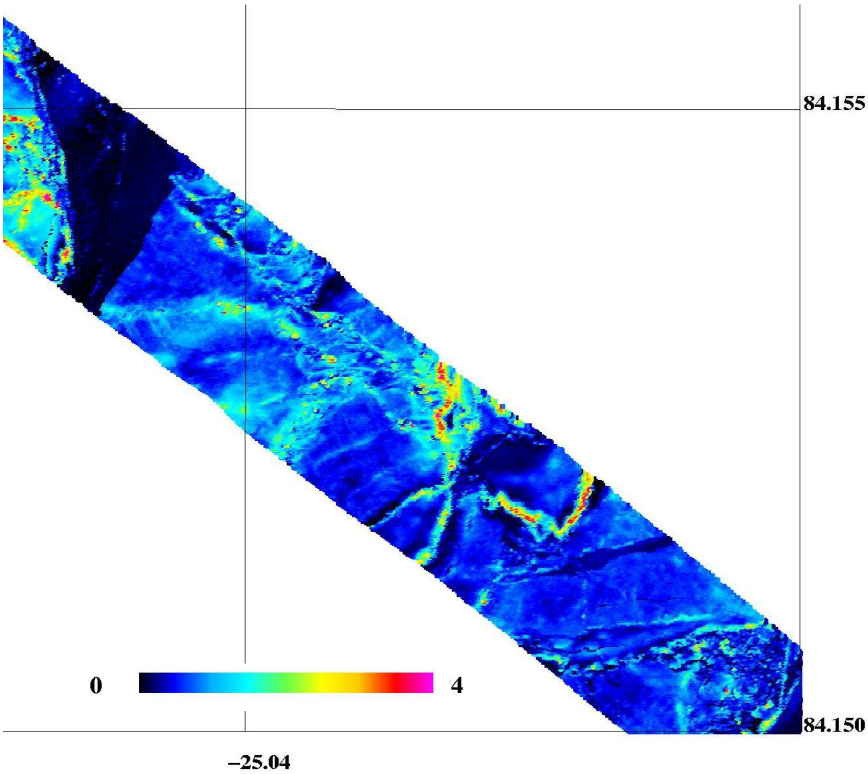
ESAG-2002

European airborne gravity and lidar survey in the Arctic Ocean

Final report
February 2003



by

R. Forsberg, K. Keller, S. M. Hvidegaard and A. Olesen
National Survey and Cadastre (KMS)
Denmark

Kort & Matrikelstyrelsen
National Survey and Cadastre - Denmark

esa

TABLE OF CONTENTS

1. INTRODUCTION

The ESAG-2002 airborne gravity and lidar (laser scanner) campaign of the European Space Agency (ESA) and Kort og Matrikelstyrelsen (National Survey and Cadastre of Denmark, KMS) has been carried out in the period April 29 – May 19, 2002), with support from ESA and the Danish Natural Science Research Council.

The purpose of ESAG-2002 was:

- To acquire high-accuracy airborne gravity measurements of the Arctic Ocean, in support of ESA's GOCE mission, filling in voids in the existing gravity coverage in the polar region and providing control ties to older gravity surveys in the region.
- To acquire scanning laser ranging (lidar) data and profiling laser altimetry over the sea-ice north of Greenland, as a mean of measuring ice elevations, to provide background data in preparation for the ESA CryoSat mission.

The airborne survey was done using a chartered Air Greenland Twin-Otter aircraft (OY-POF), operating primarily from military airfields at Station Nord (Greenland) and Alert (Canada), as well as from Svalbard.

In addition to mapping of sea-ice by lidar, laser surveys were also done in profiles across the southern Greenland ice sheet (Kangerlussuaq to Kulusuk) as well as along selected parts of the East Greenland ice cap margin. These en-route surveys are not considered part of ESAG-2002, and have not yet been processed. Following the ESAG-2002 the aircraft and KMS crew continued to Hall Beach, Canada, for a cooperative NRCan-NIMA-KMS airborne gravity survey of the Foxe Basin, til May 2002 the last major gravity void in the Canadian Arctic.

Table 1. Summary of ESAG-2002 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. Flight from Kangerlussuaq to Station Nord, via Constaple Pynt airport. Laser survey of Geikie ice cap (repeat of earlier surveys 1996-1998). Laser survey of Greenland ice sheet margin and new islands off 79-glacier enroute.
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. Test flight and check of gravimeter in Svalbard.
May 10-16	Operations from Canadian Forces Station Alert. All lines flown as planned, in spite of aircraft generator fault, which resulted in aircraft non-availability for 2 days.
May 17	Flight from Alert to Thule Airbase via Nares Strait. Planned gravity/lidar profile over Greenland ice sheet margins could not be done due to clouds. End of ESAG-2002, aircraft continues to Canada.

