International Archives of Photogrammetry and Remote Sensing, Volume XXXIV-3/W4 Annapolis, MD, 22-24 Oct. 2001

LASER MONITORING OF ICE ELEVATIONS AND SEA-ICE THICKNESS IN GREENLAND

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KEY WORDS: Laser altimetry, laser scanning, SAR interferometry, glaciers, sea-ice.

ABSTRACT

A low-cost Twin-Otter based laser altimetry and scanning system have been set up by KMS in several different commercial aircraft, and flown extensively in connection with airborne gravity activities in the Arctic Ocean north of Greenland, as well as on various research projects on the ice sheet and coastal glaciers in Greenland. The hardware system is based on a Riegl laser swath scanner or Optech laser altimeter combined with numerous GPS receivers. Roll and pitch are provided by either a medium-grade commercial INS or a low-cost custom-made IMU with fiber-optics gyros. The whole system is designed for use on non-dedicated aircraft, with a minimum of set-up time. In the paper we outline the hardware setup, processing schemes and give some examples of field campaigns and estimated accuracies. Measurements over sea-ice in the Polar Sea north of Greenland have shown that sea-ice freeboard can readily be measured combining laser altimetry and a local geoid model, yielding an indirect measurement of sea-ice thickness. Over land ice laser results have, a.o., been used to study radar penetration effects of airborne SAR interferometry, showing large height-dependent variations, corresponding to changes in snow facies.

1 INTRODUCTION

Airborne remote sensing is an efficient way to determine the elevations of the Greenland ice sheet, the surface elevations representing a delicate balance between ice flow, firn compaction, precipitation, and ice flow. The heights of the ice sheet may be determined by numerous methods: GPS and surface surveys, satellite altimetry, airborne laser altimetry and airborne or satellite SAR interferometry. Each of the methods has different accuracy and effective footprint size, and the radar methods further have varying degree of penetration into the firn.

In this paper we will primarily describe the gradual evolvement of a low-cost, easy-to-install airborne remote sensing system, used in commercial non-dedicated charter aircraft. The system has evolved slowly since 1996 based on experience from an airborne gravity and geoid project (AGMASCO, cf. Forsberg et al., 1996), smaller national Danish ice sheet mapping projects (Keller et al., 1997; Lintz et al., 1999), and a major program to map the marine areas around Greenland and Svalbard with airborne gravimetry, carried out with support mainly from the US National and Imagery Mapping Agency (Forsberg et al., 2001).

In the sequel we outline a few examples of Greenland laser projects, mainly carried out in connection with climate-related research projects in local areas. For different regions operations have been carried out in cooperation with the Technical University of Denmark (Danish Center for Remote Sensing), and the glaciological groups of the University of Copenhagen, and the Geological Survey of Denmark and Greenland. We especially have used laser methods in connection with satellite and airborne SAR interferometry, and give an example of the validation of the performance of the DTU EMISAR system (Madsen et al., 1996) for mapping ice sheet heights by intercomparison to laser heights. We will also give some examples of the potential of airborne laser measurement of sea-ice freeboard heights, allowing the measurement of ice thickness through assumptions of isostatic equilibrium. The sea-ice freeboard data have been collected since 1998 as a by-product of airborne gravity measurements in the sea-ice of the Polar Sea north of Greenland and the Fram Strait.

