AIRBORNE GRAVITY SURVEY OF FOXE BASIN, NUNAVUT, 2002

Survey and processing report

by

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Aircraft maintenance in Repulse Bay; GPS reference in front

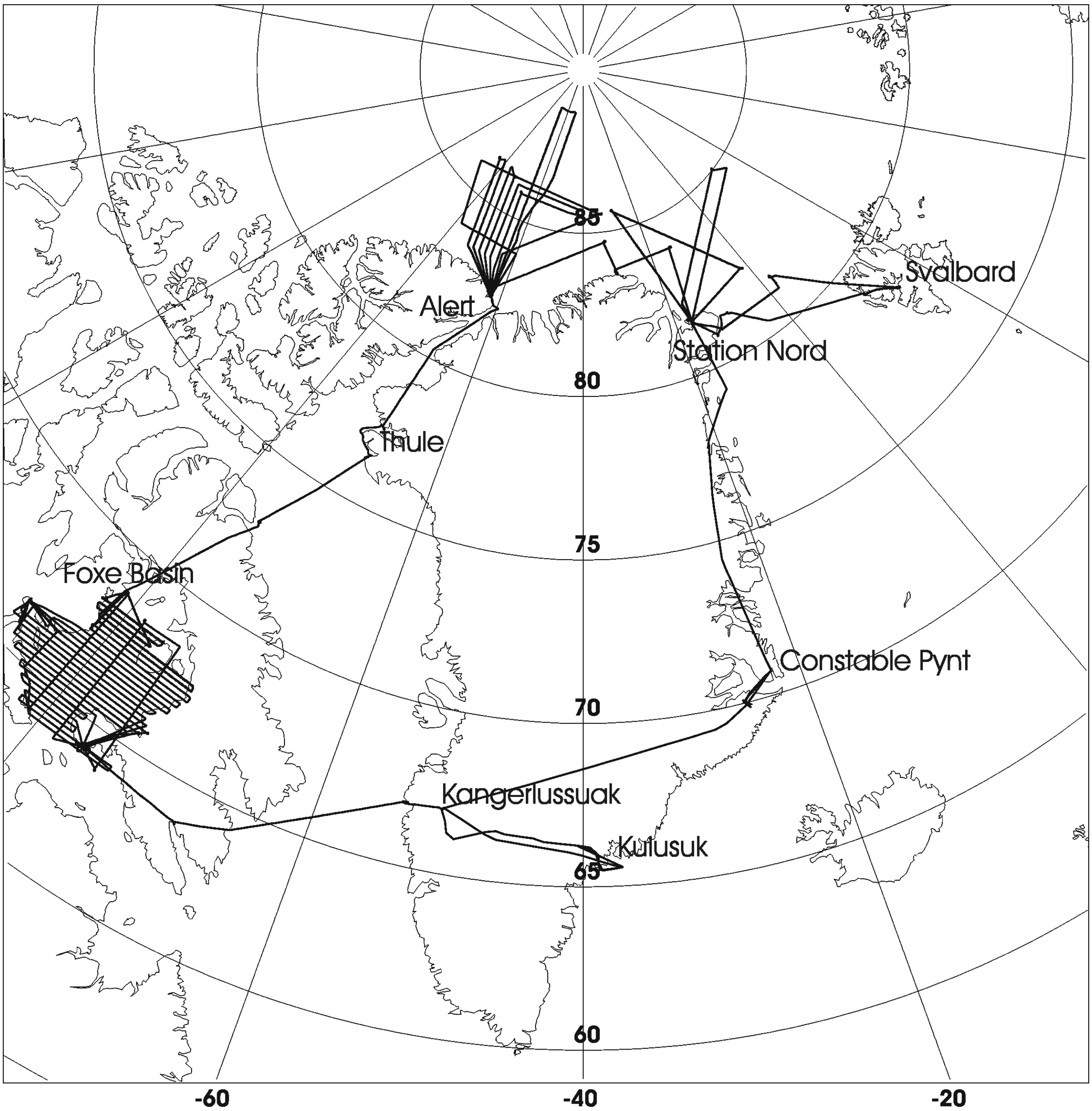


Fig. 1. Flight tracks of the 2002 KMS airborne gravity and lidar surveys, carried out in cooperation with the European Space Agency, Geodetic Survey Division/NRCan and NIMA.

1. INTRODUCTION

This report describes the field operations, hardware setup, processing and results of the 2002 KMS-NRCan-NIMA cooperative airborne gravity survey of Foxe Basin, Nunavut, Canada, the largest void in the gravity data coverage of the Canadian Arctic. The survey was initiated as an "opportunity mission", utilizing the airborne gravity survey system setup of KMS (Kort og Matrikelstyrelsen = National Survey and Cadastre), Denmark, taking advantage of an airborne gravity and lidar survey of the Polar Sea north of Greenland in April/May 2002, supported by the European Space Agency and the Danish Space Board (ESAG-2002). The purpose of the Arctic Ocean measurements was to collect airborne gravity and lidar ice thickness measurements in preparation of the ESA satellites GOCE and CRYOSAT.

