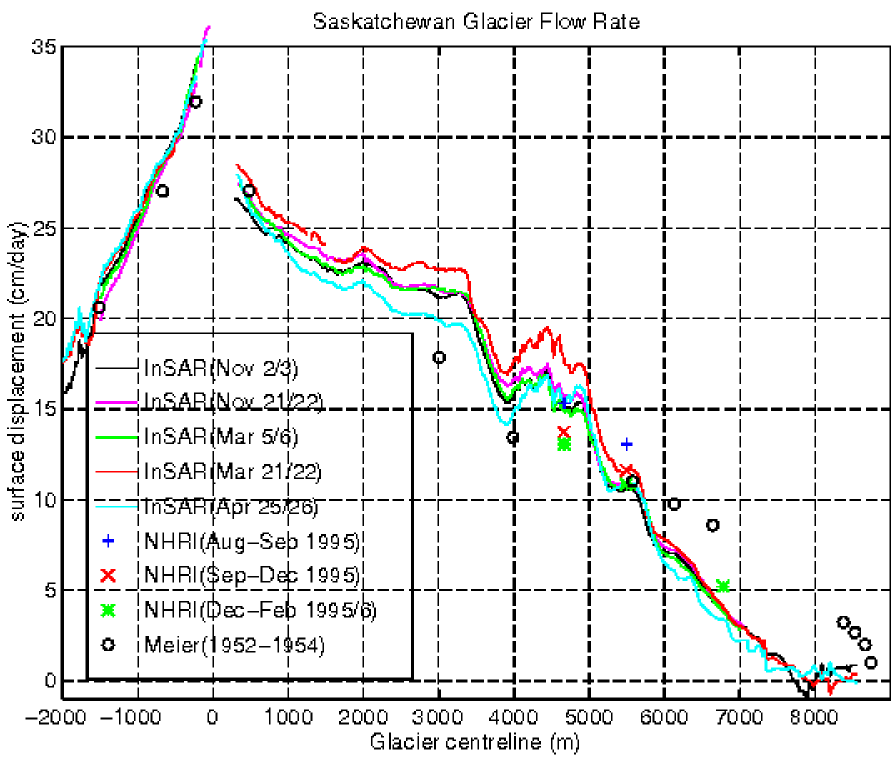

Figure 8: Glacier flow velocities from SAR data and ground measurements.

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5.2 Ground Truth Measurements

Four sets of measurements were taken by NHRI between August 1995 and February 1996, yielding 3 sets of relative displacements drawn in Figure 8. These were done by drilling 3 poles into the ice, and using theodolites to measure their position accurately every month or two. The poles were insulated to minimize their melting into the ice.

Also shown in Figure 8 are measurement taken by Meier in the 1950s. They cover a larger area of the glacier, and are the average over a whole year of observations. Both these and the NHRI measurements included 3-dimensional displacement measurements, and confirmed that our assumption of flow direction was accurate to within a few degrees.

Weather readings logged every hour confirmed that the temperatures were always below freezing and no precipitation occurred on the 5 days that the high-coherence InSAR measurements were taken. Typical temperatures of the air and of the ice were between -1^{o}C and -10^{o}C for these 5 days [Vachon, 1996].

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5.3 Discussion

First note that there is a remarkable consistency between the 5 sets of SAR measurements. The fine-scale structure is almost the same, and there is a gradual slowing down of the surface velocity, as would be expected as the ice cools down from the beginning to the end of the winter. This consistency leads us to believe that the SAR measurements are accurate to 1 or 2 cm/day, although some of the similarity of the fine-scale structure comes from the fact that the same projection direction was used in each of the 5 cases.

Second note that the agreement between the SAR and the ground measurements is very good -- in the order of 2 cm/day.

There are a number of errors in the SAR and the ground measurements, and in how they are compared, such as:

- Relative registration between the SAR and ground readings with respect to the horizontal axis of Figure 8.
- Different location and averaging methods between the readings.
- Time differences between the SAR and ground measurements.
- Assumption of glacier flow direction used in the SAR data projection.
- InSAR calibration and the choice of the zero velocity datum.
- Difference between the pole velocities (buried in the ice) and the ice surface from which the radar beam scatters.

We cannot fully quantify all these errors, but given the uncertainty caused by each of them, we are pleasantly surprised by the agreement between the SAR and ground readings.

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6. Conclusions

We have obtained glacier surface motion measurements using differential interferometry analysis of ERS Tandem Mission data over an Alpine glacier in the Canadian Rocky Mountains. The 5 sets of SAR measurements show a remarkable consistency with each other, and there is good agreement with several sets of ground measurements taken around the same time.

Compared to the limited measurements taken by a ground survey crew, the SAR measurements cover the whole glacier surface (with roughly a 30 meter spacing), and can be obtained with modest incremental cost whenever the surface of the glacier is stable. Our limited experience suggest that winter conditions provide the best SAR observation conditions.

From this we can conclude that differential SAR interferometry is a useful tool for monitoring the surface motion of Alpine glaciers. We hope that glaciologists can make good use of this new instrument, and that it will improve the accuracy of their glacier modeling work.

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References

Vachon, P., D. Geudtner, K. Mattar, A. L. Gray, M. Brugman and I. G.Cumming
Differential SAR Interferometry Measurements of Athabasca and Saskatchewan Glacier Flow Rates, Canadian J.~of Remote Sensing, Accepted for publication, September 1996.

Joughin, Ian, 1995:
Estimation of Ice-Sheet Topography and Motion Using Interferometric Synthetic Aperture Radar. PhD thesis, University of Washington.

Solaas, G. A., 1994:
ERS-1 Interferometric Baseline Algorithm Verification. *Technical Report ES-TN-DPE-OM-GS02* Version 1.0, ESA.
http://gds.esrin.esa.it:80/CEFB565F/CORBITS.