Airborne Laser Altimetry Mapping of the Greenland Ice Sheet: Application to Mass Balance Assessment

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For submission to *Journal of Geodynamics* special issue on Laser Altimetry

Popular Summary

In 1998 and '99, the Arctic Ice Mapping (AIM) program completed resurveys of lines occupied 5 years earlier revealing elevation changes of the Greenland ice sheet and identifying areas of significant thinning, thickening and balance. In planning these surveys, consideration had to be given to the spatial constraints associated with aircraft operation, the spatial nature of ice sheet behavior, and limited resources, as well as temporal issues, such as seasonal and interannual variability in the context of measurement accuracy. This paper examines the extent to which the sampling and survey strategy is valid for drawing conclusions on the current state of balance of the Greenland ice sheet. The surveys covered the entire ice sheet with an average distance of 21.4 km between each location on the ice sheet and the nearest flight line. For most of the ice sheet, the elevation changes show relatively little spatial variability, and their magnitudes are significantly smaller than the observed elevation change signal. As a result, we conclude that the density of the sampling and the accuracy of the measurements are sufficient to draw meaningful conclusions on the state of balance of the entire ice sheet over the five-year survey period. Outlet glaciers, however, show far more spatial and temporal variability, and each of the major ones is likely to require individual surveys in order to determine its balance.

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Submitted June, 2000 to *Journal of Geodynamics* special issue on Laser Altimetry

Introduction

The Greenland ice sheet, a remnant of the Pleistocene, is the largest ice mass in the northern hemisphere. Spanning an area of 1.75×10^6 km^2, and rising to an elevation of approximately 3200 m, it plays an important role in the regional and global climate systems through its exchange of energy, moisture, and momentum with the atmosphere. Moreover, with a volume of 2.95×10^6 km^3 (8% of the world's total glacier volume) it contains enough ice to raise the present sea level by more than 7 m (Warrick et al., 1996). The importance of Greenland in the changing climate and its potential impact on sea level are underscored by the fact that the high latitude regions of the earth are believed to be particularly sensitive to climate change (Mitchell et al., 1990). In contrast to the ice sheet in Antarctica, that in Greenland experiences extensive summer melting, which is responsible for an estimated 60% of its total mass loss (Weidick, 1985). Because Greenland is much more temperate than its austral counterpart, and because the arctic is believed to be more sensitive to climate change than the Antarctic, the near-term contributions of the Greenland ice sheet to sea level rise are of great concern. Consequently, it is important to understand the state of balance of the Greenland ice sheet, and its response to a changing climate.

Much of an ice sheet's characteristics are manifest in its shape. The thickness and surface slopes of ice sheets and glaciers are a response to conditions of flow and balance, while changes in these characteristics are a direct measure of the mass balance. For this reason, much attention has been paid in recent years to mapping the elevation of the more comprehensive assessment of ice sheet thickening/thinning at lower elevations, and for major outlet glaciers. Such measurements are crucial to understanding and interpreting the ice sheet mass balance. Prior to the AIM program, these areas were not reliably included in large-scale mass balance studies.

In this paper we discuss recent airborne laser surveys of Greenland ice sheet elevations and elevation changes, and assess the extent to which the survey strategy was effective. Areas that received sufficient coverage for glaciological interpretation are identified, but more importantly, areas requiring more detailed surveys and improved sampling are also defined. Factors that determine spatial coverage necessary to assess mass changes are also discussed.

