Ice Flow in Northeast Greenland Derived Using Balance Velocities as Control

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ABSTRACT

Satellite radar interferometry provides an important new means for measuring ice motion. To make absolute velocity measurements, ground-control points typically are required to refine interferometric baseline estimates. The vast scale and remote location of the ice sheets make it difficult to obtain *in situ* ground-control data. Balance velocities derived from satellite altimetry digital-elevation models (DEMs) provide an alternate, though less accurate, source of control data. We demonstrate a case in which we are able to achieve an accuracy of just over 3 m/yr using this type of control.

INTRODUCTION

Although satellite radar interferometry provides a means of measuring ice sheet motion, application of the technique is limited by the need for ground-control points. There are large areas on the ice sheets of Greenland and Antarctica where there are no suitable *in situ* velocity measurements available. We demonstrate here that balance velocities are a viable alternative to control points measured via the Global-Positioning System (GPS). The impact of balance-velocity errors on the interferometric estimates is minimized by carefully selecting the control points from slow-moving regions, where the errors are small in an absolute sense.

VELOCITY MAP

Fig. 1 shows a map of the across-track component of velocity for the Northeast Greenland Ice Stream. We generated this map using data from several ascending ERS interferograms, which were collected during the ice and commissioning phases of ERS-1 and the tandem phase of ERS-1 and 2. The velocity data are plotted as contours over the associated amplitude imagery. The track headings differ for each strip, so the across track-direction is slightly different for each strip. These directional differences are small enough that the data can be compared in the overlap regions as though they were acquired along the same track heading.

Most of the scenes contain no ice-free areas, so we had to rely entirely on ground-control points located on the ice sheet. The elevation control data were extracted from the Danish National Survey and Cadastre (KMS) DEM [1]. These elevation data were derived primarily from satellite altimetry. For the strip closest to the coast (far upper right strip), we did use some control points from ice-free areas. The data from this part of the KMS DEM were derived photogrametrically. The locations of the ground-control points are shown as black dots in Fig. 1.

We generated a balance-velocity map of Greenland [2] to provide velocity control on the ice sheet. Balance velocities are the depth-averaged velocities necessary to maintain the steady-state shape of the ice sheet and are estimated from surface slope ice, ice thickness, and accumulation data. The depth-averaged velocities were adjusted by a factor of 1.11 to obtain surface velocity estimates. Errors in the source data can lead to large errors in the balance-velocity estimates. Furthermore, since the elevation data must be heavily smoothed, balance-velocity estimates have inherently low resolution. To minimize the impact of balance-velocity errors on our baseline estimates, we selected control points in slow-moving areas, where the absolute errors in the balance velocities are small. For example, if the velocity is 10 m/yr, then a 50 percent error leads to a balance-velocity error of only 5 m/yr. By selecting points in this manner, we anticipate control-point errors in the range of 1-10 m/yr. We used several dozen control points for each scene to reduce the random component of the control-point noise. Systematic trends in the control-point data (i.e., a linear error in the balance velocities across a scene) will not be overcome by using a large number of points.

To compute our horizontal across-track velocity estimates, we used the KMS DEM to determine slope for removing the effect of vertical displacement [3]. With the low resolution of the DEM, we were unable to compensate for short-wavelength components of vertical motion (i.e., less than 5 km). This results in errors equal to a few percent of the horizontal across-track velocity. Since the KMS DEM also was used to

