APPLICATION OF AIRCRAFT LASER ALTIMETRY TO GLACIER AND ICE CAP MASS BALANCE STUDIES

W. Abdalati and W.B. Krabill

Laboratory for Hydrospheric Processes
NASA Goddard Space Flight Center
U.S.A.
waleed.abdalati@gsfc.nasa.gov

Commission III, Working Group 3

ABSTRACT

The Arctic ice caps and glaciers serve as important indicators of climate change and also make a small, but significant, contribution to changes in global sea level. Consequently, understanding their mass balance is of considerable interest. We are examining the current state of mass balance of the major Canadian ice caps in the greater Baffin Bay area in the context of recent climate conditions through analysis of precise elevation changes and recent climate history. Using the series of airborne laser/GPS elevation measurements made with the Airborne Topographic Mapper (ATM) in 1995, in conjunction with planned repeat surveys in the year 2000, we will quantitatively measure and interpret ice thickness changes in the context of recent climate conditions. Such elevation surveys provide the most direct large-scale means of examining the state of balance of these caps. In addition the application of airborne laser altimetry to the study of flow characteristics of glaciers is presented and discussed for three outlet glaciers on the Greenland ice sheet.

This work is a complement to the current ATM-based ice sheet analyses that are being conducted for Greenland, but it is focused on smaller ice masses with different temporal responses to climate variations. Recent results of the Greenland missions have shown interesting thickening and thinning characteristics, with the most significant changes found in the more temperate parts of the ice sheet near the margins and in outlet glaciers. Consequently, the assessment of changes in the smaller Arctic ice masses will be an important complement to the results from Greenland, and they will help provide a more complete picture of the current state of balance of the Arctic ice masses.

1 INTRODUCTION

Understanding the behavior of Arctic ice masses in the changing present-day climate is important for a number of reasons. First, the Arctic is believed to be highly sensitive to changes in Global climate, primarily because of the positive albedo feedback effects associated with surface melt and snow metamorphism processes. Recently-fallen snow is highly reflective with an albedo of as much as 90%, but as temperatures rise, and the surface begins to melt, the albedo reduces to 60 to 70%. This translates to a 3- to 4-fold increase in absorbed energy, which further enhances the melt process. Even in the absence of melt, warming temperatures increase grain growth, which in turn reduces the albedo, and creates a similar self-compounding effect, but to a lesser degree. Because of this unstable positive feedback, perturbations to the system are greatly amplified in the Arctic, and other snow- and ice-covered areas.

Secondly, the large ice masses influence sea level, which has been rising at a rate of as much as 2 mm/yr over the last century. In a warming climate, ice caps, glaciers and ice sheets can increase sea level if they are in a negative balance, by mass loss through ablation and discharge. However, it is possible that they can reduce the rise in sea level if they are in a positive balance, i.e. if they are gaining mass through increased accumulation. For the large ice sheets, Greenland and Antarctica, the current mass balance is not known. In the case the smaller ice masses, such as glaciers and ice caps, many

appear to be shrinking, while others seem to be growing. Quantitative assessment of the state of balance of the larger ice masses, such as those in the Arctic and some of the smaller glaciers, is essential to understanding their behavior and associated implications in a changing climate. Currently, laser altimetry provides the best means for assessing ice mass balance through the measurement of large-scale elevation changes.

In recent years, the utility of aircraft laser altimetry for measuring surface elevation changes on the Greenland ice sheet to better than 10 cm rms, has been clearly demonstrated (Krabill et al., 1995). This technology has been employed to investigate the mass balance of the Greenland ice sheet through a series of repeat elevation surveys separated by 5 years. Initial results for the southern half of the ice sheet (south of approximately 70°N) show interesting spatial variability, with very large thinning of some outlet glaciers in the east, and more subtle changes, both thickening and thinning, at the higher elevations (Krabill et al., 1999). These results suggest that some of the more dynamic areas of interest are the outlet glaciers and smaller ice masses, where the responses to climate forcing are more extreme.

Building on that technology, we are now applying those same survey techniques to perform similar studies of Canadian ice caps and other smaller ice masses. This paper will summarize some of the applications of airborne laser altimetry to studying the dynamics of fast-moving glaciers, as well as describe plans

for applying similar technology to the Canadian ice caps. The intent is that that by studying these smaller ice masses, observed changes in the state of balance of Arctic ice, and their relationships to a changing climate can be more comprehensively understood.

