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Airborne Gravity Survey of Lincoln Sea and Wandel Sea, North Greenland

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Abstract. In June 1998 National Survey and Cadastre - Denmark (KMS) carried out an airborne gravity survey over the Polar Sea to the north of Greenland. A Twin Otter from Greenlandair, equipped with autopilot and additional fuel tanks, was employed for the survey. A modified marine LaCoste & Romberg gravimeter and geodetic GPS receivers operating in differential mode made up the basic scientific instrumentation used to monitor the gravity field variations. A laser altimeter and a low cost inertial measurement unit consisting of three gyros and three accelerometers were included to sustain the postprocessing of the GPS data. The presentation will focus on the integration and validation of the system, including comparison with marine and ice gravity measurements. Gravity results from Lincoln Sea and Wandel Sea between latitude 82 N and 85 N, covering the shelf region and the continental slope and rise, will be presented.

1 Introduction

Airborne gravimetry has become a truly operational tool in the recent years, mainly because of developments in positioning with the Global Positioning System - GPS. Both satellite constellation, receiver performance and processing software have improved, since the first pioneering large scale airborne gravity survey was performed by Naval Research Laboratory, USA, Brozena, (1991).

The principle of airborne gravimetry is quite simple. A triad of accelerometers measures total acceleration vector and the kinematic accelerations are derived from a position or velocity record for the flight. The difference between total and kinematic acceleration gives the gravity vector. Due to the high noise level only the magnitude of the gravity vector is interpreted in present applications, Schwarz (1997).

The uniform coverage of land and sea and the ability to cover

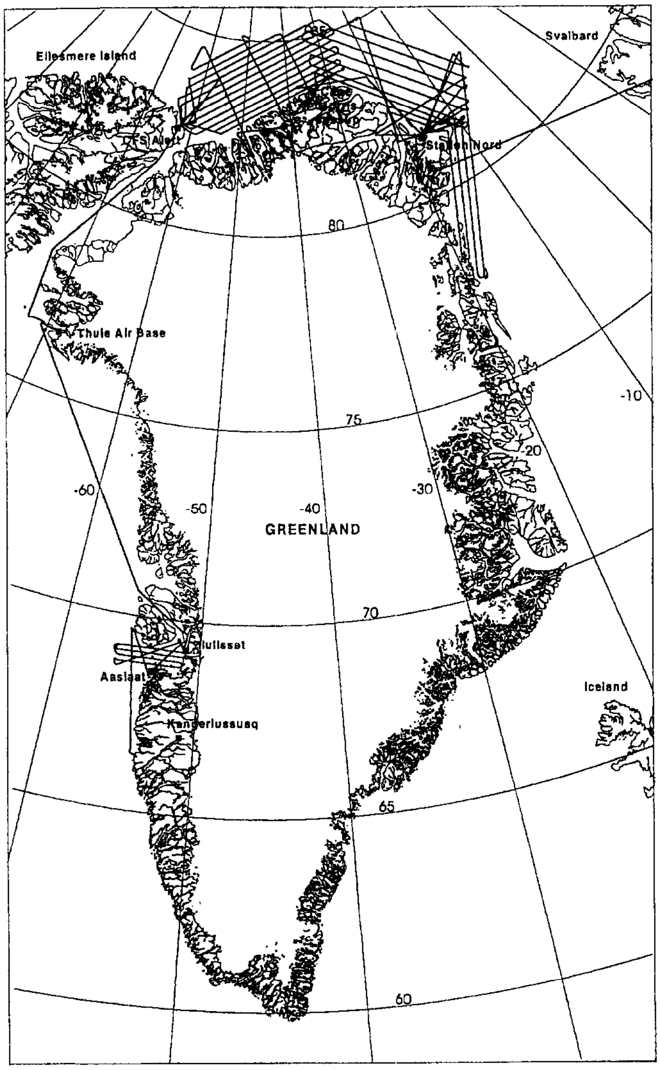

Fig.1. KMS airborne gravity tracks 1998.

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remote and inaccessible areas are two of the greatest advantages of airborne gravimetry.