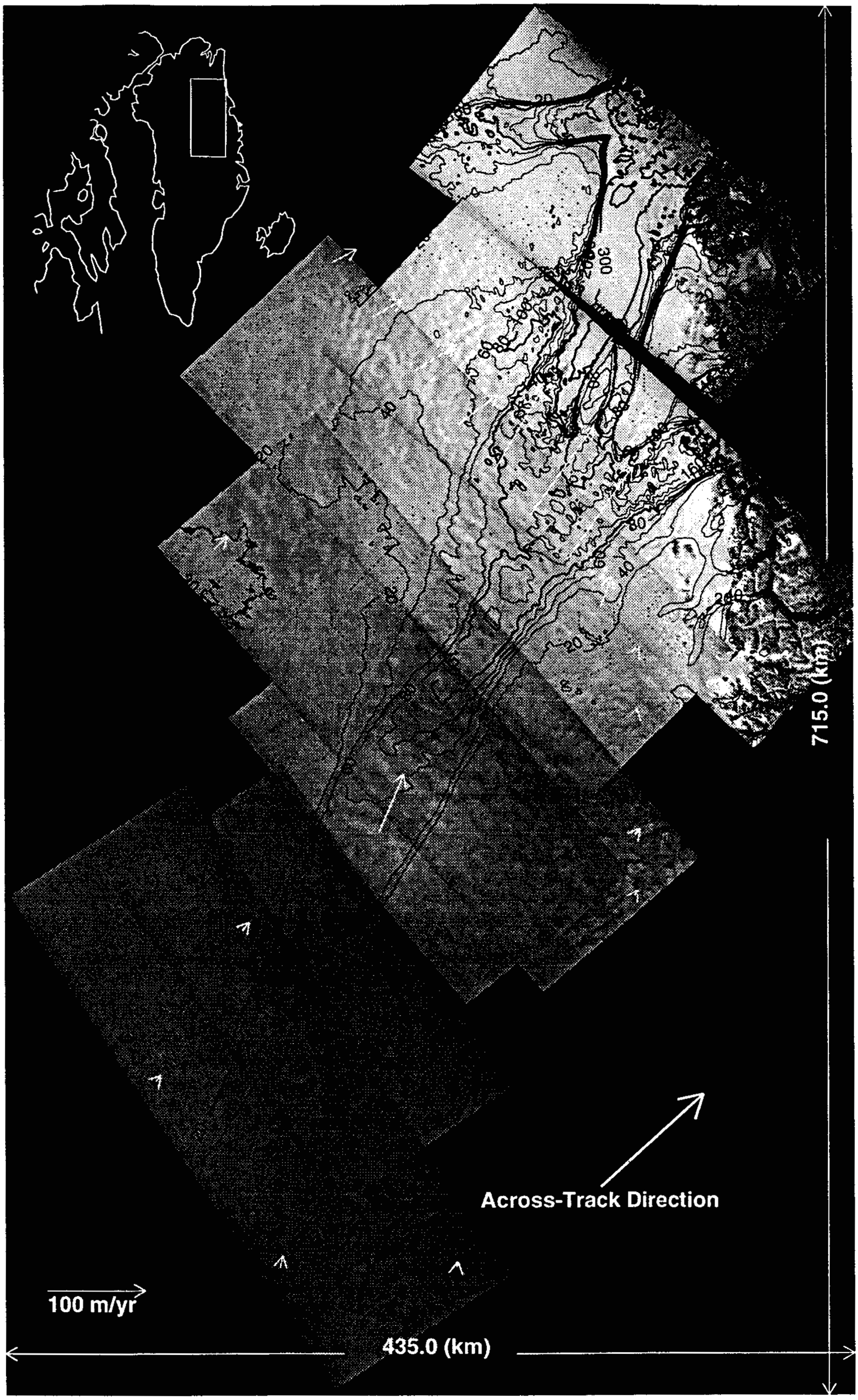

Figure 1. Interferometrically derived estimate of the across-track component of velocity (black contours) for the Northeast Greenland Ice Stream. Baselines were estimate using control points, which are shown as black dots. The thin white arrows show the velocity vectors measured using GPS. The indicated across track direction is only approximate, with the actual across-track direction varying slightly from strip to strip.

remove the direct effect of topography, there are additional errors caused by topographic fringes from short-scale topographic features. Ultimately, we will combine our data with descending passes and interferometrically derived DEMs to estimate the full 3-component velocity field using a surface-parallel flow assumption [4].

COMPARISON WITH GPS DATA

GPS data were collected by National Aeronautics and Space Administration (NASA) along the 2000-meter contour of Greenland to measure ice sheet outflow. Additional data were collected near the onset area of the Northeast Greenland Ice Stream for use as interferometric control points. The GPS points that fall within our velocity map are shown as white arrows in Fig. 1. While we eventually plan to use these data as control, they were in no way used to control the velocity shown in Fig. 1, which was derived using only balance velocities and the KMS DEM as sources of control data.

Velocity Data	**Error (m/yr)**		
	Mean	**Std.Dev.**	**RMS**
Entire Map	2.08	2.42	3.14
Tandem Data	2.76	2.40	3.60
Ice & Commissioning	1.44	3.60	3.74

Table 1. Across-track velocity error for GPS points shown in Fig.1.

We projected the GPS measurements onto the across-track direction for comparison with the interferometric data. The GPS points were determined by repeat surveys of stakes separated by an interval of nearly one year so that the errors are well under a 1 m/yr. Thus, we assume that any difference between the GPS and interferometric data represents an error in the interferometric measurement.

Table 1 shows the difference between the 18 GPS points and the interferometric map shown in Fig. 1 (entire map). Note that all of the strips used in this comparison were controlled solely with points from the ice sheet. The RMS difference is 3.14 m/yr with a maximum error of 6.7 m/yr. The results indicate that the balance velocities are a reasonable source of control. It is important to also note that some portion of the error can be attributed to uncompensated topography and vertical motion, which can be reduced with additional interferometric data and processing.

Three strips were from either the ice or commissioning phases (the first, third, and sixth strips from lower left to upper right) and have temporal separations of 6 days or more verses 1 day for the tandem data. Since the displacement is observed over a longer period the ice/commissioning data should be more accurate. Indeed, inspection of the velocity data reveals that these estimates are smoother and appear to have less noise, such as artifacts from residual topography. To quantify these differences we separately compared the tandem and ice/commissioning data with the GPS data and were surprised to find that the errors were similar. The largest differences for both phases occurred on the fastest moving areas and/or on the strips nearer the coast, where larger balance velocities had to be used. The larger balance velocities will tend to be less accurate, resulting in greater velocity errors over the entire strip for which they provided control. In the faster moving areas, the effects of uncompensated vertical displacement will be greater, and this effect is insensitive to temporal separation. Thus, the errors for the different phases are probably similar because they are dominated by a few points where the sources of error are independent of temporal baseline. Over slower moving areas the ice/commissioning data should be more accurate. Note that the error for the total map is smaller than for the individual acquisition phases because accuracy is improved by the averaging that occurs in areas of overlap.

CONCLUSIONS

Our results indicate that balance velocities can provide an acceptable substitute for *in situ* GPS measurement and that single-component velocity accuracies of just over 3 m/yr can be achieved. Some portion of the error is due to topography and vertical motion effects that can be removed to provide further improvement with a higher resolution DEM.

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