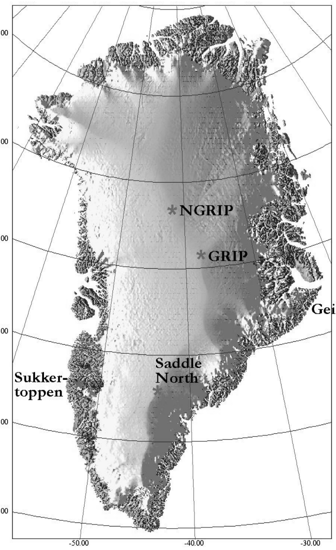

Fig. 1. Main ice sheet field sites

2 HARDWARE SYSTEM SETUP

The KMS airborne laser system has been set up to be easily installable in various airplanes. In Greenland most installations have been done in a Greenlandair Twin-Otter (OY-POF), normally used as a freight airplane (Fig. 2). The aircraft is for survey flights equipped with 2-3 geodetic GPS receivers, sharing two GPS antennas mounted on top of the aircraft. Attitude of the aircraft is determined by inertial sensors: For early flights (1996) a clinometer assembly was used, which together with horizontal GPS accelerations allowed a crude roll and pitch to be estimated; in 1997 a low-cost strap-down prototype fiber-gyro IMU (Inertial Measurement Unit) made by Greenwood Engineering was added to the system; and finally in 2000 a proper medium-grade INS (Honeywell H-764G) was used for superior determination of attitude angles. The H-764G incorporates an embedded GPS receiver, making time synchronization much simpler than in the early flights.

Fig. 2. Twin-Otter aircraft at Station Nord, May 2001

Laser units flown include single-beam laser altimeters from Optech, Inc., and – since 2001 – a swath laser scanner manufactured by Riegl, Austria. The Riegl scanner is a linear scanner used a rotating mirror, generating a software-controllable linear cross-pattern. In the sea-ice tests north of Greenland and tests in Denmark reported here a 40 Hz scan rate and 8kHz data rate is used, which at 1000 ft flight elevation and typical airspeeds corresponds to a distance between points on the ground of roughly 1.5 m.

All laser and INS data are logged on laptops and partially also on an integrated data logger and IMU control unit, manufactured by Greenwood Engineering. For airborne gravimetry a modified Lacoste and Romberg marine gravimeter (S-99) is added to the system. Other equipment flown includes ice-penetrating radar, fed from a simple dipole antenna mounted through a tie-down point through the aircraft tail. Depending on the project, equipment is typically installed in 1-2 days, and operated in flight by a single person. On some Danish tests with other aircraft (two different photogrammetric planes) installation times have been as low as a few hours.

3 LAND ICE APPLICATION EXAMPLE

To study the performance of airborne SAR interferometry, a laser survey and surface GPS survey including a strain net and positioning of radar corner reflectors was done on the Geikie Ice Plateau, East Greenland. The measurements were done in cooperation with the Danish Center for Remote Sensing, cf. Dall et al., 2000.

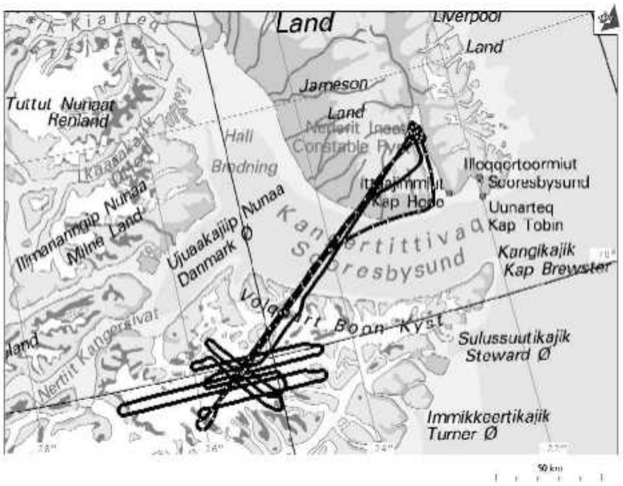

Fig. 3. Airborne laser tracks, Geikie ice cap

The Geikie ice plateau is an elongated, narrow ice-dome, located at more than 2000 m elevation on top of the northern terminus of the steep tertiary basalt province just south of Scoresbysund. It is a region of extreme topography and the poorest mapped part of Greenland. The Geikie operations took place 1996-98, and included repeated GPS measurements at the assumed top of the plateau and four surrounding points, repeated mapping by airborne laser altimetry, and the positioning by GPS of corner reflectors for airborne SAR operations. In addition a shallow ice core was extracted and the subsurface bedrock mapped by ice radar. Due to weather and logistical constraints not all repeated measurements were carried out as planned, and evaluation of results are still ongoing.