Airborne Topographic Mapper (ATM)

The instruments used for the AIM surveys are two versions of the Airborne Topographic Mapper (ATM-1 and ATM-2) flown on the NASA P3-B Orion aircraft. These sensors combine high pulse-rate laser ranging (up to 5000 Hz) with a scanning capability (Krabill et al., 1995). The ATMs are currently operated with Spectra Physics TFR laser transmitters, which provide a 250 μJ pulse that is 7ns wide at a frequency-doubled wavelength of 523 nm in the blue-green spectral region, or with Continuum EPO5000 transmitters, which provide a 125 μJ pulse that is 1.5ns wide at a frequency-doubled wavelength of 532 nm, also in the blue-green spectral region. The scanning is achieved

Measurement Strategy

Spatial considerations

Elevation surveys require a representative sampling that provides the most effective coverage for the limited resources. Sampling across topographic boundaries (Figure 1) is necessary because regions on opposite sides of major ice-sheet ridges are subject to different climate and flow conditions. Spatially homogenous areas, such as the smoother high-elevation regions of the ice sheet (generally above 2000 meters), require less detail than the lower elevations which generally have more varied topography and dynamic flow characteristics. Consequently, for the purpose of change detection, less coverage is required at higher elevations, where essentially the only significantly variable mass balance term is accumulation, which in general is relatively low (Ohmura and Reeh, 1991), and flow rates are small and unlikely to change over the time period between surveys. More measurement detail is needed at lower elevations, where accumulation rates are greater and more variable, melting becomes a significant balance term, and flow is more dynamic. This becomes especially important in the fast-moving, high-ablation outlet glaciers. As a result, the desired sampling density for each topographic/climatologic zone is such that sampling should increase with decreasing elevation. Moreover, as each outlet glacier is unique, periodic surveys of each major outlet glacier would be desirable. However limited resources requires a prioritization, with the highest-discharge glaciers taking precedence. Among these are Jakobshavn

Temporal sampling is a critical component of the change-detection measurement strategy, both in terms of the time interval between surveys, and timing of the surveys within the annual cycle of mass loss and gain. Given the stated accuracy of the surveys, a detected change of less than 10 cm is within the measurement errors and is therefore not considered significant.

Even changes in excess of 10 cm may be a part of the natural variability of ice sheet surface elevation, as conditions do not remain constant from year to year, but rather fluctuate. Consequently, selecting a time interval of sufficient length is necessary such that the effects of natural variability can average out over time. Van der Veen (1993) showed that the probability that the observed signal may be attributable to natural fluctuations in accumulation exceeds Δ_l is:

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

where the number of years between surveys is n, and σ_c is the standard deviation of the interannual accumulation rate. Using this relationship for the Summit area of the Greenland ice sheet, where σ_c is small, Van der Veen and Bolzan (1999) showed that a five-year time interval separating surveys is sufficient to identify a climate signal, and that little is gained by longer time separations. It follows from Equation 1, however, that the likelihood that an observed elevation change is attributable to something other than natural fluctuations is strongly tied to the magnitude of the change in relation to the backdrop of the interannual balance variability; i.e. the more variable the net annual balance, as is the case further south and at lower elevations, the greater an observed

Prior to these surveys, very little was known about the actual elevation change rates on the ice sheets, with the exception of some strongly contested satellite radar altimeter analyses of the higher elevations (Zwally et al., 1989). Consequently, in addition to providing intrinsic dh/dt information, these surveys yielded reconnaissance data at coarse resolution that can be used to identify areas of most significant change, which could then be the focus of more detailed studies in the future.

The chosen survey flight trajectories are shown in Figure 1. They were planned in the early 1990's without any foreknowledge of the patterns of thickening and thinning, and reflect our best efforts to balance spatial and temporal considerations, with feasibility and resource issues. The time interval selected between repeat surveys was 5 years, with the southern regions (south of 71°N) surveyed in 1993 and again in 1998, and the northern areas (north of 71°N) in 1994 and 1999. The size of the ice sheet made coverage of the entire ice sheet in a single year impractical.