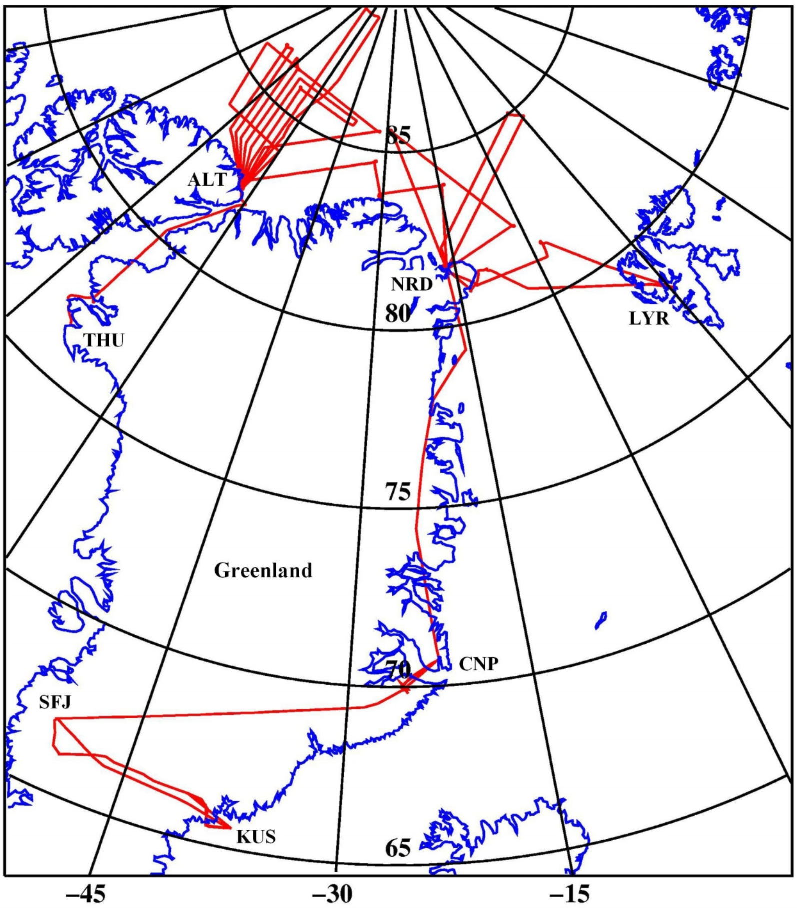


Fig . 1. Flight tracks of ESAG-2002. SFJ = Kangerlussuaq base airport; operations bases LYR = Longyearbyen, Svalbard; NRD = Station Nord, Greenland; ALT = Alert, Canada

The details of the field operations and science background may be found in appendix I (Progress report #2 – Field Operations), dated June 2002, and the detailed descriptions of the recorded raw data in appendix II (Raw data acquisition report), dated September 2002. A detailed map of the flights North of Greenland is in appendix III.

This report mainly describes the processed GPS, gravity, and laser altimeter data for ice thickness measurement. These data have been enclosed on a CD-ROM as well.

The scanning lidar data processing is still underway, and is very much an area of active research. Due to the large volume of scanning lidar data (approx. 30 CD-ROMs of raw data), the final lidar-swaths of ice thickness are *not* included, but rather some examples of results are included. Beside that all raw data and a general recipe are given on how to convert the scanning lidar data into ice freeboard heights. Table of contents of the CDs is in appendix V.

2. AIRCRAFT POSITION AND ATTITUDE PROCESSING

Aircraft GPS positions are fundamental for both airborne gravity and lidar processing.

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 2. Three separate geodetic dual-frequency GPS receivers (AIR1: Trimble 4000 SSI; AIR2: Ashtech Z-Surveyor; AIR3: Javad Legacy) were connected to the two antennas. All GPS data were recorded at 1 Hz.

Table 2 shows the used reference positions. The reference coordinates were computed using "AutoGipsy" of JPL and typically have an accuracy better than 5 cm in ITRF2000. (http://www.unavco.ucar.edu/data_support/processing/gipsy/auto_gipsy_info.html.)

Table 2. Reference GPS coordinates as computed by KMS.

Station	Lat	Lon	Ell. height	Comment
SFJ	67 00 21.6517	-50 42 9.6773	72.01	
KUS	65 34 40.5259	-37 9 11.9715	72.04	
NRD1	81 36 5.0977	-16 39 43.5273	70.04	
NRD2	81 35 49.7660	-16 39 24.8776	67.51	
LYR (8/5a)	78 14 51.4679	15 29 35.0743	52.52	*
LYR (8/5b)	78 14 51.4649	15 29 35.0779	52.56	*
LYR (9/5)	78 14 51.4646	15 29 35.0683	52.55	*
ALT1	82 30 41.5574	-62 19 36.3358	56.27	
ALT2	82 30 39.9955	-62 18 55.6712	42.81	
THU	76 32 16.4222	-68 47 48.0292	43.88	*
CNP	70 44 40.2403	-22 38 53.4847	70.77	*

* Only one file used to determine position

At least two independent aircraft GPS solutions were made by combinations of different reference stations and antenna. It is estimated that the GPS solutions are generally accurate at the 20-30 cm level r.m.s., for an example see fig. 3. The GPS conditions of 2002 were generally OK, with relatively few problems due to ionospheric problems. An example of the aircrafts natural phugeoid motion is shown in Fig. 2.