In a cooperative venture between Geodetic Survey Division, National Ressources Canada, KMS and National Imagery and Mapping Agency (NIMA), USA, it was decided to carry out the Foxe Basin survey immediately after ESAG-2002, to fill in the void prior to the compilation of an Arctic-wide gravity grid of the entire Arctic region ("Arctic Gravity Project", cf. Kenyon and Forsberg, 2000), released into the public domain December 2002 (see http://164.214.2.59/GandG/agp/readme.htm).

The airborne gravity data have been acquired by low-level Twin-Otter flights, using a Lacoste and Romberg gravimeter supported by GPS kinematic positioning, and are estimated to have accuracies around 2 mGal r.m.s. at 6 km resolution. The processed data was transferred to NRCan and NIMA in September 2002 in the form of a file with free-air anomalies at altitude.

Air Greenland Twin-Otter at Repulse Bay

2. THE KMS AEROGRAVITY HARDWARE SETUP

The hardware system for the 2002 aerogravity survey was essentially identical to the 1998-2001 airborne gravity surveys in Greenland and Svalbard (described in Forsberg et al., 1998, 2001). The set-up consists of a Lacoste and Romberg gravimeter (S-99/ZLS-Ultrasys, owned by University of Bergen, Norway); an electronics rack holding GPS receivers, computers, data logging and power/controller (custom-made by Greenwood Engineering, Denmark); a floor-mounted prototype Inertial Measurement Unit (IMU; Greenwood Engineering); and a Honeywell H-764G Inertial Navigation System (INS). The lidar sensors include an Optech laser altimeter and a Riegl laser scanner mounted in the tail luggage compartment. Two GPS antennas mounted front and aft of the wings, serving Ashtech, Trimble and Javad GPS receivers, as well as the GPS unit embedded in the Honeywell INS.

All surveys were done with the same aircraft, an Air Greenland Twin-Otter (OY-POF), normally used as a freight/passenger charter airplane. The used Air Greenland Twin-Otter is a well-suited airplane for aerogravity, due to the availability of a fine-tuned autopilot, and an optional extra ferry tank, giving a maximal flight endurance of 6.5 hours. The typical airspeed of the Twin-Otter during survey flights is around 135 knots or 250 km/h.

The gravimeter used is a Lacoste and Romberg marine gravimeter (S-99), modified for airborne use by ZLS Cooperation. The gravimeter sensor is mounted on pressurized vibration dampers, and placed inside a floor-mounted aluminium box. Data is logged on the control PC

Front of cabin with electronics rack

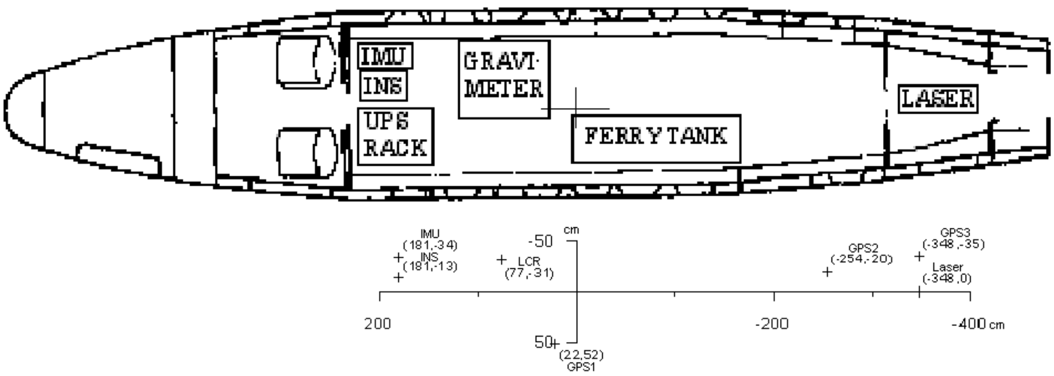
as well as the central data logger. A 4-minute platform period was used throughout the survey, with feed-back levelling systems turned off during turns.

The GPS units on the aircraft include a Trimble 4000 SSI ("AIR1"), an Ashtech Z-Surveyor ("AIR2") and a Javad Legacy GPS receiver ("AIR3"). The Trimble and Ashtech shared the front antenna. All data were recorded at 1 Hz.

A sketch of the aircraft installation is shown below. The offsets of the various sensors relative to a zero-point below the wings are given in Table 1.

Table 1. The offset of the various sensors relative to a zeropoint below the wings.