National Survey & Cadastre – Denmark (KMS) and University of Bergen have in cooperation made a new system setup based on a LaCoste & Romberg S gravimeter and a Greenlandair Twin Otter. This new airborne gravity system is a spin-off from the AGMASCO project, Airborne Geoid Mapping System for Coastal Oceanography, Forsberg (1996).

In June 1998, KMS performed a first test and production campaign with the new system, with the Polar Sea to the north of Greenland as the main target area, see Fig. 1. It is planned to continue the measurements in the coming years around the coast of Greenland, to provide a seam-less gravity coverage across the shelf regions into the satellite altimetry derived gravity fields of the open ocean.

This paper's focus is on the validation of the gravity system, accomplished by comparison to all available surface gravity data and by internal crossover error analysis. Hardware setup, processing outline and resulting gravity anomalies will also be described.

2 Hardware setup

Greenlandair's Twin Otter OY-POF is an ideal platform for gravity operations in remote areas like Greenland. It is equipped with an autopilot, which is a necessity in getting good airborne results, and a low cruising speed (appr. 130 knots) enhances resolution of the resulting data. The long flight endurance, appr. 7 hours, and the ability to land and take off almost every where gives flexibility to the flight operations. This includes deployment of GPS reference receivers.

A LaCoste & Romberg "S" gravimeter updated to airborne use were placed near the center of mass in the aircraft. A laptop controls the operation of the meter and logs data from it.

Two Trimble 4000 SSI receivers were installed with antennas on the airplane fuselage and 1 Hz data were stored in the 10 MB internal memory.

A lowcost inertial measurement unit (IMU), consisting of 3 gyros and 3 accelerometers was, included in the instrumentation to provide attitude changes of the aircraft and thereby making it possible to correct for the lever arm effect between GPS antenna and gravimeter.

Airplane heights above sea-surface (mainly icecovered) were measured with an Optech 501 SX laser altimeter and logged on a PC together with IMU data. To get a backup of the gravimeter data, those were stored too on this PC.

GPS reference receivers were deployed at CFS Alert, a Canadian military base, at the Danish military outpost Station Nord and at Cape Morris Jessup the north tip of Greenland, see Fig. 1.

3 GPS processing

To obtain acceleration estimates good enough for airborne gravimetry the relative position accurracy must be at the centimeter level, whereas the requirements for absolute positioning are more relaxed and is determined by the free air gradient (0.3086 mGal/m) and 0.5 m will be satisfactory in most applications. Normally this is obtained routinely with commercial GPS processing software, even with baselines up to several hundred kilometres.

Now and then, when the GPS receiver loose lock on the GPS carrier wave, e.g., due to ionospheric scintillation or when the satellite constellation changes, artificial jumps can be introduced in the position estimates. It is of crucial importance to identify such jumps and remove the effect on the resulting gravity. Due to the dynamics of the flight it is not possible to identify the jumps directly in the raw position estimates, but fortunately both the laser altimeter and the IMU have proven to be a valuable help in the search for position jumps.

4 Gravity processing

The LaCoste & Romberg meter uses a combination of two internal measurements - spring tension and beam velocity - to obtain the relative gravity variations. The gravity sensor is mounted on a gyro-stabilized platform, levelled by a feedback loop with two horizontal accelerometers and two gyros. Details of the operation principle of the LCR gravimeter can be found in Valiant (1991).

The basic gravimeter observation equation for relative gravity y is of the form

$$y = sT + kB' + C \qquad (1)$$

where T is spring tension, s the scale factor, B' the velocity of the heavily damped beam and the factor k the beam velocity/acceleration scale. A beam-type gravimeter like the S-meter is sensitive to horizontal accelerations even when the platform is levelled, and a cross-coupling correction C is computed in real time by the gravimeter control computer.

Free air gravity anomalies at aircraft level are obtained by

$$\Delta g = y - h'' - \delta g_{eotvos} - \delta g_{tilt} - y_0 + g_0 - \Upsilon_0 + 0.3086\,(h-N) \qquad (2)$$

where h'' is the GPS acceleration, δg_{eotvos} the Eotvos effect computed by the formulas of Harlan (1968), g_0 and y_0 the ground gravity value and spring tension, Υ_0 normal gravity, h the GPS ellipsoidal height and N the geoid undulation. The platform off-level correction δg_{tilt} is expressed as

$$\delta g_{tilt} = y - \sqrt{y^2 + A_x^2 + A_y^2 - a_x^2 - a_y^2} \qquad (3)$$

where a and A denotes horizontal kinematic aircraft accelerations and horizontal specific forces measured by the platform accelerometers, respectively. Because of the potential high amplitude of horizontal accelerations, and the small difference between accelerations from accelerometer and GPS measurements, computed tilt effect is quite sensitive to the numerical treatment of the data. Calibration factors for the accelerometers have been determined by a FFT technique due to the frequency dependent behaviour of the platform, LaCoste (1967); Olesen et al (1997).