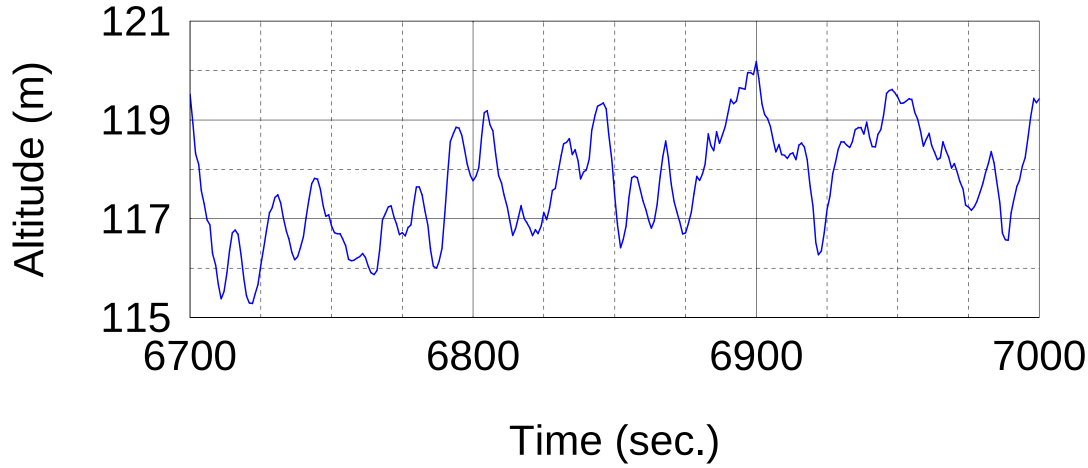


Fig. 2. Example of aircraft height during survey flight. Phugeoid motion of aircraft is seen.

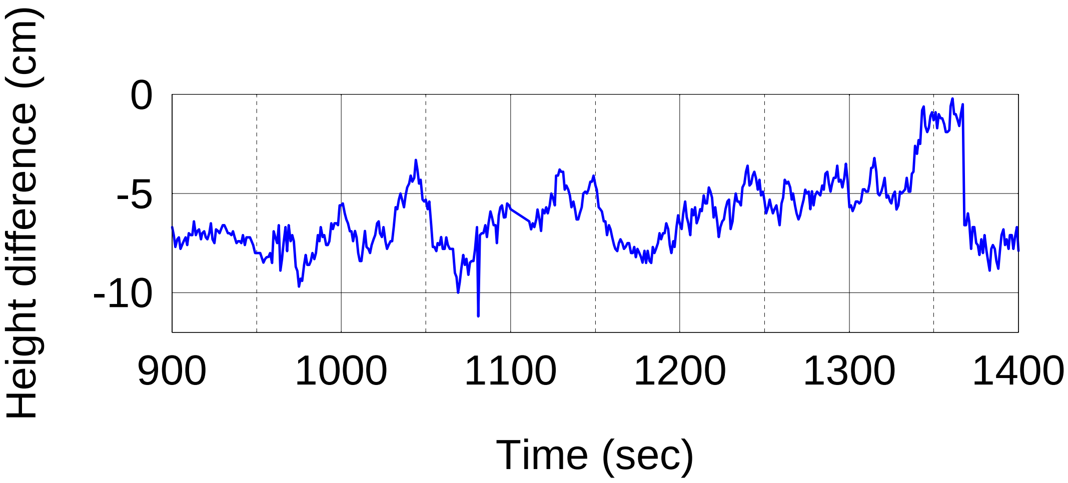


Fig. 3. Example of difference in height determination of AIR1 from different references (May 6).

GPS solutions were included in the raw data files provided to ESA September 2002.

Attitude data (roll, pitch and heading) are obtained from the Honeywell H-764G INS, an embedded GPS-INS military inertial navigation system. The INS was initialized for 5-8 minutes prior to the survey, allowing the system to align and find the north direction by gyro compassing. Gyrocompassing was successful in all cases, despite the northern latitudes (Alert, 82°N).

The H-764 generates output data both in free-inertial and Kalman-filtered GPS-INS mode. The pitch and roll differences between these two modes were generally below a fraction of a degree, and thus fully satisfactory for laser pointing and GPS antenna coordinate transfer to the lasers and the gravimeter sensor. Fig. 4 shows an example of roll and pitch variations during survey flight.