Units: cm	X (pos. forward)	Y (pos. left wing)	Z (positive up)
Gravimeter sensor	77	-31	40
IMU sensor	181	-34	10
INS sensor	181	-13	10
GPS antenna #1	22	52	163
GPS antenna #2	-348	-35	147
Lidars	-348	0	-15



Sketch of the gravity system installation in the Twin-Otter

Back of aircraft. Gravimeter at left, ferry tank at right

The total weight of the equipment is less than 200 kg and designed for 1-man operation. The remaining payload of the "POF" Twin-Otter gave large operational flexibility, as the aircraft could move between operations bases transporting both project scientists and equipment, as well as doing routine measurements.

3. GREENLAND AND FOXE BASIN 2002 GRAVITY OPERATIONS

The main schedule of the KMS Greenland-Canada airborne surveys 2002 is outlined below. Generally weather conditions were good in the north, with more mixed weather in Foxe Basin (clouds, wind and icing conditions). Most flights were flown at altitudes between 500 and 1000 ft, with a few flights at 3000 ft due to weather.

Personnel for the Foxe Basin survey were Rene Forsberg, Arne V. Olesen (KMS), John Halpenny (NRCan) and Eva H.Ditlevsen (Univ. Cph., GPS assistant). The KMS staff in the Greenland surveys included K. Keller and S. M. Hvidegård (KMS) and R. Haagmans (ESA).

Table 2. Main ESAG-2002 / Foxe Basin survey operations

April 26-29	Installation of scientific equipment in Air Greenland hangar at Kangerlussuaq. Test flight.
April 30-May 3	Lidar survey of East Greenland ice sheet margin, Kulusuk region. Ice sheet landings in different elevations for snow pit measurements.
May 4-9	First ESAG-2002 gravity flights from Station Nord. Overflights of Swedish ice breaker “Oden” on May 6 and May 9 in Fram Strait.
May 10-16	Operations from Canadian Forces Station Alert. All lines flown as planned, in spite of aircraft generator fault, which gave aircraft non-availability for 2 days.
May 17	Flight from Alert to Thule Airbase via Nares Strait. End of ESAG-2002, aircraft continues to Canada.
May 22-23	Transit flight from Thule Air Base to Hall Beach, Nunavut. Low-level measurements over Baffin Bay. Measurement flights from Hall Beach.
May 24-29	Measurement transit to Repulse Bay, flights over central Foxe Basin. E.H. leaves for Cape Dorset to set up remote GPS reference. Flights from Repulse Bay, somewhat hampered by weather.
May 30-June 2	Flights over southern Foxe Basin from Cape Dorset. Conclusion of Foxe Basin survey
June 3-4	Flight back to Greenland, with overnight stop in Iqaluit. Low-level measurements over Davis Strait.

The details of the measurement flights are shown in Table 3. The track letters are the waypoints used for planning and air traffic control, and the track numbers identify the individual tracks, cf. Fig. 2.

Table 3. Details of all Foxe Basin 2002 flights

Date/JD		Track	Track number	Take off UTC	Landing UTC	Airborne	Operator
May 22/142	THU-HAL	XTH-XHA	1, 2	13:55	17:47	3 h 52 m	AVO/EH
May 22	HAL-HAL	A-B-C-XC	3, 4, 5, 6	20:23	24:36	4 h 13 m	RF/JH
May 23/143	HAL–HAL	XE-D-E-XE	7, 8, 9, 10	14:17	18:34	4 h 17 m	AVO/EH
May 23	HAL-HAL	XF-F-G-XG	11, 12, 13, 14	19:37	24:23	4 h 46 m	RF/JH
May 24/144	HAL-REP	XX-WW-XWW	15, 16, 17	14:43	18:53	4 h 10 m	AVO/RF
May 24	REP-REP	L-M	18, 19	20:23	01:26	5 h 3 m	AVO
May 26/126	REP-REP	H-I	20, 21	15:13	20:23	5 h 5 m	RF/JH
May 27/127	REP-REP	J-K	22, 23	14:18	19:13	4 h 55 m	AVO
May 30/150	REP-DOR	N	24, 25, 26	15:03	18:27	3 h 24 m	RF

May 30	DOR-DOR	Q-R	27, 28, 29, 30	19:56	01:15	5 h 19 m	AVO
May 31/151	DOR-REP	P	31, 32, 33	13:39	17:49	4 h 10 m	AVO
May 31	REP-DOR	O	34, 35, 36	19:00	22:28	3 h 28 m	AVO
June 01/152	DOR-DOR	ZZ-YY	37, 38, 39, 40, 41	13:47	19:22	5 h 45 m	AVO/JH
June 01	DOR-DOR	Y-X-W-Z	42, 43, 44, 45, 46	20:28	01:03	4 h 35 m	AVO/JH
June 02 / 153	DOR-DOR	S-T-U-V	47, 48, 49, 50, 51, 52, 53	13:57	19:15	5 h 18 m	AVO/JH
June 02	DOR-DOR	Z'-Y'	54, 55	20:20	21:45	1 h 25 m	AVO
June 03 / 154	DOR-IQA	ferry		13:56	15:38	1 h 45 m	
June 04 / 155	IQA-SIS	Davis Strait	56	11:13	14:53	3 h 40 m	AVO
June 04	SIS-SIS	Scanner		15:33	16:17	0 h 44 m	AVO
June 04	SIS-SFJ	runway scanner		16:40	17:22	0 h 42 m	AVO
Total						76 h 36 m	+3 h 20 m block