To minimize the effects of seasonal variability, the surveys were planned for May of each year, prior to the onset of melt. However, the 1993 and 1998 surveys of the southern Greenland ice sheet could not be made until late June/early July because of necessary aircraft maintenance and availability issues. Fortunately, these surveys were made at the same time of year relative to each other, so differences due to the seasonal effects are believed to be minimal, particularly at the higher elevations.

throughout the southeast (as far north as Kangerdlugssuaq), southwest (south of Kangerlussuaq) and northwest (between Jakobshavn and Thule), has been observed (Krabill et al., in press). In these cases, it is likely that the glaciers and ice sheet margins between these surveys are behaving similarly in a qualitative sense, but quantitative assessments will require detailed surveys of each glacier.

To assess the degree to which the dh/dt measurements shown in Figure 2 adequately describe the ice sheet elevation changes, it is necessary to gauge the distance over which dh/dt measurements themselves (Fig. 3) were spatially coherent. In areas where the variability between dh/dt measurements is low, the separation between flights can be large, and while conversely, in areas where the variability is found to be high, flight line spacing must be small. To estimate variability, we examined, for each grid point, the standard deviation of all measured values of dh/dt within a distance of 22 km – approximately the average distance from points on the ice sheet to the nearest flight line. Results are shown in Figures 4 and 5. We assume the along-track dh/dt variability to be representative of all directions, which is supported by general consistency in different directions at crossover points. We further assume that the areas between the measurements behave similarly to those locations where the observations were made. The elevation change characteristics of the ice sheet are sufficiently small that errors associated with these assumptions are likely to be small. Closer to the margins, these assumptions are less valid; however, in these regions we sampled some of the most variable features and, therefore, have a reasonable upper bound on the dh/dt standard deviations.

sheet, even at low elevations, sampling is sufficient, in an average sense, to characterize the elevation changes.

Outlet glaciers are more difficult to characterize. As each of these individual glaciers may be subject to unique balance conditions, sufficient understanding of the behavior of each cannot be interpolated or extrapolated using data from nearby surveys. For example, some glaciers show thinning rates of several m per year, such as Kangerdlugssuaq (Thomas et al., 2000), while at nearby locations, e.g. King Christian IV Glacier, 100 km to the East, thinning rates are nearly an order of magnitude lower. In parts of western Greenland, thinning glaciers are in close proximity (100 km) to thickening ones (Krabill et al., in press). Furthermore, the thickening/thinning behavior observed with the surge of Storstrommen Glacier (Reeh, et al., 1994) is not at all indicative of the behavior of other glaciers in the vicinity, that have not surged. It is clear that individual detailed surveys are needed to adequately characterize the behavior of individual outlet glaciers, which collectively are responsible for roughly an estimated 40% of the ice sheet mass loss (Weidick, 1985).

Conclusion

Prior to the AIM program, there was considerable debate over the state of balance of the higher elevation regions of the Greenland ice sheet, and virtually nothing was known about mass balance at the more dynamic lower elevations. The AIM program has not

The role of airborne laser elevation surveys in the future is likely to focus more specifically on the study of the outlet glaciers. With the planned launch of the Ice Cloud and Land Elevation Satellite (ICESat), coverage of the ice sheet will be very dense, with laser shots fired approximately every 175 m in the along-track direction. Ground tracks will be approximately 7 km apart near the southern tip of Greenland, and near the northern ice sheet margin, separation will be 2 km. Moreover, the capability of ICESat to make measurements on relatively steep slopes will provide excellent coverage of most of the main ice sheet, including the lower elevations, which are changing rapidly. However, while some information about outlet glacier elevation changes will be retrievable, the ground tracks will be limited. Efforts to understand the detailed behavior of the mechanisms that affect discharge will require targeted airborne surveys along the glaciers, with trajectories specifically tailored to each.

Acknowledgements

This research was supported by NASA's Polar Research Program. We would like to thank the crew of the NASA P-3 aircraft used for the Greenland surveys.

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m (shown in green), the variability is much greater, and a larger dh/dt signal is necessary in order to be determined significant. The combined results are shown in black.