In addition, lessons learned and insight gained from the analysis of airborne laser altimetry will be incorporated in the future into the analysis of data from the Geoscience Laser Altimeter System (GLAS), to be flown on the Ice Cloud and land Elevation Satellite (ICESat), scheduled for launch in July, 2001.

2 INSTRUMENTATION AND MEASUREMENTS

The laser altimetry system used in these studies is the Airborne Topographic Mapper (ATM), which combines high-pulse laser ranging with a scanning capability. The ATM instruments are operated with Spectra Physics TFR laser transmitters, which provide a 7 ns wide, 250 μJ pulse at a frequency-doubled wavelength of 523 nm. The laser beam is reflected toward the surface off a nutating mirror, which can be adjusted to angle settings of 5, 10, and 15 degrees off nadir. The scan mirror rotational frequency is 10-Hz, which provides a ground-track of overlapping elliptical spirals. For a nominal flight altitude of 400 meters, and an off nadir pointing of 10°, the scan swath is approximately 140 meters wide. At higher flying altitudes, and for the larger angle settings, the swath width is approximately 250 meters wide. The spot-density on the ground is a function of the sample rate, aircraft velocity, and swath width. For nominal conditions with the aircraft flying approximately 150 m/s, the spot density is roughly 1 every 6 m^2, but with a much denser sampling along the edges of the swath, and a more coarse sampling near the center.

Topographic mapping surveys of ice are designed for optimum sampling, which varies with the size and shape of the ice-mass of interest, and the limitations of the aircraft platform. In the case of the Arctic Ice Mapping (AIM) program, these surveys have been made with the intent of repeating the exact flight tracks for thickness change measurements. In the initial surveys the aircraft is flown through a series of waypoints by means of an automated navigation system, which links the GPS information in real time, to the aicraft navigation system. After post-processing of the GPS data, and the correcting for attitude variations, the range measurement to the surface below can be converted to a footprint elevation. The accuracy of the elevation measurement is better than 10 cm rms (Krabill et al., 1995).

The GPS-based automated navigation capability is then used on the re-surveys to fly the aircraft as closely as possible along the original flight lines. Typically these re-flights are within 20 meters of the original flight line, allowing sufficient overlap for comparison of elevation changes. The elevation of the footprint within each laser shot from the initial survey, is then compared to those from the re-survey that fall within a specified search radius (typically 1 to 5 meters for shot-to shot comparisons, and

more with smoothed data), and the elevation change is determined.

3 CANADIAN ICE CAPS

The state of balance of the Canadian and other Arctic ice caps is of considerable interest because these ice masses are likely to be particularly sensitive to climate changes. Although their contribution to sea level rise is far less than that of Greenland or Antarctica, they are likely to respond to climate changes more rapidly than the large ice sheets; thus in some ways these final remnants of the Laurentide ice sheet may be more of an immediate concern. Moreover, their behavior in response to climate forcing may hold clues about the future of the Greenland ice sheet as well.

In 1995, as a complement to the Greenland missions, airborne laser elevation surveys were made of ice caps on Baffin, Devon, Ellesmere, Axel Heiberg, and Meighen islands, as well as a few ice cap outlet glaciers. The Canadian survey lines are shown in Figure 1. While the surveys have provided valuable information on the topography of the ice caps, their greatest value is likely to come from repeat surveys for elevation changes. These measurements are planned for May of 2000.
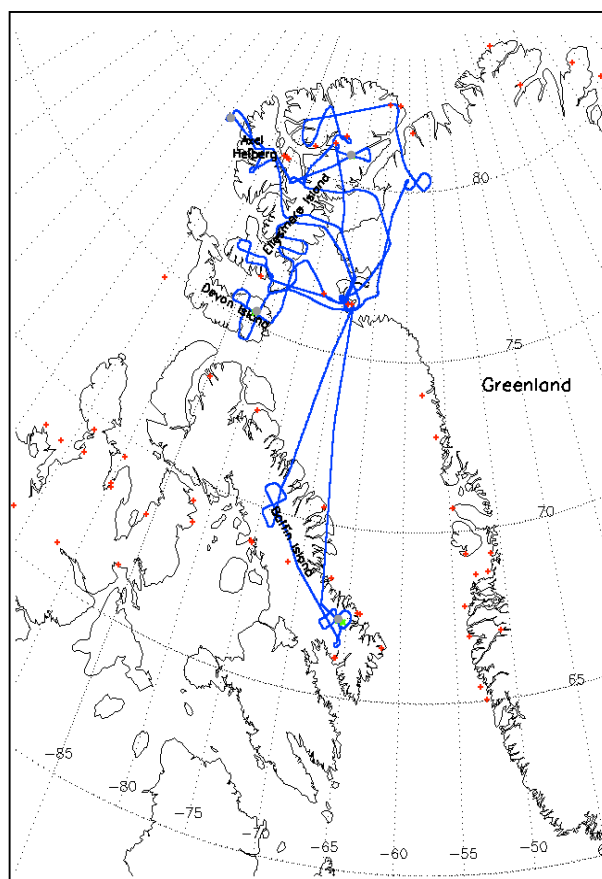