Fig. 4. Radar reflector on Geikie ice cap

The Geikie ice cap shows very large changes in ice velocity and elevations due to the fairly high yearly accumulation (3-4 m of snow). It is therefore a special target area for the investigations of SAR interferometry, and both elevation- and ice velocity models have been derived based on ERS tandem mission SAR interferometry combing descending and ascending passes using the method of Mohr et al. (1997). The conversion of the SAR satellite data into heights and velocities are complicated significantly by the extreme topography (south of Geikie some valleys are flanked by 1000 m vertical walls), which produce radar shadows and layovers, and makes the unwrapping of interference fringes ambiguous.

Fig. 5. G3 with EMISAR XTI radar

Airborne SAR C-band interferometry has the advantage over satellite data of higher accuracy and resolution, and by using dual antennas (cross-track interferometry, XTI) the uncertainties connected with ice movements disappear and radar interferogram fringes represent topography (and errors) only. Over Geikie both XTI and RTI (repeat track interferometry) was flown in 1997 and 1998 using the EMISAR system of the Danish Center for Remote Sensing, DCRS, (Madsen et al., 1996), mounted in a Gulfstream jet of the Royal Danish Air Force. Radar reflector GPS positions were used to calibrate the airborne SAR data in the sense of fitting an overall bias in the elevations, but otherwise the corner reflector GPS coordinates were not used for SAR calibration. The SAR data were processed at DCRS in a 5 m-resolution grid subsequently averaged to 25 m. At present only the XTI 1997 data have been processed.

The SAR data was evaluated primarily using airborne laser altimetry. A single-beam laser altimeter (Optech 501SX) was used in combination with kinematic GPS positioning and aircraft attitude information to map the ice surface with an error of around 50 cm, as evidenced from laser track cross-overs. The main part of this error is probably due to kinematic GPS, as the reference GPS site used was more than 150 km away (at the airport of Constaple Pynt). A part of the error is due to insufficient roll and pitch of the aircraft. In the first flight (1996) we did not have a proper INS available, but only a horizontal accelerometer unit, which combined with GPS accelerations, can give a somewhat noisy roll and pitch signal (the influence of roll and pitch was limited flying a draped survey at a nominally 300 ft terrain clearance). In 1997 a prototype fiber-gyro IMU manufactured by Greenwood Engineering was used to provide high-resolution roll and pitch and a more safe flight elevation was used. Unfortunately bad weather prevented laser operations in 1998. The laser data were measured at 10 or 50 Hz, and averaged to 1 sec averages, corresponding to 60 m on the ground.

Since the laser-SAR DEM comparison is critically dependent on the correct processing of the kinematic GPS surveys, including sensor offsets, the airborne laser altimetry was checked by comparing to overflights of the Constaple Pynt runway. A dense geometric pattern of points was independently established on the surface of the runway using a kinematic GPS survey by car. The runway comparison is shown in Table 1, and shows a good fit (20 cm), indicating no gross errors in the GPS processing. At the longer baseline lengths to Geikie the accuracy will degrade, however, but airborne GPS results should still be accurate well below half a meter or so.

The comparisons between the laser altimetry in two consequent summer surveys (1996 and 1997), as well as comparisons between laser altimetry and airborne SAR interferometry and ERS satellite tandem interferometry are additionally shown in Table 2. The laser internal cross-over errors are in part due to a large laser sampling interval (60 m on the ground). The laser intercomparison between 1996 and 1997 show height changes on the order of 0.5-1 m, which is in accordance with the general variations in the snowfall. The annual snow accumulation is 2-3 m, as inferred from a shallow ice core taken in 1998. Overall the snow surface increased by roughly 0.5 m from 1996 to 1997, a number confirmed by static GPS measurements at the radar reflectors, and explained by a relatively large snowfall in the 1996-97 season.