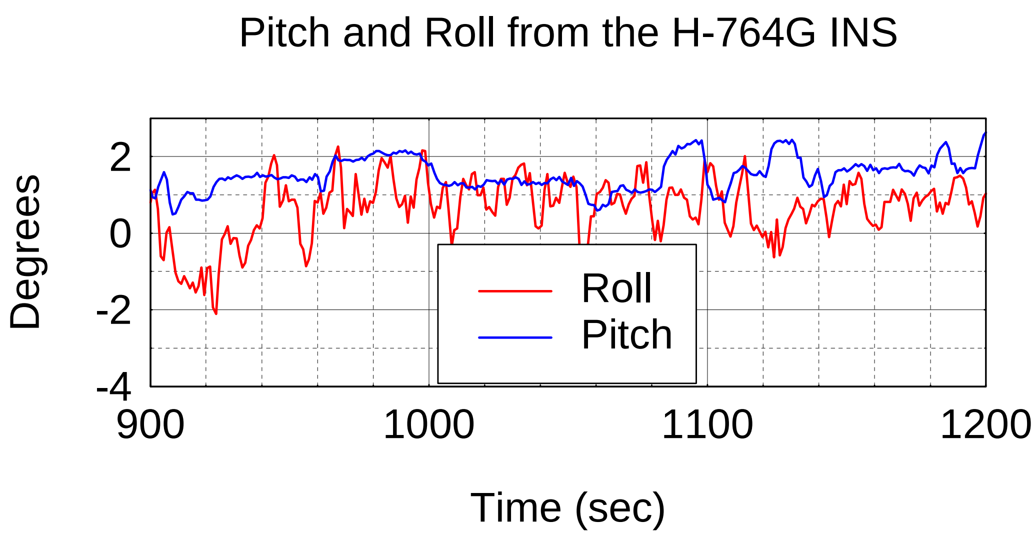


Fig. 4. Example of pitch and roll during straight-line survey (May 6)

The attitude data are time tagged in UT due to the embedded GPS receiver in the H-764 INS. The merging of GPS positions with raw H-764G (“EGI”) INS data is done with a program “GPSEGI”, that reads the raw Honeywell data files (.ddk files), logged at 50 Hz on a laptop PC through a 1553 military data bus interface.

The combined GPS-INS result files are in the form

Id, lat, lon, h, heading, pitch, roll

The Id is the time in UT in decimal hours. The heights h are by default ellipsoidal heights. To convert to height above the geoid the EGM-96 geoid model is routinely used. Alternative geoid models, based on the Arctic Gravity Project, may also be used. All geoid models are stored in GRAVSOFT grid formats (E-W rows from N to S, with a label header defining lat/lon limits and spacing).

An alternate inertial measurement unit – the Greenwood IMU – was also running and collecting data at 18 Hz during ESAG-2002. This unit is an experimental strapdown IMU sensor with fibre optics gyros. The unit served as a back-up unit, and have not been further utilized for ESAG-2002, since the H-764G functioned without problems.

3. AIRBORNE GRAVITY RESULTS

The airborne gravity data are obtained using the S-99 gravimeter. The data have been synchronized by the “READSYNC” programme to correct for the spring tension drifts of the 2002 survey due to some hardware problems, cf. appendix II. The corrected raw data files are equivalent to conventional raw data files, and the loss of accuracy by the manual spring tension synchronization is estimated to be below 0.2 mgal r.m.s.

The Lacoste and Romberg “S” gravimeter 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, kept horizontal by a feed-back 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 gravimeter 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. For the S-99 the following factors were used: s = 0.9967 mGal/CU and k = 29.3 mGal/(mV/s). The latter value was determined by an autoregression technique between measurements and GPS accelerations. The value is in good agreement with laboratory measurements.

Free-air gravity anomalies at aircraft level are (omitting second order terms) obtained by

$$\Delta g = y - h'' - \delta g_{eötvös} - \delta g_{tilt} - y_0 + g_0 - \gamma_0 + 0.3086\,(h - N) \qquad (2)$$

where h'' is the GPS acceleration, $\delta g_{eötvös}$ the Eötvös correction (computed by the formulas of Harlan, 1968), y_0 the basereading, 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

$$\delta g_{tilt} = y_{obs} - [y_{obs}^2 + A_x^2 + A_y^2 - a_x^2 - a_y^2]^{1/2} \qquad (3)$$

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, cf. Olesen et al. (1997).

Basereadings of the survey were very consistent, with negligible drift, allowing an independent check on the quality of basereadings before and after flights. The reference gravity values used in the airports were based on relative ties to the absolute gravity precision nets of Svalbard, Greenland and Canada, and are generally better than 0.1 mgal. The reference gravity values, forming the basis of the airborne gravity survey, are listed below.

ESAG-2002 gravity reference gravity values

Longyearbyen, Svalbard (apron)	982962.94 mgal
Station Nord (Garage)	983068.75 mgal
Alert apron (Hilton building)	983127.49 mgal

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 anomaly 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 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 non-linear terms, mainly represented by the tilt correction, are quite sensitive to the initial filtering.