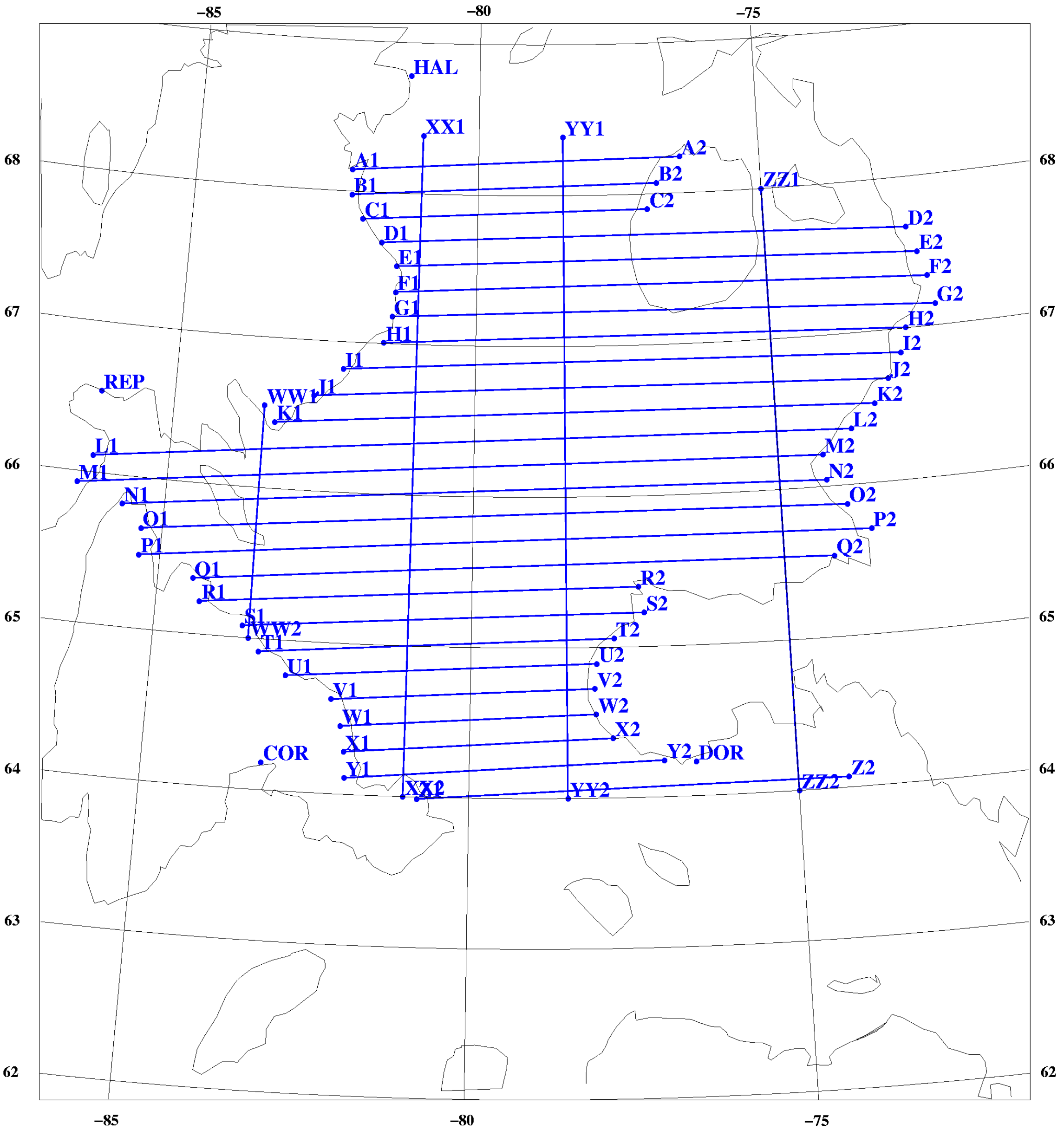


Fig. 2. Tracks and waypoints for the Foxe Basin airborne gravity survey.

All flights were successful, and gravimeter data were only lost in a couple of cases where the aircraft had to change height due weather conditions. The data routinely used for the processing is the gravimeter and GPS data; INS, IMU and laser altimeter data was additionally logged, but not used in the routine processing. Laser scanning was only collected for a few tracks over the Foxe Basin, to get some typical ice free-board scan profiles over the very rough ice conditions apparent in most of the Foxe Basin.

