COMPARISON OF RADAR-ALTIMETRY DATA OVER GREENLAND WITH SURFACE TOPOGRAPHY DERIVED FROM AIRBORNE LASER ALTIMETRY

R H Thomas¹, W Krabill², S Manizade³, R Swift³, and A Brenner⁴

¹Code YS, NASA HQ, Washington DC 20546; ²NASA/Wallops Flight Facility; ³EG&G; ⁴Hughes STX

ABSTRACT

During the summers of 1991, 1992 and 1993, NASA flew a scanning laser altimeter over transects of the Greenland ice sheet. Airplane location was measured precisely using differential Global Positioning System (GPS) surveying techniques, allowing all altimetry data to be reduced to estimates of ice-surface elevations relative to the Earth ellipsoid. Repeat flights over the same areas indicate data consistency to 10-20 cm. Many of the aircraft flights were made along the ERS-1 "radar-altimeter footprint track" for a commissioning-phase orbit. Rigorous comparison between the ERS-1 altimeter measurements and those from the laser altimeter will require analysis of individual ERS-1 altimeter waveforms and we have not yet received the information needed to do this. Consequently, we present here results from comparison of TOPEX/POSEIDON (T/P) radar-altimetry data with laser data obtained at the northernmost limit of the T/P orbits.

Keywords: Altimetry; ice sheets; Greenland; laser

INTRODUCTION

The ice sheets of Greenland and Antarctica contain enough water to raise sea level by some 70 meters but we do not yet know whether these ice sheets are contributing to sea-level rise. Available glaciological data suggest that they are in balance to within an equivalent sea-level rise or fall of about 3 mm per year. This large uncertainty is partly because the ice sheets are very large and very remote, but also because mass-balance is generally computed by comparing estimates of total snow accumulation with estimates of total loss, by both melting and ice discharge - the comparison of two very large numbers, each of which has significant errors.

A more direct indication of ice-sheet mass balance can be obtained by comparing repeat measurements of many surface-elevation profiles across the ice sheet. Such profiles can be estimated from satellite radar-altimetry data (Ref. 1), and by comparing data obtained at points where orbit tracks from one survey cross those from an earlier survey, Zwally et al (Ref. 2) conclude that, south of 72° N, the Greenland ice sheet thickened by 1.3 meters between 1978 and 1987 - an average of 15 cm/year. This result has not yet been confirmed by estimates of ice-sheet mass balance based on more conventional approaches. Potential errors include orbit errors, radar penetration into the surface snow, and errors introduced by differences in the characteristics of the radar altimeters on different spacecraft. Although orbit errors were minimized by referring all measurements to the ocean surface around Greenland there is an urgent need to validate the radar measurements of ice topography, and to obtain independent estimates of ice thickening/thinning rates.

In September 1991, April 1992, and June/July 1993, NASA flew laser-altimeter missions over Greenland. Initially, the objective was to determine whether ice-surface elevations can be measured from an aircraft to the accuracy needed to detect ice thinning or thickening, but we also made several flights along an ERS-1 Commissioning Phase orbit (Fig 1) in order to compare the laser-derived ice surface with that obtained from the radar altimeter data. Delays in obtaining the data needed to make a rigorous intercomparison led us to include, during the 1993 campaign, flights along the northern limit of TOPEX/POSEIDON (T/P) coverage. In this paper, we describe the approach planned for intercomparison of the laser and ERS-1 data, and we present early results from intercomparison of the laser and T/P data.
We used a conically scanning laser - the Airborne Oceanographic Lidar (AOL). This has the advantage of providing a swath of measurements beneath the aircraft, and the disadvantage of magnifying the effect of errors in aircraft attitude, which consequently must be known to within a few hundredths of a degree. The laser beam of the AOL is deflected by a nutating mirror to produce an elliptical spiral of data points as the aircraft moves forward. This provides elevation estimates within a swath of diameter approximately half the aircraft ground clearance. In 1991, we operated 400 meters above the surface, giving a swath width of 200 meters. At this height, the laser spot on the surface had a diameter of about 0.6 meters. In 1993, we operated the laser at a smaller scan angle and a higher elevation (600 meters) so that the swath width was still approximately 200 meters. However, we were using a larger beam divergence, giving a spot size of 2 meters. The laser pulse rate was 800/second, with 5 conical scans per second. Ranges were calculated from the time interval between laser-pulse transmission and receipt of the reflected pulse. The error of measured ranges is estimated to be less than 10 cm. The aircraft flew at approximately 110 meters/second providing a very dense, irregular array of data points within the scanned swath. The maximum along-track distance between adjacent points was about 20 meters, with a cross-track separation of less than 4 meters.