A typical processing output file is shown in Fig. 5. All data were filtered with a symmetric second order Butterworth filter with a half power point at 200 seconds, corresponding to a resolution of 6 km (half-wavelength). The impulse response and spectral behaviour of the used filter are shown in Fig. 6.

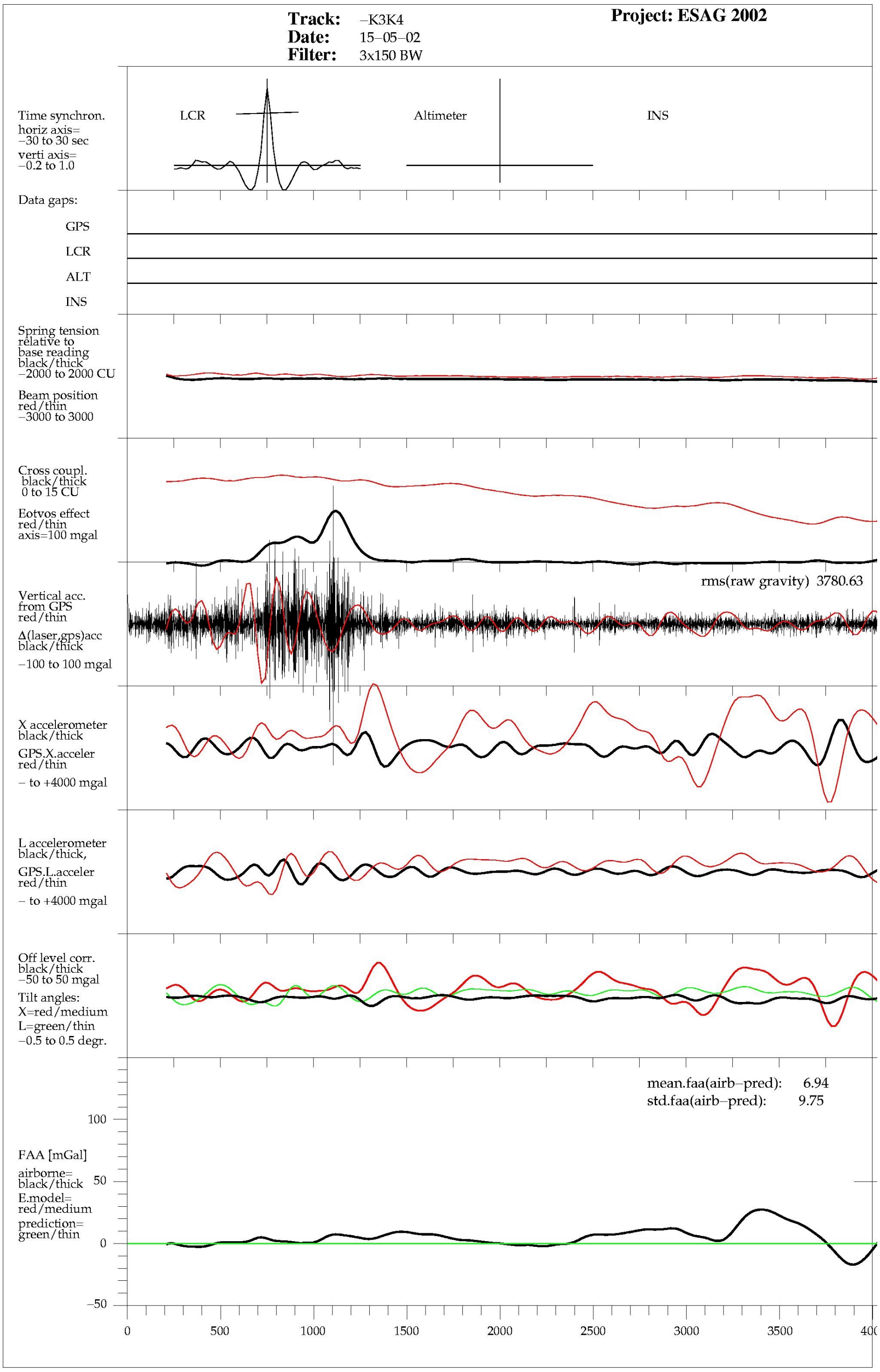


Fig. 5. Typical graphical example of line processing. The plots show from top to bottom the raw gravimeter data, accelerations from GPS, tilt corrections and the final gravity anomalies.