Lowpass filtering plays a fundamental role in airborne gravity processing. The objective of the filtering is both to account for the difference in filtering inherent from the data, and to remove the high frequency noise masking the gravity signal. The gravimeter data acquisition system uses a 1 sec. boxcar filter on internal 200 Hz data, whereas the inherent filtering of the accelerations derived from the GPS positions depends both on the GPS processing software and the algorithm applied for differentiation. This difference in filtering has little impact on the linear terms in our processing algorithm, because of the heavy final filtering. But the nonlinear terms, mainly represented by the tilt correction, are quite sensitive to initial filtering.

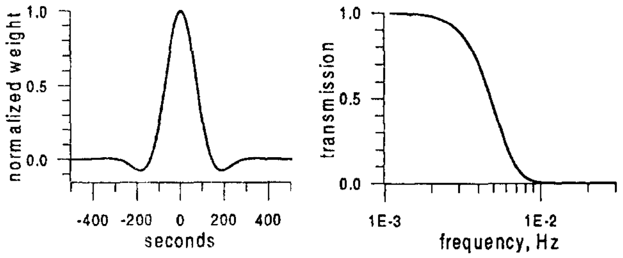

Fig. 2. Impulse response and spectral representation of the applied filter.

All data were filtered with a symmetric 2nd order Butterworth filter with a half power point at 200 seconds corresponding to a resolution of 6 km (half wavelegth). The impulse response and spectral behaviour of the filter are shown in Fig. 2.

5 Data validation

The final processed data set comprised 69 crossovers and an analysis of the difference in the crossing points is shown in Table 1. The RMS difference of 2.6 mGal indicates a noise level of less than 2 mGal (2.6 mGal divided by square root 2) on the separate tracks, if the noise is assumed white noise.

In marine gravity processing it is common practice to subject the profile data to a crossover adjustment to reduce the crossing difference. With a good gravimeter, reliable basereadings and proper data processing there should be no physical justification for such an adjustment in airborne works and the 2.1 mGal crossing error after bias adjustment will give an optimistic estimate, to our opinion, of the noise level (1.5 mGal).

Table 1. Results of crossover analysis, 69 crossovers

Units: mGal	RMS difference	Max difference
Before adjustment	2.6	6.0
After adjustment	2.1	6.0

The western part of the survey area, near Ellesmere Island, is covered by surface gravity data, see Fig. 3. Predictions of free air gravity anomalies along the airborne tracks have been made by collocation. Comparisons were only made for points sufficiently close to the surface data, using only points where the a-posteriori prediction error is less than 3 mGal. The 2.4 mGal RMS difference in Table 2 for the Polar Sea comparison indicates a noise level that agrees with the estimate from the crossover analysis, taking into account that part of the error comes from the predicted values.

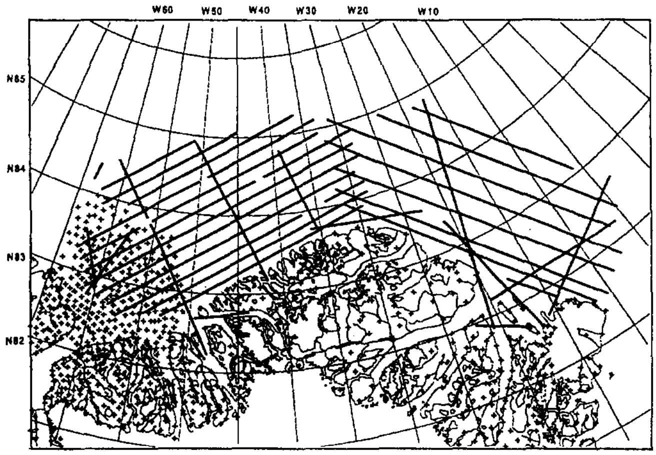

Fig. 3. Distribution of surface (crosses) and airborne gravity data in north Greenland and Lincoln Sea.