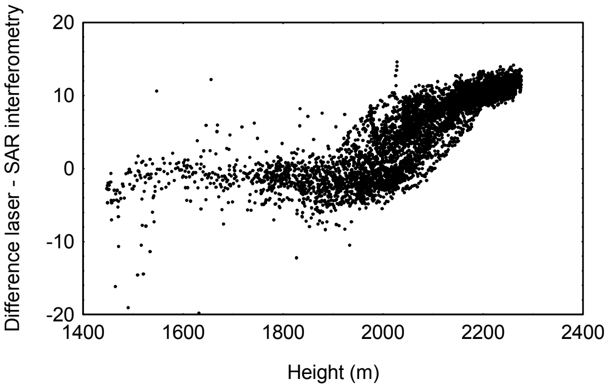

Fig. 6. Difference between laser altimetry and SAR interferometry, Geikie ice cap (outliers are mainly rocks)

The comparison to the airborne SAR interferometry shows that a 4.7 m r.m.s. agreement has been obtained, with a bias of 7 m. The bias is mainly due to penetration effects of the radar signals into the ice sheet. The bias turns out to be height dependent, with shallow penetration (virtually no bias) below 1900 m, and a 10 m bias above 2100 m. This probably corresponds to the difference between the lower-elevation percolation zone (where the firn contains ice layers due to yearly melting/refreezing of the snow) and the upper-elevation dry-snow zone, where little melting occurs, and volume scattering thus is the predominant mechanism for the radar return.

When restricting the SAR interferometry to the dry-snow zone, an r.m.s. fit of 1.9 m is obtained between laser and SAR, so at present airborne SAR interferometry may be assumed to be just barely useful for detecting climate-related height changes, but extremely useful for precise DEM determination for mapping. Satellite SAR interferometry are also useful for this purpose, showing a fit over Geikie of 14 m r.m.s. (the bias value is not significant as the SAR DEM was fitted to the average level of the static GPS at the radar reflector elevations).

Table 1. Comparisons of laser altimetry and SAR interferometry at Geikie Ice Cap, East Greenland.

Comparison (units: m)	Mean	Std. dev.
Airborne laser vs. Airport runway kinematic GPS	0.16	0.25
Internal accuracy of laser survey (1996; 87 cross-overs)	0.02	0.63
Do. (1997; 130 cross-overs)	-0.01	0.65
Laser altimetry 1997 minus 1996 (545 crossings)	0.47	0.94
Laser altimetry minus airborne SAR interferometry (1997)	7.06	4.67
Do., above 2100 m only	9.89	1.90
Laser altimetry minus ERS satellite interferometry	-3.48	13.75

4 ACCURACY OF LASER SCANNING

A Riegl laser scanner unit have been flown over major part of the Arctic Ocean area north of Greenland during April/May 2001, and also used for digital elevation model tests in Denmark.

To obtain a quantitative estimate of the accuracy of laser scanning, a number of tests have been done in connection with overfligths of airport runways, as well as buildings, as measured in detail with kinematic GPS methods. Table 2 gives some results of overflights over the Kangerlussuaq airport, western Greenland (May 2001), as well as overflights of Roskilde Airport, Denmark (July 2001, Piper Navajo aircraft installation). In both cases reference GPS stations were close by, so that GPS errors play a minor role, and comparisons where done by interpolating the surface "ground truth" data to the location of the laser points, if the points were sufficiently close (< 1 m).

The results show an excellent performance in the tests in Denmark (< 10 cm accuracy), whereas the Greenland comparisons are much poorer, likely a consequence of some inconsistencies in timing and coordinate offsets, and a suspected lack of rigidity in the improvised scanner mount of the Greenland 2001 campaign. Overflights over Longyearbyen airport, Svalbard, showed even larger comparison error values (90 cm r.m.s.), and work is in progress to try and solve the problems.

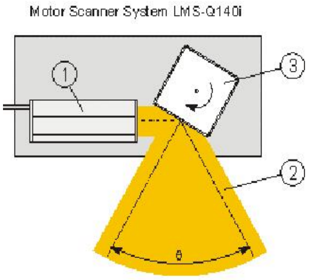

Fig. 7. Riegl laser scanner principle

Table 2. Comparisons of airborne laser scanning and runway kinematic GPS car surveys

Comparison (units: m)	Mean	Std. dev.
Kangerlussuaq: 2000 runway survey vs. 2001 laser scanning	0.24	0.32
Roskilde: Runway road survey vs. Laser scanning	-0.03	0.04
Roskilde: Comparison of two separate laser scanning flights	-0.04	0.10