Sea-ice in the southern Foxe Basin

4. DATA PROCESSING

4.1 GPS kinematic solutions

The precise GPS positions of the two physical aircraft antennas were computed mainly using Trimble's software "GPSurvey" (v. 2.35) – keeping fixed the reference values of Table 4. At least two independent aircraft GPS solutions were made by combinations of different reference stations and antennas. The reference coordinates were computed using "AutoGipsy" of JPL and typically have an accuracy better than 5 cm in the ITRF2000 reference system, see (http://www.unavco.ucar.edu/data_support/processing/gipsy/auto_gipsy_info.html.). All GPS reference stations in Canada were temporary points located either in the airport or in proximity to the hotels in the villages, using either Javad, Trimble or Ashtech receivers.

Table 4. Reference coordinates for Foxe Basin 2002.

Station	Lat	Lon	Ell. height	Comment
DOR1	64 13 46.0790	-76 32 42.9169	16.903	Cape Dorset
DOR2	64 13 46.3322	-76 31 37.0993	16.869	-
HAL1	68 47 38.8535	-81 14 24.4969	-16.889	Hall Beach
HAL2	68 46 04.6245	-81 13 27.4753	-18.582	-
HAL3	68 46 04.6243	-81 13 27.4765	-18.510	-
IQA1	63 45 02.5662	-68 30 22.3648	72.426	Iqualuit
IQA2	63 44 56.4572	-68 32 08.4982	9.350	-
REP1	66 31 31.1091	-86 13 53.0475	-12.141	
REP2	66 31 31.6346	-86 13 55.3545	-12.057	
SIS1	66 57 04.863	-53 43 23.294	32.52	Sisimiut (short file)
THU3 (perm)	76 32 13.3708	-68 49 30.1241	36.275	Thule

GPS reference station HAL1, Hall Beach

It is estimated that the GPS solutions are generally accurate at the 20-30 cm level r.m.s., with the independent GPS solutions often with internal agreements at the 10 cm-level. The GPS conditions of 2002 were generally OK, with relatively few problems due to ionospheric problems. In two cases no GPS solutions could be found for small parts of the track; this yielded small breaks in the final data.

An example of the computer aircraft heights is shown below. The regular phugoid motion of the aircraft is gives a quasiperiodic variation in aircraft height, which is used to cross-correlate the time-offset between gravimeter and GPS systems. This can be done with accuracies of a fraction of a sec, and experience has shown this to be a strong tool to detect timing offsets.

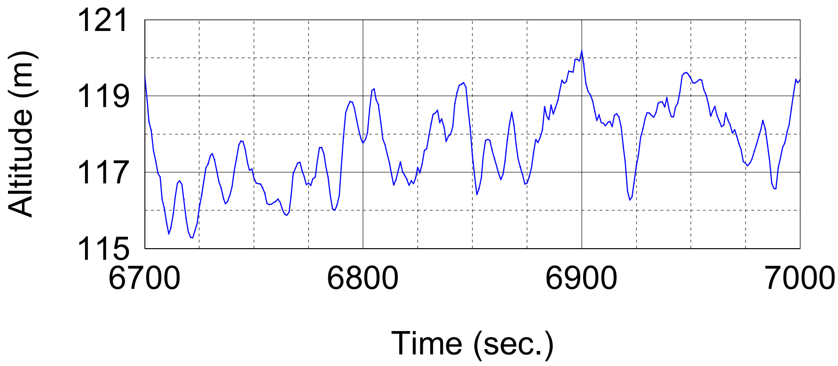
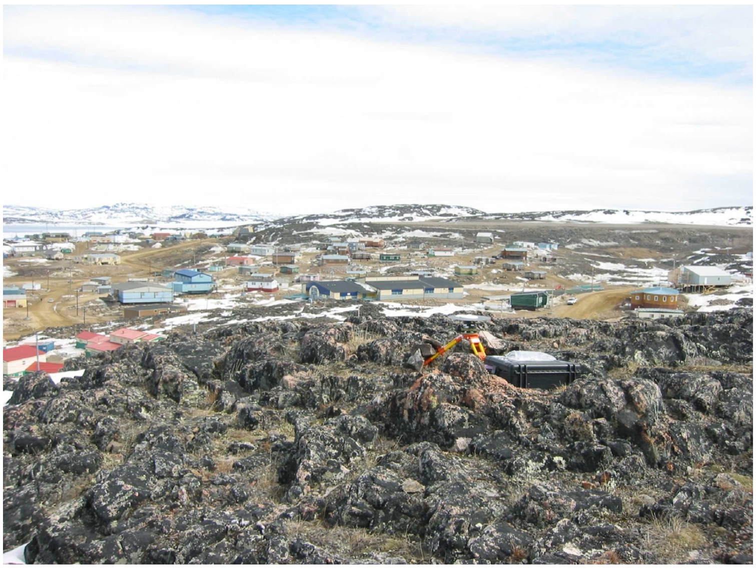


Fig. 3. Example of aircraft heights during survey flight.