Knowledge of the airplane location to within approximately 10 cm was achieved using kinematic GPS (Ref. 3), tracking the difference in the phase of the two GPS L-band carriers between a fixed receiver located over a precisely known benchmark and a mobile receiver located in the aircraft. Aircraft attitude was obtained from the Inertial Navigation Unit (INU), which was calibrated using data collected over the ocean. In addition, data from three widely separated GPS antennae aboard the airplane were used to provide inflight monitoring of INU drift.

In order to provide an independent set of data against which to compare aircraft-derived estimates of surface elevation, we optically levelled a 42-km traverse running approximately NNE from 69.8N, 47.1W (figure 1). Estimated levelling errors along the entire traverse are less than 5 cm. The

Figure 1. Aircraft laser-altimetry flights over Greenland along an ERS-1 commissioning-phase orbit, and within the region covered by TOPEX/POSEIDON (T/P) orbits. The aircraft flew out of Sondrestrom air base (S), and the 42-km optically-levelled traverse was centred on Latitude 70° N.

MEASUREMENTS

The NASA P-3 aircraft operated out of Sondrestrom Air Base (Fig 1) and was equipped with Global Positioning System (GPS) receivers, two laser altimeters, a radar altimeter operating at Ku band and, in 1993, a low-frequency radar to measure ice thickness. The GPS receivers were used in a differential mode, with receivers at Sondrestrom, to provide aircraft locations continuously during flight. Optical levelling along a 42-km traverse on the ice-sheet surface provided independent information against which to compare the aircraft measurements of surface topography. Several flights were made over the surface-levelled traverse, and along a radar-altimeter footprint track of the European Space Agency's Remote Sensing satellite (ERS-1) which carries a radar altimeter operating at Ku-band. Flights were also made along parallel tracks, offset from the main track by 1 and 2 km, thus mapping the surface topography within a 4-km band along the radar-footprint track.
results of this intercomparison are still preliminary but they suggest that the AOL-derived surface elevations are accurate to better than 20 cm. The accuracy of 1991 data is limited, primarily by the number of GPS satellites then available for tracking. The impact is to degrade the accuracy of derived ice topography with increasing flight time. In 1992 and 1993, this aspect of the experiment progressively improved as more GPS satellites were launched. Moreover, we have continued to discover small corrections that can be applied to the AOL data to effect further improvements. However, we believe that this stage of the experiment is approaching closure, and that we have detected all the significant sources of error. We are currently making a definitive comparison between the 1991 airborne measurements and data from the optically-levelled traverse along the flight track. The results presented here are from a 1993 flight that included several crossing points. Data at these locations indicate an internal consistency at the 10-cm level.

RESULTS

Figure 2 shows a section of the ERS-1 altimeter-footprint track, the airplane tracks along which AOL data were collected, and a series of transverse profiles derived from these data. The ERS-1 altimeter wavefront is also shown. Knowing the precise orbit of the satellite, we can simulate the interaction of successive wavefronts with the ice surface and reproduce return waveforms. Comparison of these with the actual waveforms will allow us to assess the accuracy of satellite radar altimetry for measuring ice-sheet topography, and to investigate the effects of penetration into the surface snow. Unfortunately, we have not yet received the ERS-1 data needed for this study, and here we present results from intercomparison of 1993 AOL data with ice surface elevations derived from T/P measurements.

Figure 1 shows the T/P orbit tracks across southern Greenland, with the flight track of the NASA P-3 superimposed. The T/P data were retracked using the technique developed at Goddard Space Flight Center (GSFC) and described by Martin et al (Ref. 1). Figure 3 shows two sections of a P-3 flight line that crossed four T/P orbit tracks almost tangentially, and that were within a few hundred meters of the orbit tracks for a total distance of more than 100 km. The aircraft and orbit tracks run east-west, crossing elevation contours almost at right angles.