5 SEA-ICE LASER MEASUREMENTS

In the period 1998-2001 the Greenland coasts have been mapped with airborne gravimetry at roughly 10 n.m. line spacing, with laser altimeters routinely collecting data over the ocean as well, and – since 2001 – also a Riegl laser scanner. Because of fog and limited visibility not all tracks have given useful data. Flights have been flown at low elevations (500 to 1000 ft), and GPS tracked from a number of base stations at the various airports in the area. GPS heights are generally accurate only at the 0.3-0.5 m level due to the long baselines and ionospheric conditions.

The laser altimetry measurements provide a direct measurement of ice freeboard heights, which might be useful, e.g. for validation of future satellite missions such as Icesat and CryoSat, as well as for general studies of sea-ice thickness changes. The basic principle is

$$F = h_{GPS} - H_{laser} - N$$

where F is the ice free-board height, h the height of the aircraft, H the measured range to the ice surface and N the geoid. To this equation should be added the instrument offsets, measurement errors, tides, and permanent sea-surface topography, the latter assumed to be small and of relatively long wavelength. It is therefore possible to correct for these errors by filtering and adjusting data to a "lowest level" representing open water or new ice. The ice freeboard values may subsequently be converted to total ice thickness, based on assumption of isostatic equilibrium between the sea-ice (normal density 915 kg/m^3) and the water (density 1024 kg/m^3). A constant freeboard to thickness ratio K around 7.84 has been taken from a model presented in Wadhams et al. (1992). The K factor is a mean value for the season, and depends on the thickness and density of overlying snow, as well as on variations on the density of the sea-ice itself or the ocean density.

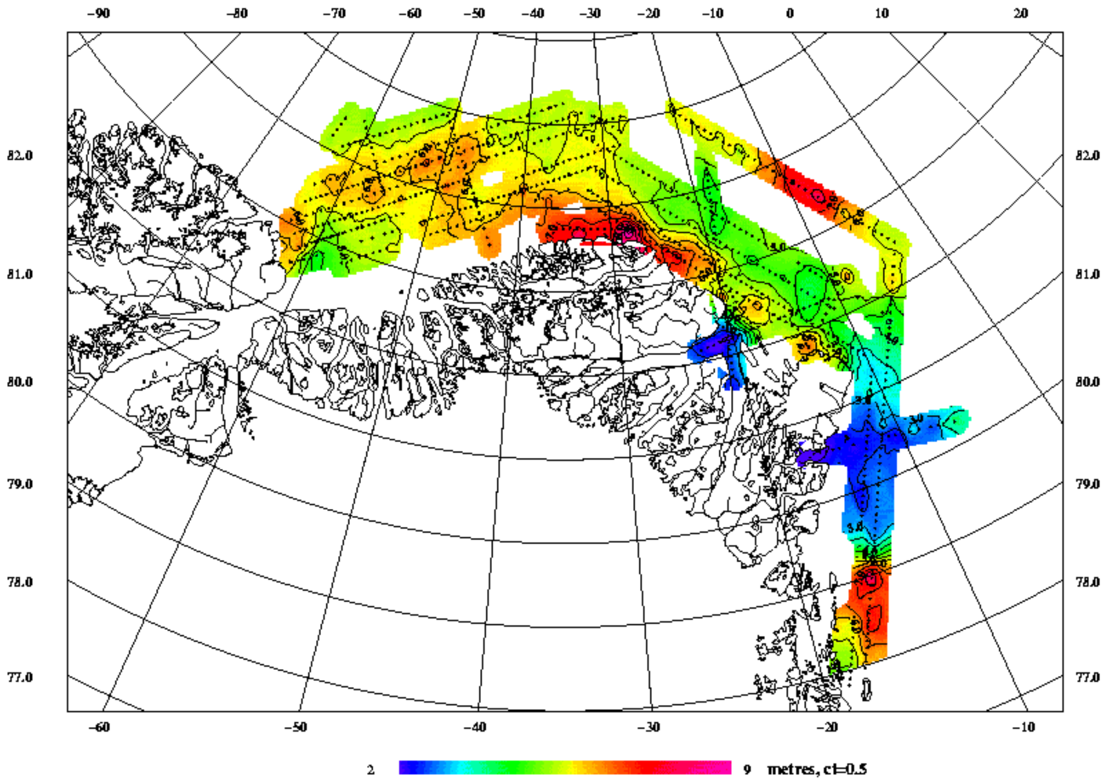

Fig. 8. Sea-ice thickness north of Greenland determined from airborne laser measurements