GPS reference station, Cape Dorset

4.2 Gravity reference values

The reference gravity values used for the flights were based on gravimeter ties from nearby NRCan reference points, measuring to the aircraft parking spot on the airfield level. Gravity ties were done using the G-867 gravimeter of KMS. Table 5 gives the apron gravity values used for reference.

Table 5. Reference gravity values of gravity base stations (mGal)

KMS no.	NRCcan no.	g	location
38801		982921.631	Thule absolute
99991		982916.817	Thule apron
921	9209-62	982488.620	Hall Beach radar station
922	9812-65	982489.080	Hall Beach hangar
920		982489.308	Hall Beach apron
924	9813-64	982346.310	Repulse Bay Northern store
923		982343.284	Repulse Bay airport
99992		982343.317	Repulse Bay apron
925		982180.598	Cape Dorset airport
99993		982180.794	Cape Dorset apron

The apron gravity values were corrected by –0.4 mgal to account for the height of the gravimeter above the apron (1.3 m) in the airborne gravity processing.

Gravity reference measurement, Repulse Bay

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

$$y = sT + kB' + C$$

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 leveled, and a cross-coupling correction C is computed in real time by the gravimeter control computer.

For the 2002 survey, some communications or embedded computer problems meant that the spring tension T was not recorded properly on the data logger (but T-counter was OK on the gravimeter itself). It was therefore necessary to read the gravimeter and PC real-time display at frequent intervals (every 2-4 min) to monitor the offsets. The data data was subsequently corrected in a program "readsync" which would correct the errors. This turned out to work reasonably well, and the residual errors from the synchronization are believed to be less than 0.5 mgal r.m.s. The gravimeter embedded computer was repaired at ZLS corp. after the survey, with the unusual error fixed but still unexplained.

From the relative gravity measurements y, free-air gravity anomalies at aircraft level are obtained by

$$\Delta g = y - y_0 - h'' + \delta g_{eotvos} + \delta g_{tilt} + g_0 - \gamma_0 - (h - N)\frac{\partial \gamma}{\partial h}$$

where h'' is the GPS vertical acceleration, δg_{eotvos} the Eotvos correction (computed by the formulas of Harlan, 1968), y_0 the base reading, g_0 the apron gravity value, γ_0 normal gravity, h the GPS ellipsoidal height and N the geoid undulation (EGM96 used throughout). The platform off-level correction δg_{tilt} is expressed as

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

where a and A denotes horizontal kinematic aircraft accelerations and horizontal specific forces measured by the platform accelerometers, respectively.

Base readings y_o were done a daily basis, typically upon arrival. The S-99 was were stable over the whole period, with a total drift of less than 2 mgal for the 14-day period.

Results were finally filtered with a symmetric 2nd order Butterworth filter with a half power point at 200 seconds, corresponding to a resolution of 6 km (half-wavelength). The used filter is shown in Fig. 4. All processing was done on as line-by-line basis, using an interactive postscript plotting interface for inspecting results and fixing possible problems in GPS (cycle slips) or the gravimeter.

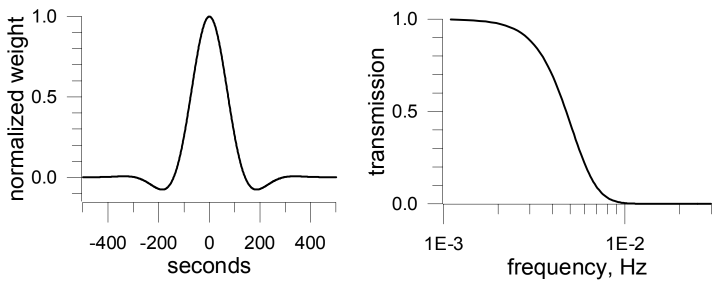


Fig. 4. Impulse response (normalized) and spectral representation of the filter

5. Final results and evaluation

The final data are given in a file in the form: *id, lat, lon, H, g, Δg, time (JD),* where id = lineno*1000 + running no, H the orthometric height, g absolute gravity and Δg the GRS-80 free-air anomaly in GRS80. Heights are orthometric heights with the EGM96 geoid. The numeric line numbers are indicated in Table 3. Plots of the processed free-air anomalies are shown in Fig. 5 and 6.

R.m.s. cross-overs of the airborne data was 2.6 mgal. If errors are assumed uncorrelated this corresponds to invidual track errors below 2 mgal. Comparisons to the existing data along the coasts (cf. Fig. 5) showed a mean offset of –1.1 mgal and a standard deviation of 3.5 mgal for points within 1 km of the airborne tracks. It should be noted that local terrain effects and upward continuation effects will affect this comparison, and results are therefore consistent at the estimated 2 mgal level.