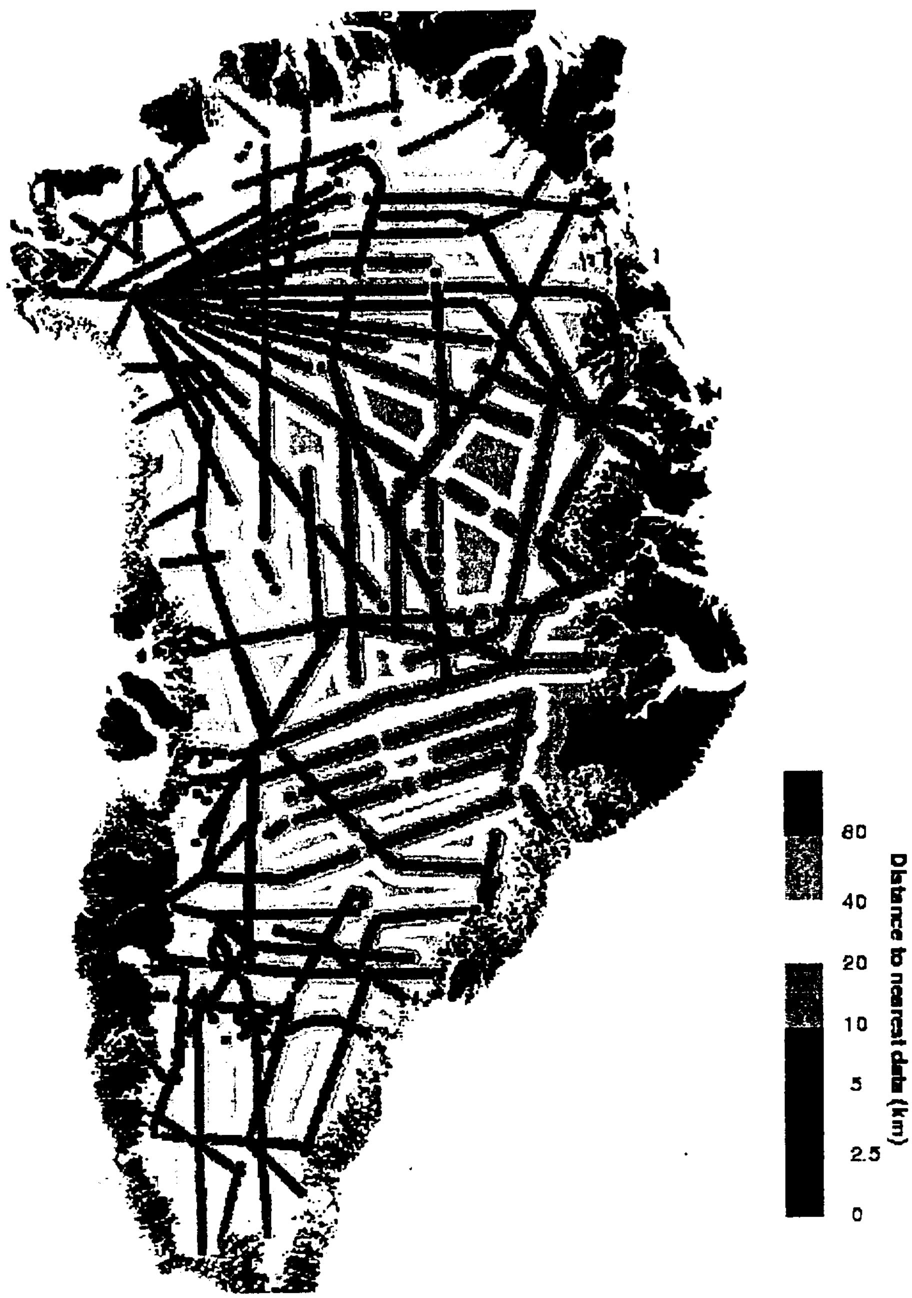

Figure 2

Figure 4