Fig. 8 shows an example of ice thickness for the Polar Sea north of Greenland, derived from June 1998 laser profile measurements. Data have been processed onto a 0.1^o resolution grid from available fog-free filtered laser track data, using a geoid model derived from the airborne gravity measurements. The thick accumulation of sea-ice north of Greenland is likely due to compression and ridging due to the dynamics from the Transpolar current. Investigations are ongoing to analyze 1999 and 2001 data and compare with remote sensing imagery. The use of laser scanner data provides an additional capability to map the ice floe geometries in greater detail, including the study of pressure ridges and leads.

Fig. 9. Polar pack sea-ice north o f Greenland

Fig. 10 shows an example of the ice freeboard field for a region of the Arctic Ocean north of Greenland, as mapped by airborne laser scanning using the Riegl system. The plot shows the actual measured freeboard heights along a typical track north of Greenland. The laser scanning freeboard data clearly shows the typical 50-100 m-scale individual ice floe features, as well as pressure ridges between floes. Work is currently ongoing at KMS to analyze the sea-ice laser scanning data, along with analysis of onboard video data collected and remote sensing data from ERS-2 and Radarsat.

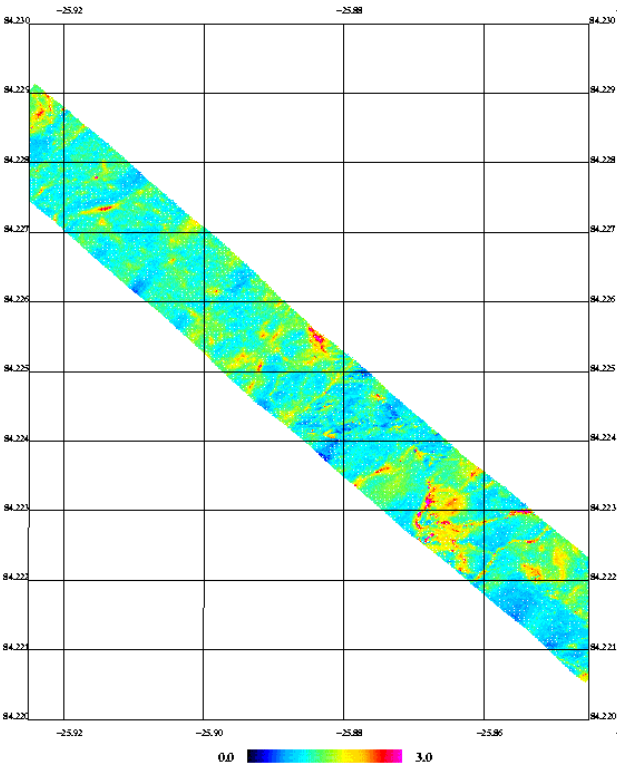

Fig. 10. Ice freeboard heights (m) of Arctic pack ice. Swath width is approximately 150 m (flight elev. 500 ft)

6 CONCLUSIONS

We have outlined some examples and results of Greenland laser projects, based on a low-cost Twin-Otter system setup. We are currently refining and developing software and tools, a.o. to provide estimation of laser scanner orientation angles, changing with every new installation and field project. In Danish tests the used Riegl scanner system have obtained very good results (accuracy down to the 5 cm level), whereas Greenland applications have generally been noisier. Applications of laser scanning for sea-ice studies appears very promising, and airborne measurements can provide a good understanding of the signatures of the future satellite missions such as Icesat and CryoSat, and help in studying climate-induced changes in the polar sea-ice cover.

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