Figure 1. Flight trajectory of 1995 survey lines over several Canadian ice caps. These lines will be re-surveyed during the 2000 field season, for the purposes of measuring elevation changes. The red + symbols indicate the locations of coastal weather stations, and the Green dots indicate the location of several ice core sites.

Such elevation surveys will provide the most direct large-scale means of examining the state of balance of these caps. Unlike mountain glaciers, whose variations are often manifested in the advance and retreat of their termini, significant changes in ice caps can occur with little indication along the perimeter. This research is intended to detect and quantify any such changes, and to do so in the context of the local climate. Initial results from the Greenland measurements (Krabill et al., 1999) show the most dramatic changes near the ice sheet edges, while the more central regions show far more subtle changes. These Greenland results underscore the importance of understanding the current behavior of the surrounding temperate ice caps.

Meaningful interpretation of the observations, however requires an understanding of the climate conditions in the region. Much of this information is available from coastal weather station data from the last 20 years from approximately 40 coastal weather stations in the region. However, a more complete interpretation requires some detailed knowledge of the in situ temperature, accumulation, and mass balance history. An understanding of the variability of these parameters over time, and the degree to which they are (or are not) anomalous during the time period that separates the repeat surveys is essential to assessing the significance of observed elevation changes, and understanding their causes.

Toward that end, collaborations have been established with various Canadian glaciologists, who have a fairly comprehensive set of relevant in situ observations spanning the last 40 years in some cases. These data sets and their intended uses are as follows:

Ice core data from 6 ice caps will provide long records of the accumulation history (mass input) and its variability over time for six major ice caps. Van der Veen (1993) has shown that the statistical significance of observed elevation changes made from repeat measurements separated by a time of n years is given as:

$$P(\Delta_1) = \frac{1}{2}[1 - erf \ (\frac{\Delta_1}{\sigma_c}\sqrt{\frac{n}{2}})] \qquad (1)$$

where $P(\Delta_1)$ is the probability that the observed changes in surface elevation are attributable to fluctuations in accumulation is greater than Δ_1, and σ_c is the standard deviation of accumulation. Using this relationship, data from these ice cores will be used to assess the statistical significance of the observed elevation changes. Moreover, the data will be used to assess the degree to which the accumulation during the 1995-2000 survey period has been anomalous.

Up to 40 years of mass balance measurements will provide information on the recent mass balance history and its variability over time. As with the ice cores, but on larger spatial scales, this information will be used to assess the statistical significance of the observed elevation changes and the anomalous nature of the 1995-2000 survey period, by adapting Equation (1) to account for mass balance rather than accumulation.

Automatic weather station observations from 12 stations will provide a recent temperature history in different ice cap zones, which can be used to approximate ablation through degree-day analyses. These data will also be used to assess the 1995-2000 climate characteristics for interpretation of the elevation changes and the role of ablation in these changes. In addition, the accumulation sensors mounted on nearly all of the stations will complement the ice core accumulation data.

Detailed elevation maps of White and Thompson Glaciers, developed from survey data in 1960 (Cogley et al., 1996). Will be compared to laser altimetry measurements This will allow assessment of a long-term elevation changes of two major drainage glaciers of the Müller Ice Cap on Axel Heiberg. Although this comparison will be somewhat limited by the accuracy of the earlier maps, the 40-year time separation between the different data sets should prove to be quite valuable.

Through a combination of the repeat laser altimetry surveys, and all of the ancillary data sets, elevation changes (if elevations have in fact changed) will be measured and interpreted in the context of the present and recent climate. Results from the Canadian ice cap missions will be an important complement to those from Greenland, and they will help provide a more complete picture of the current state of balance of the Arctic ice masses.