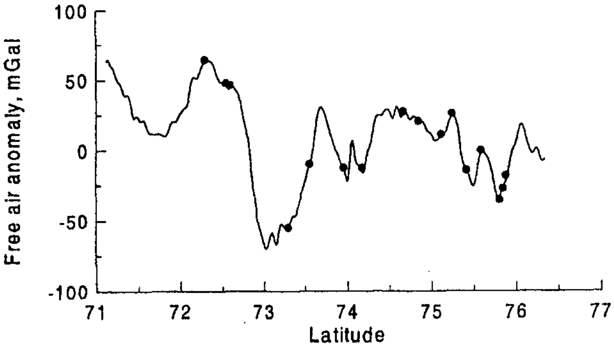

Fig. 4. Comparison to marine gravity in Baffin Bay.

Table 2 also clearly shows that the bias adjustment degrades the airborne data, e.g., the RMS difference increases from 2.4

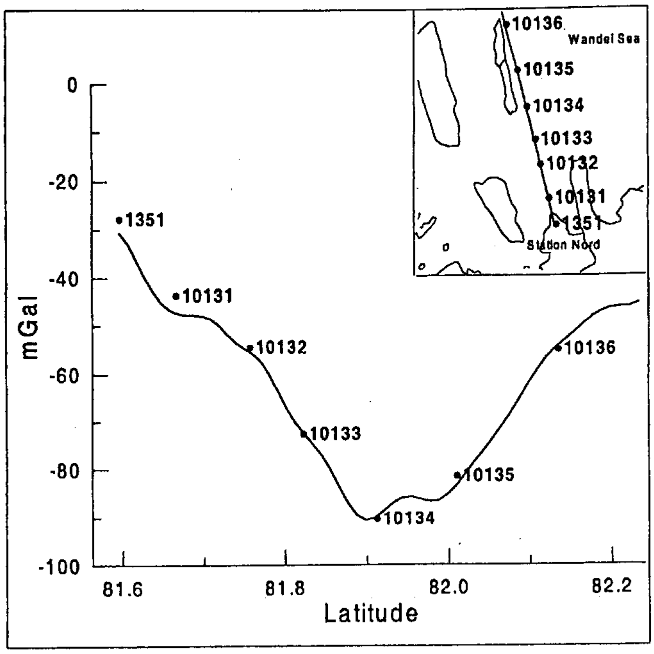

Fig. 5. Station Nord controle profile. 6 gravity readings on the sea ice

to 2.9 mGal, when applying a bias adjustment to the airborne data. The final gravity results are based on the unadjusted data set.

Due to the low flight altitude (100 to 300 m), the data has not been subjected neither to upward nor downward continuation before the comparison.

Fig. 4 shows a comparison to marine data in Melville Bay at the West Coast of Greenland between 72 and 76 north latitude. The comparison is made in the marine/airborne crossing points, and the only processing performed to the marine data is a linear interpolation between two adjacent data points to get an estimate for the surface gravity field in the crossing point.

Table 2. Comparison to surface gravity data

Difference in mGal	Mean	RMS	Max
Polar Sea, 288 points - Before crossover adjustment - After crossover adjustment	 -0.1 0.6	 2.4 2.9	 8.8 9.5
Melville Bay, 16 marine crossings	-1.5	2.2	4.8
Station Nord ice profile, 6 points	-0.8	1.7	3.5

In 1997, a dedicated short test profile was surveyed by helicopter near Station Nord, northeast Greenland. 6 point readings were made in a straight line extending 60 km to the north of Station Nord, see Fig. 5. The line was reflown in 1998 with the airborne gravity system. This is a direct comparison between data obtained on the sea ice with a conventional land gravimeter and data obtained at an altitude of 100 metres and a speed of 130 knots with the airborne gravity system.