Figure 3 also shows the AOL-derived and T/P-derived surface profiles and the T/P altimeter beam front, and it is readily apparent that the altimeter first return generally comes from a location upslope from the nadir point. Even over the shallow slopes depicted here (3X10^{-3} and 5X10^{-3}), the T/P-derived ice surface is well above the actual ice surface. Consequently, we have included the surface profile that T/P should produce if the altimeter retracking yields ranges to the closest portion of ice sheet within the T/P beam front, and assuming zero slope in a north-south direction. This agrees extremely well with the actual T/P data points, which were obtained from all data along the orbit tracks in Figure 3 that were acquired from mid June to mid July 1993, including two or three repeat sets of data along each orbit. The repeat-track data are internally consistent to within a few tens of
Figure 3. The lower panels show the laser-altimetry flight track (solid lines) crossing four T/P orbit tracks (broken lines). The upper panels show the corresponding laser-derived (solid lines) and T/P-derived (dotted lines) surface profiles. The large T/P beam front yields "closest-point" measured ranges - generally to locations uphill from satellite nadir. The circles indicate a theoretical T/P-derived surface equivalent to the actual ice topography, assuming zero surface slope normal to the profile.

cm, but a preliminary crossing-point analysis of all Greenland T/P data from this period shows considerable scatter and an apparent bias of about 0.5 meter between surface elevations derived from ascending and descending orbits. At this time we have no explanation for this.

DISCUSSION

The excellent agreement between theoretical and actual T/P-derived ice surfaces in Figure 3 suggests that T/P-measured ranges over ice, retracked by the GSFC algorithm, provide a reliable estimate of the range from the satellite to the closest surface within the altimeter footprint. Uncertainties in the T/P data and, more seriously, in cross-slope effects on the T/P data, prevent us from assessing whether radar penetration is significantly affecting the T/P-derived elevations. The T/P data include results from both Ku- and C-band transmissions, and these do not display obvious differences, but we would expect radar penetration to be minimal during June/July, when the surface snow is often wet at this latitude, and we have not made a detailed analysis of the waveform shapes.

With the available data we can say only that the T/P- and laser-measured ranges agree at the sub-meter level. Clearly, of course, all satellite radar measurements include a large slope-induced error, and we suggest that this can be corrected only if the surface
topography is already known. Correction for local or regional slopes is not adequate; first reflections are generally from the crests of undulations. Nevertheless, comparison of data from different missions may give reliable estimates of ice thickening/thinning rates, because slope-induced effects should be common to both sets of data. But even these results must be viewed with caution for these reasons:

- The height of the satellite orbit determines where on the ice sheet the first radar return will come from; slope-induced errors are not the same, even at orbit-crossing points, for two satellites in orbits with different altitudes.

- It is highly probable that altimeter characteristics, such as satellite-attitude control, radar frequency, altimeter beam width, pulse length, and onboard return-pulse tracking software, all influence the ranges measured over ice.

For these reasons, it is important to complete the detailed analysis that we planned using ERS-1 data. This will require access to the ERS-1 data collected during August/September, 1991 over the region that we mapped with the AOL in sufficient detail to allow full account to be taken of the effects of surface topography on the altimeter data.

Our future plans call for systematic airborne surveys of the entire Greenland ice sheet, with the objective of measuring thickening/thinning rates over an approximately 5-year interval. Figure 4 shows all the flight tracks covered so far, most of them during June/July 1993. These flight tracks include many crossing points, and each flight included a 50-km section that was overflown by every flight. If analysis of these data demonstrates consistency at the 20-cm level or better, we plan to survey the northern part of the ice sheet in 1994, with a view to repeating all flight lines after a five-year interval.

![Figure 4. NASA laser-altimetry flight tracks over southern Greenland.](image)

**Acknowledgements**

We thank all those who helped make the aircraft-altimetry measurements, and we thank John DiMarzio for preparing the T/P data sets used in this work. Funding support was provided by the NASA Polar Research Program.

**REFERENCES**