In addition, two sets of baseline data (with 5 years of separation between them) will be available for comparison to future GLAS observations, which, in its 183-day repeat orbit will have ground track separations in the vicinity of the ice caps of approximately 6 km for the more southerly ones, and 1.5 km for the more northern ones. Furthermore, the detailed topographic information will be useful for pre-launch simulation of laser-pulse return waveforms that GLAS will acquire over such ice caps. Because these ice caps are generally rougher and more steeply sloping than the large ice sheets, interpreting their waveforms may be more complex. These detailed topography measurements will improve these interpretations considerably.

4   FAST MOVING GLACIERS

4.1 Approach

For ice elevation change measurements, a series of surveys is made over an ice mass with the intent of resurveying the same flight lines at a later date. In the case of the Greenland ice sheet, these surveys were made during the spring of 1993 and 1994 for the southern and northern portions of the ice sheet respectively, and they were repeated in 1998 and 1999. Results for the southern half of Greenland have been published by Krabill et al., (1999), and the results from the north are pending. In 1997, a detailed grid of the Jakobshavn Isbrae was surveyed, during which time multiple measurements over or near the ice stream were made. Some tracks were exact repeats of others with a time separation of two to six days. These surveys provided the initial proof of concept of velocity

retrieval from ATM data (Abdalati and Krabill, 1999), which holds promise for highly detailed studies of individual glaciers.

The method for velocity determination relies on the tracking of distinguishable elevation features over time. Because the scanner, unlike a profiler, measures over a swath rather than along a single line, many features can be identified unambiguously in a single-survey, and again, somewhere downstream in a second survey. This requires that the terrain be of sufficient topographic variability (about one meter rms roughness), and the surface topographic characteristics are sufficiently preserved in the time period that separates the surveys. Moreover, if the repeat survey time separation is on the order of a few days, motion must be sufficiently rapid that measurement errors are small when compared to the motion signal. Largely crevassed, fast-moving glaciers, such as those found in some of the Greenland ice sheet drainage basins, are well-suited for such purposes.

In order to make comparisons between two sets of scanning surveys, the data must first be interpolated onto a consistent grid. We choose a 1 meter grid (roughly the size of a single laser shot) and perform an inverse distance weighting interpolation of the data within 7 meters of the grid point. 7 meters is chosen because for a normally operating scanner on an aircraft flying at 150 m/s, it represents one half of the largest linear gap in the data that should occur. Once the data from the pair of surveys are interpolated onto a consistent grid, their elevation features are compared to one another to determine the offset between features. This comparison is done using the method and software of Scambos et al., (1992). In the earlier of the two "images", a small sub-sample region, ranging from 16 to 128 pixels (meters in our case) on a side, is identified, and its nearest match in the second image, within a pre-defined search area, is found. The offset is determined and is then converted to a velocity by dividing the distance by the time elapsed between surveys.

Figure 2 shows an example of a segment of a pair of 1997 surveys in the Jakobshavn Isbrae (Location A in Figure 3) that are separated by six days (May 13th – May 19th). Distinct elevation features, crevasses in particular, are clearly visible in both elevation images with an easily detectable offset between the first and second. Superimposed on the image are arrows showing the magnitude of the offset between the two, and the corresponding velocity scale.

Some of the flight lines over the faster parts of the Jakobshavn area were repeated (twice) for velocity measurements again in 1998, along with two regions on the east coast (Figure 3). Coincident with the altimetry measurements were thickness measurements made with the University of Kansas ice-penetrating radar (Chuah, et al., 1996). In the cases where velocities and ice thicknesses can be successfully retrieved across a glacier, flux estimates can be made. Such estimates require sufficient swath width (in relation to flow rate) so that features can be matched across the width of the swath in the survey pairs. Retrieval of thicknesses in steep-walled glaciers, however is particularly challenging because of clutter in the