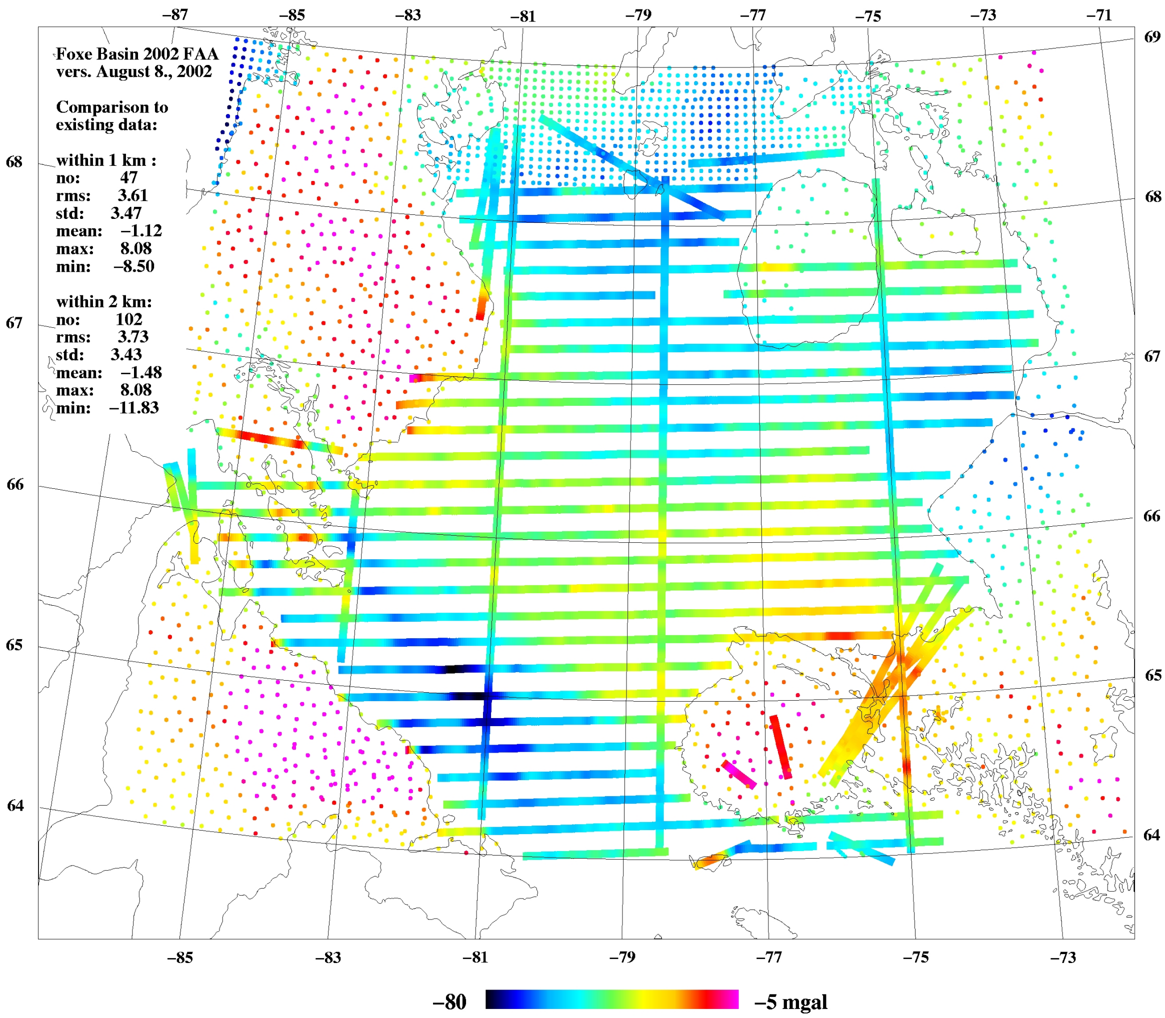


Fig. 5. Processed free-air anomalies and existing NRCan point data in the Foxe Basin region.