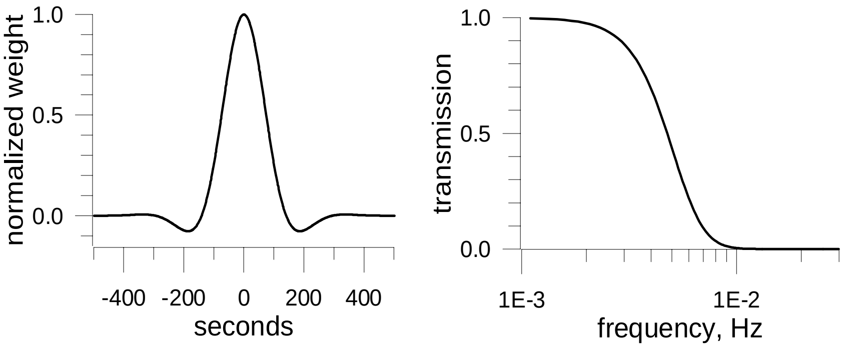


Fig. 6. Impulse response (normalized) and spectral representation of the filter

The results of the processing resulted in more than 95% of all flights being successful. Processing could be extended on the lines to within approximately 3 minutes of the line end. Data are presented in file format in the form

$$id,\ lat,\ lon,\ H,\ g,\ \Delta g,\ time\ (JD)$$

where *id = lineno*1000 + running no,* H the orthometric height, g absolute gravity and Δg the GRS-80 free-air gravity anomaly.

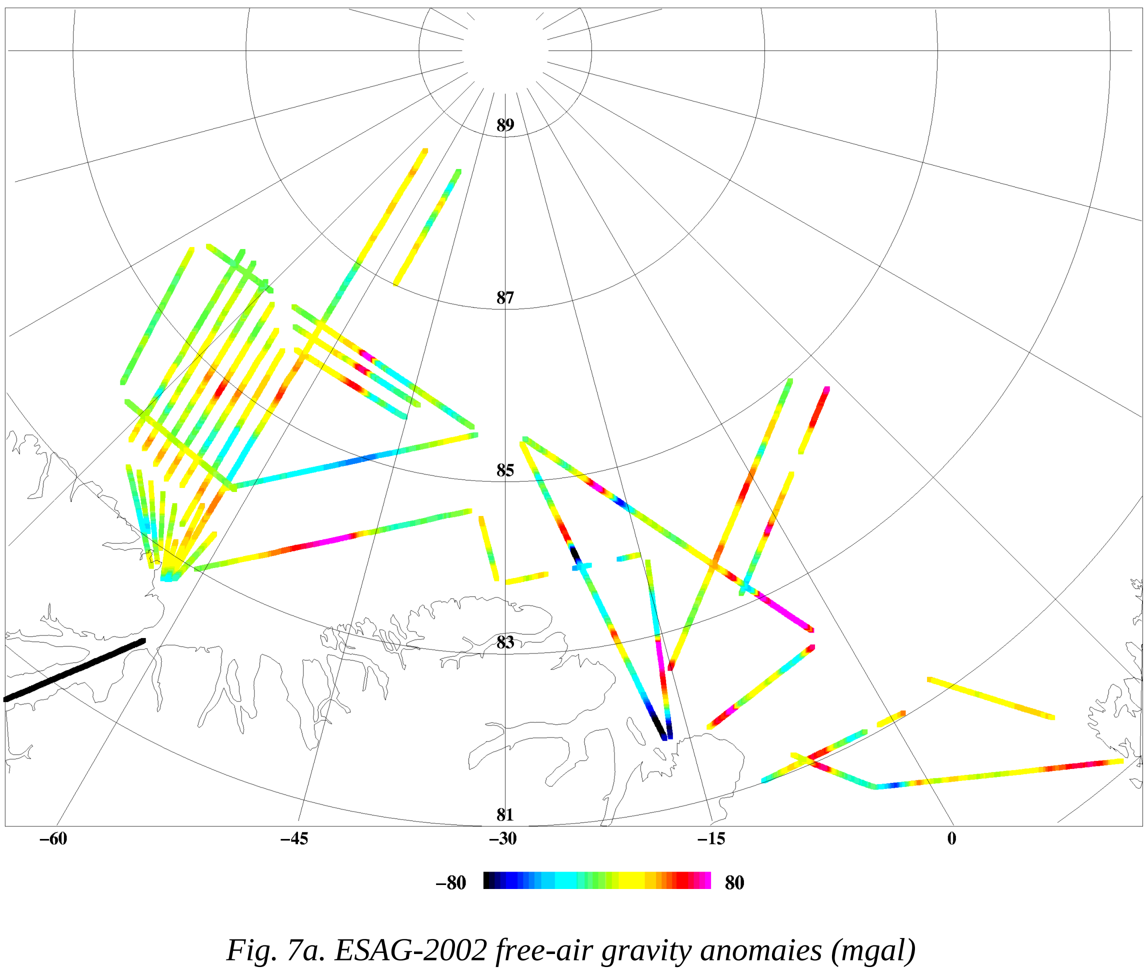


Fig. 7a. ESAG-2002 free-air gravity anomaies (mgal)

The final track data were evaluated by a bias-only cross-over adjustment. This showed a standard deviation of

$$\sigma = 2.4 \text{ mgal}$$

Assuming that the track noise is uncorrelated, the estimate of the noise on individual tracks would be $2.7/\sqrt{2} = 1.7$ mgal. We therefore estimate that the survey results are good to 2 mgal r.m.s. with a resolution of 6 km. It should be pointed out that *no* cross-over adjustment was applied to the final data. Fig. 7a and 7b shows the final ESAG-2002 free-air anomaly data by itself and merged with other data.