radar imagery due to reflections off the bedrock walls (S. Gogineni, personal communication). In the case of the Jakobshavn ice stream, thickness retrieval is further complicated by the extreme depth of the channel and the temperate character of the ice.
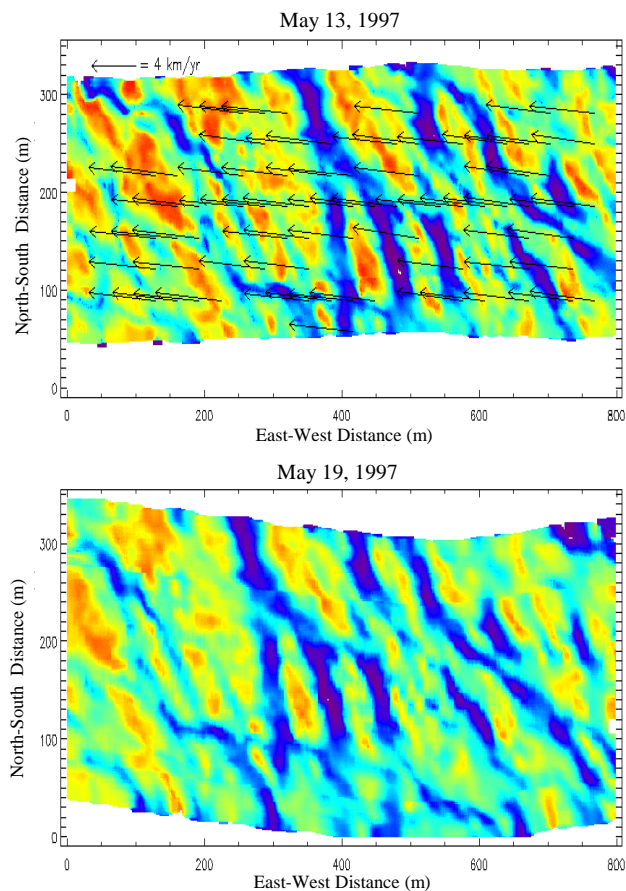

Figure 2. Interpolated elevation data from ATM measurements over a small section the Jakobshavn Ice Stream (location A in Fig. 3). Elevations range from a low of 88 m (blue) to a high of 113 m (red), and offsets of the features is apparent between the two images. The arrows represent the displacement over the intervening six days. Reprinted with some modification from Remote Sensing of Environment, Vol. 67, Calculation of ice velocities in Jakobshavn Isbrae area using airborne laser altimetry, W. Abdalati, and W.B. Krabill, pp. 194-204 Copyright (1999) with permission from Elsevier Science.

The 1998 flight trajectories are shown in Figure 3 along with the regions for which ATM-derived velocities were studied. The figure shows the Jakobshavn region in the west, where repeat surveys were made in 1997 and 1998, as well as two areas in the east, Kangerdlugssuaq Glacier, and the ice margin at 65°N.

4.2 Results and Discussion

Velocity vectors for the areas of survey pairs are shown in Figure 3, and the vectors are overlaid on ERS Synthetic Aperture Radar imagery (© European Space Agency, Copyright 1992). In the vicinity of the Jakobshavn Isbrae, the flow character is very clear in the flow vectors. The boundaries between the ice streams and the more stagnant ice are easily distinguished by the changes in direction and magnitude of the

flow vectors. The maximum velocity near the calving front is nearly 7 km per year.

Similar views are given for portions of the Kangerdlugssuaq Glacier and the ice margin near 65°N; however, the Jakobshavn transects yield the best results, as can be seen in Figure 3. This is because the region has the most distinct topography and these flights were flown on very clear days. Results could be

obtained in areas where the standard deviation of topography was on the order of approximately one meter (Abdalati and Krabill, 1999). Smoother surfaces do not produce sufficiently unique correlations in between the reference image sub-section in the first observation, and the search image sub-section in the second.