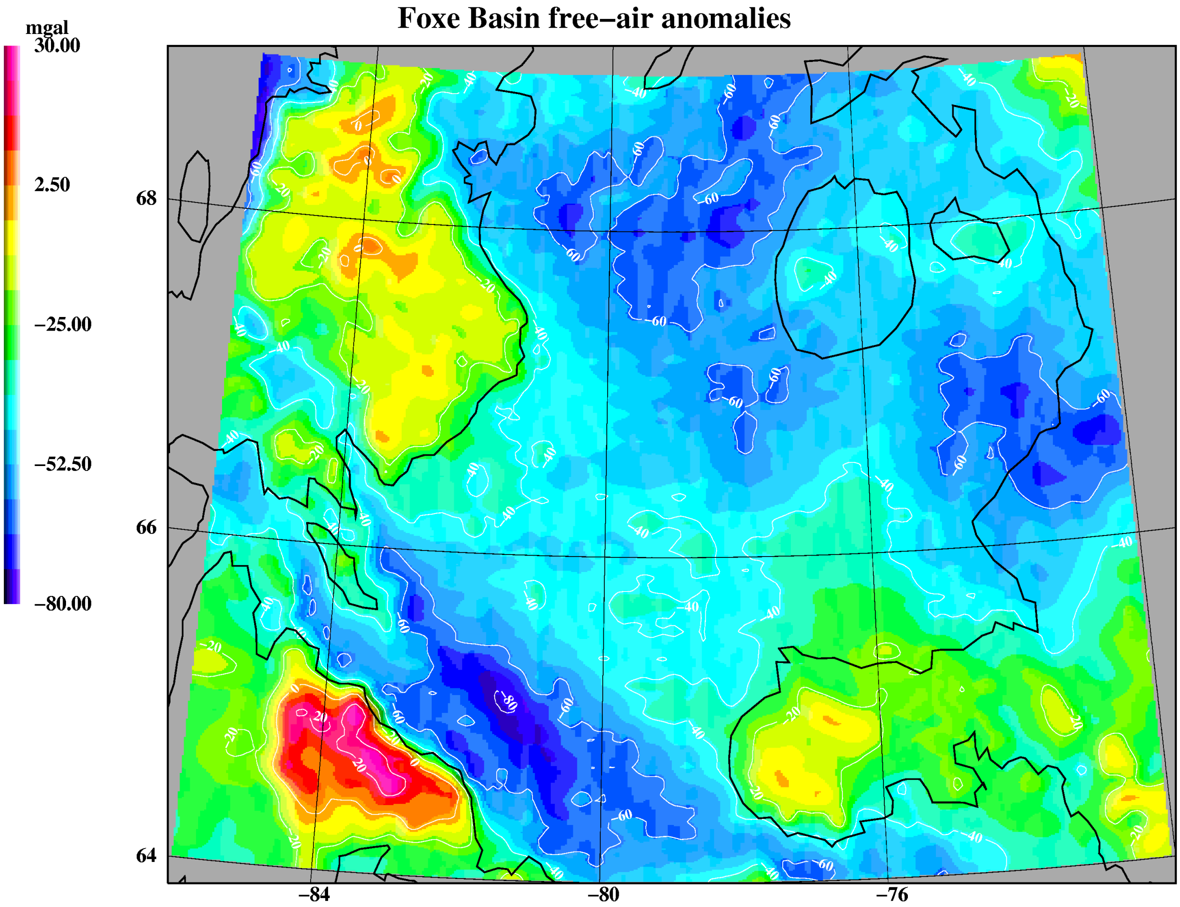


Fig. 6. Composite free-air anomalies.

6. Conclusions

A successful and cost-effective survey of the last major void in the Canadian Arctic was done, and made an important contribution to the Arctic Gravity Projects. Free-air gravity anomaly results are estimated to have an accuracy of 2 mgal at 6 km resolution.

Acknowledgements

The Foxe Basin airborne gravity survey was done with economic and in-kind support from NRCan, NIMA and KMS. The post-survey processing effort was done mainly by A. V. Olesen, N. S. Dalå and E. Howe.

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APPENDIX

The raw and processed data of the Foxe Basin project are placed CD-ROM, together with some internal KMS processing files. The main content of the CD-ROM is:

foxe2002.doc – this report
FINAL – the final data (Foxe Basin and connecting lines from Greenland)
RAWGPS – raw GPS files ordered by Julian data. These data have earlier been forwarded.
LCRSYNC – synchronized Lacoste and Romberg eaw gravity data
BASEREAD – basereadings
G_PROC – processing option files for KMS internal system
GPS – GPS solutions
DOC – overview of flights and GPS data

Head and tail of the final results file (foxe.faa.aug8):

```
   30001  68.15434  -81.93848   161.67  982399.3  -48.7  142.86796
   30002  68.15552  -81.90857   161.54  982399.4  -48.7  142.86819
   30003  68.15671  -81.87872   161.49  982399.5  -48.7  142.86843
   30004  68.15802  -81.84893   161.50  982399.3  -48.9  142.86866
   30005  68.15937  -81.81929   161.54  982398.9  -49.5  142.86889
   30006  68.16075  -81.78970   161.56  982398.2  -50.2  142.86912
   30007  68.16188  -81.75992   161.58  982397.5  -51.0  142.86935
   30008  68.16293  -81.73003   161.60  982397.2  -51.4  142.86958
   30009  68.16409  -81.70018   161.63  982397.3  -51.3  142.86981
   30010  68.16529  -81.67042   161.69  982397.9  -50.7  142.87005
   ................

  550072  64.24342  -76.62695   313.40  982104.1  -35.0  153.89565
  550073  64.24344  -76.65642   313.38  982105.4  -33.8  153.89588
  550074  64.24337  -76.68623   313.28  982106.1  -33.1  153.89611
```

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