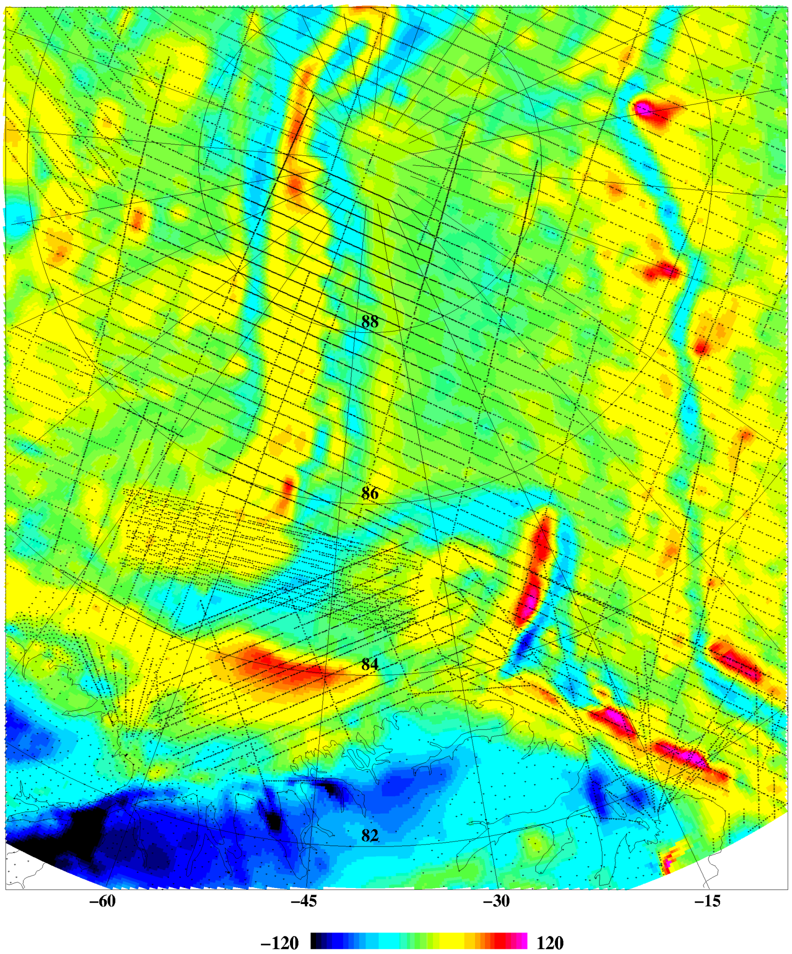


Fig 7b. Composite free-air anomalies (Bouguer on land) north of Greenland. Locations of airborne gravity data from KMS, NRL and PMAP shown. Major anomalies are associated with the main bathymetric features (Lomonossov Ridge and Morris Jesup Rise)

For an external data comparison, the ESAG-2002 data were compared to earlier collected airborne data:

1) The US Naval Research Laboratory 1998-99 data, collected north of the ESAG-2002 area by long survey lines from Svalbard (proprietary data, data provided by J. Brozena, NRL). The NRL data were collected at 2000 ft flight elevation, but due to larger aircraft speed filtered more heavily than the ESAG-2002 data.

2) Airborne gravimetry of the PMAP 1998 Canadian/German airborne geomagnetics survey (the smaller area NE off Alert with dense tracks). The PMAP aerogravity data have been provided by J. Halpenny, Geodetic Survey Division, Canada. The estimated standard deviation is 5 mgal.

3) KMS airborne gravity data 1998-2001 (1998 data only in Lincoln Sea). These data were processed using the same methods as ESAG-2002.
4) Airborne gravity data collected 1997-99 by the Alfred Wegener Institute, Germany, as part of the NORDGRAV and NOGRAM projects. The data was provided by T. Boebel, AWI, and are preliminary.

The comparisons were done by predicting from the KMS data sets at the location of the other data sets, comparing only values within short distance (less than 2 or 3 km). Table 3 shows the statistics of this comparison for the different other data sets, as well as the internal KMS data set consistency. Fig. 8 shows the location and magnitude of the misfits between the KMS 1998-2002 airborne surveys and the NRL 1998-99 surveys. It is not straightforward to do this comparison due to different flight elevations and filtering applied. In areas with a large gravity field variability (Lomonossov Ridge and Morris Jesup Rise) the large gradients of the gravity field will give relatively higher discrepancies between the surveys than in the gravitationally more smooth areas. Overall, however, the consistency of the data sets is good, and biases reasonably small.