Results for the Kangerdlugssuaq region were very limited because on the dates of the later flights, low clouds inhibited
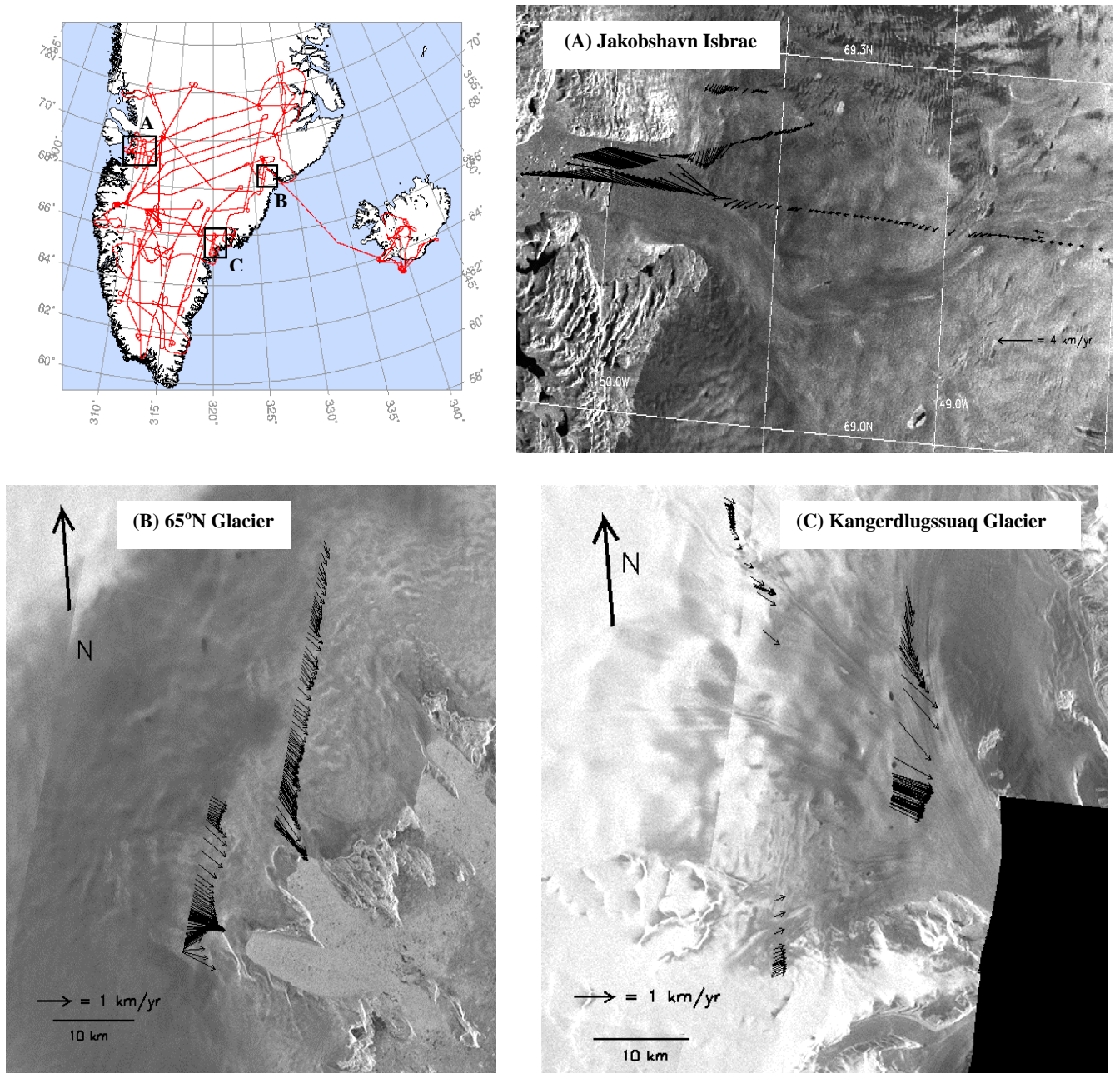

Figure 3. Maps of 1998 flight trajectory (upper left panel) identifying areas with multiple surveys during the 1998 field season (and 1997 in Case A, the Jakobshavn Isbrae) Retrieved velocity vectors are overlaid on ERS-1 SAR imagery in the other three panels. The SAR imagery is from the Digital SAR Mosaic provided by the EOSDIS NSIDC Distributed Active Archive Center at the National Snow and Ice Data Center a he University of Colorado at Boulder. The mosaic was assembled from ERS-1 SAR (© European Space Agency, Copyright 1992), by M. Fahnestock and R. Kwok). The upper right panel is reprinted from Remote Sensing of Environment, Vol. 67, Calculation of ice velocities in Jakobshavn Isbrae area using airborne laser altimetry, W. Abdalati, and W.B. Krabill, pp. 194-204 Copyright (1999) with permission from Elsevier Science.

the collection of elevation data along many parts of the transects, leaving many gaps in the elevation data. Those areas for which estimates could be made are indicated with velocity vectors. In these areas, details of the flow character are clear, but the failure to retrieve velocities over part of the eastern flight line, and nearly all of the western flight line demonstrate one of the limitations of using laser altimetry for velocity estimates – the weather.

Results on the northeastern line at the 65°N ice margin show roughly parallel flow along the transect with some local areas of varied direction. In the southern portion of that same line, velocities are almost 1.4 km/yr. The southwestern flight line shows well-developed flow emptying into the basin with a maximum velocity of nearly 1.2 km/yr. Such flow rates are unusual, given the fact that the ice in this region appears to have the characteristics that are more like an ice sheet margin rather than an outlet glacier.