The statistics for both the Melville Bay and the Station Nord

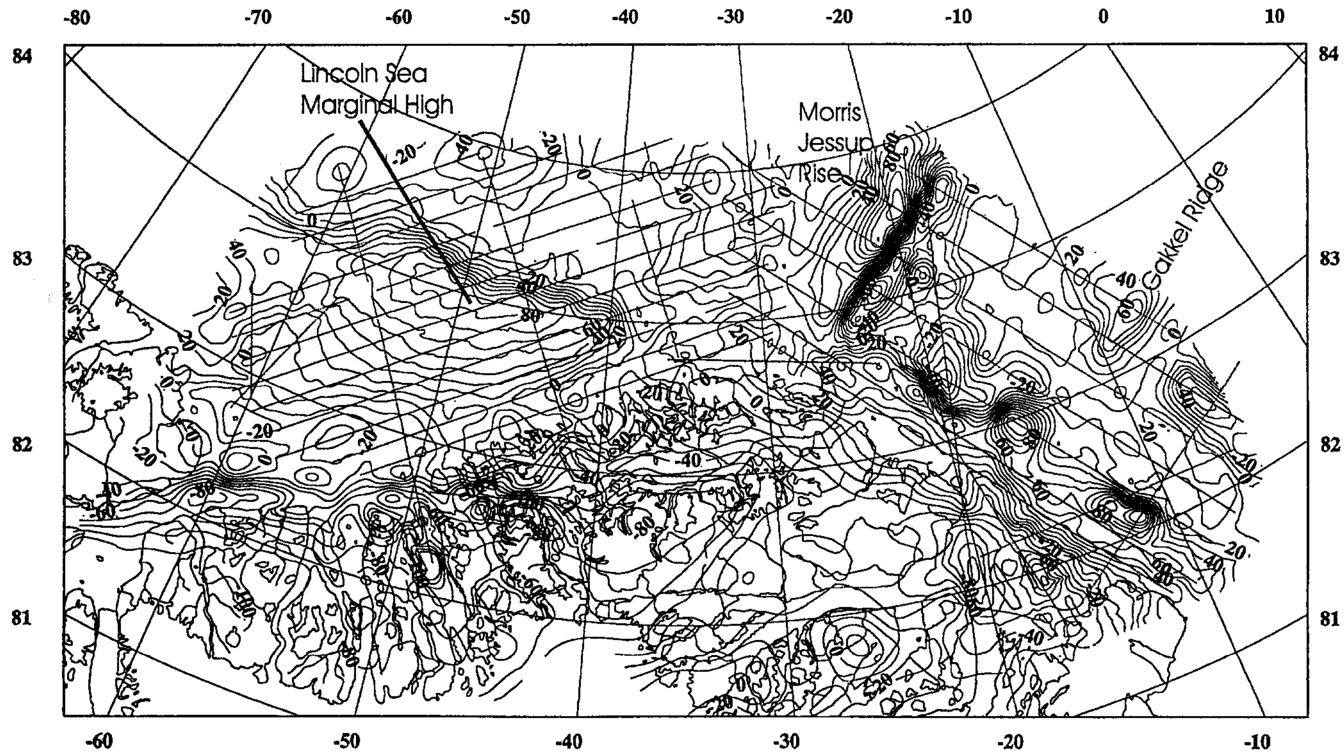

Fig 6. Resulting free air anomalies (Bouguer on land). Surface data incorporated.

comparison, shown in Table 2 indicate a noise level around 2 mGal or better for the airborne data.

6 Conclusion

The Danish-Norwegian airborne gravity system based on a LaCoste & Romberg gravimeter and a Twin-Otter has proven to be a reliable tool for regional gravity mapping even under difficult logistic and operational conditions. It showed 2 mGal accuracy at 6 km resolution, and it should be noticed that this performance is obtained in an area with quite steep gradients of the gravity field.

No crossover adjustment has been applied, due to the high data quality.

The resulting gravity anomalies are shown in Fig. 6, incorporating available surface data. The marginal high in the Lincoln Sea is a new feature in the polar gravity picture. The anomalies show also a very steep gravity gradient associated with the eastern edge of Morris Jesup Rise.

The new gravity anomalies of the North Greenland shelf will be a contribution to the Arctic Gravity Project, an international cooperation to compile and release an Arctic-wide gravity grid by year 2001, see the web-site http://164.214.2.59/GandG/agp/index.htm.

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