The results of the ATM-derived velocity estimate indicate that for sufficiently rough surfaces, detailed velocities can be retrieved along essentially a straight line. While such an application is not very useful for large-scale ice sheet studies, it is quite useful for detailed glacier studies (either for outlet glaciers in Greenland, or for smaller mountain glaciers). Because the elevation characteristics are accurately measured with the ATM, a three-dimensional velocity field can be retrieved. Moreover, when combined with thickness data, generally collected coincidentally using an airborne ice penetrating radar (Chuah, 1996), velocities derived from cross-glacier passes allows for the calculation of ice fluxes.

A series of passes up an down a glacier would provide a complete description of velocity fields, and subsequently the full strain-rate tensor could be derived. In this way, the surface flow mechanics of an entire glacier could be quickly characterized. To make similar observations manually would be extremely difficult, if not impossible. For practical purposes, however, such an application of the ATM would require that the instrument be mounted on a more maneuverable aircraft than the P-3 that is currently used for the Greenland surveys. The capability of conducting topography surveys from a more agile Twin Otter platform using the ATM has been clearly demonstrated through a series of beach-mapping missions along most of the United States' east, west, and Gulf coasts. Thus the application of the ATM for detailed surveys of smaller glaciers is quite feasible.

5   SUMMARY

Building on the success that the Arctic Ice Mapping Program has achieved for Greenland, the prospect for obtaining important information on the state of balance of the Canadian ice caps is quite good. Their smaller mass, in contrast to that of the Greenland ice sheet makes them more likely to respond to climate changes. A combination of these observations with the in situ data that the Canadian researchers are providing, will also allow an assessment of the significance of the observations, and the relative contributions of ablation and accumulation to the ice cap mass balance. By quantifying their current mass balance, a clearer picture of the large-scale response of the Arctic to the changing climate will be obtained. The results from Canada are expected to provide useful insight to the results obtained for Greenland, and those from Greenland should be useful for the interpretation of the Canadian data as well.

For more detailed studies of smaller glaciers, the ATM observations show considerable potential, with the capability of velocity determination based on the tracking of the movement of elevation features. It is this measurement of detailed elevation characteristics, as opposed to just visible features, that allows a three-dimensional velocity field to be retrieved. For future applications, a series of passes up an down a glacier would provide a complete description of velocity fields and subsequently the full strain-rate tensor. In this way, the surface flow mechanics of an entire glacier could be quickly characterized. The success of the ATM beach mapping missions on a Twin Otter platform suggest that such a program for detailed glacier studies is quite feasible.

6   REFERENCES

Abdalati, W. and W.B. Krabill, 1999. Calculation of ice Velocities in the Jakobshavn Isbrae area using airborne laser altimetry. *International Journal of Remote Sensing*. 67, 194-204.

Chuah, T.S., 1997. Design and development of a coherent radar depth sounder for measurement of Greenland ice sheet thickness. RSL Technical Report 10470-5. The University of Kansas Remote Sensing Laboratory, Lawrence, KS. U.S.A.

Krabill, W.B., R.H. Thomas, C.F. Martin, R.N. Swift, and E.B. Frederick, 1995. Accuracy of airborne laser altimetry over the Greenland ice sheet. *International Journal of Remote Sensing*. 16(7), 1211-1222.

Krabill, W.B., E. Frederick, S. Manizade, C. Martin, J. Sonntag, R. Swift, R. Thomas, W. Wright, and J. Yungel, 1999. Rapid thinning of parts of the southern Greenland ice sheet. Science, 283, 1522-1524.

Cogley, J.G., W.P. Adams, M.A. Ecclestone, F. Jung-Rothenhausler, and C.S.L. Ommanney, 1996. Mass balance of White Glacier, Axel Heiberg Island, N.W.T., Canada 1960-1991. *Journal of Glaciology*, 44, 315-325.

Scambos, T.A., M.J. Dutkiewicz, J.C. Wilson, and R.A. Bindschadler, 1992. Applications of image cross-correlation to the measurement of glacier velocity using satellite data. *Remote Sensing of Environment*, 42, 177-186.

Van der Veen, C.J., 1993. Interpretation of short-term ice sheet elevation changes inferred from satellite altimetry. *Climate Change*, 23, 383-405