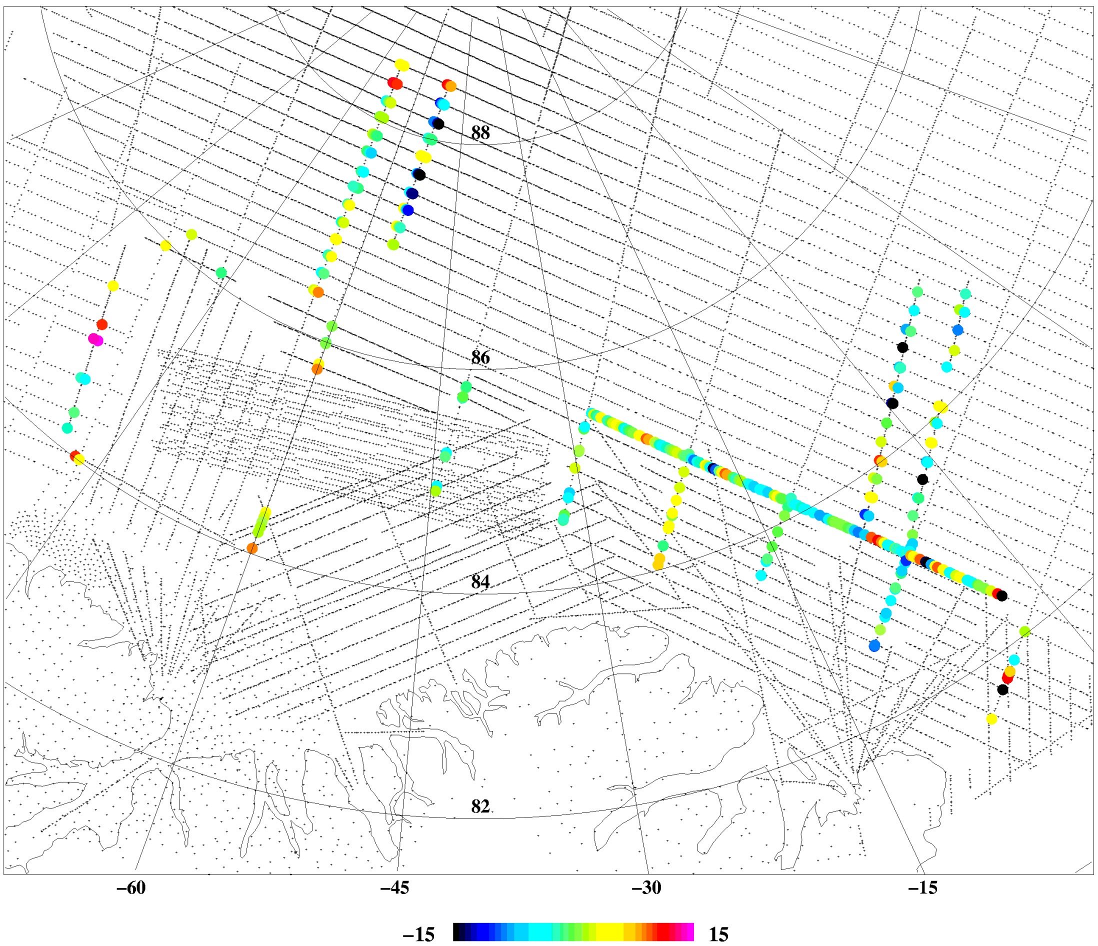


Fig. 8. Comparisons of ESAG-2002 data and NRL 1998-1999 airborne arctic data. Unit: mgal.

Table 3. Comparisons between different airborne gravity data sets in the Arctic Ocean (unit: mgal)

Data set	mean	std.dev.	min	max
ESAG-02 internal cross-overs	-0.1	2.4	-4	6
ESAG-02 vs. KMS1998-2001	-0.8	3.7	-16	13
ESAG-02 vs. NRL 1998-99	-0.5	5.8	-19	16
ESAG-02 vs. PMAP	1.2	5.1	-17	15
ESAG-02 vs. AWI	-5.8	11.2	-84	95

4. ICE FREEBOARD HEIGHTS FROM LASER ALTIMETER DATA

Data from a single-beam Optech "Rangefinder" infrared laser unit was logged on the Greenwood data logger at 100 Hz. The unit only provided useful data for less than half of the tracks, due to low fog, cold, or open water. The 1000 ft flight elevation is close to the maximum range of the unit. The laser altimeter data was supplemented with the vertical component of the lidar data, in some cases where the Optech unit did not provide returns, and the Riegl scanner did. More details of the lidar data can be found in the next chapter.

To reduce noise and data volume all laser altimeter data is averaged to 10 Hz, which correspond to 7 m along track ground resolution. Each laser range measurment has a footprint of approx. 1 m.

The processing of the laser altimeter data involve the several steps:

1) Finding ellipsoidal heights of sea-ice surface using GPS position, attitude angles and laser range.
2) Obtain sea-surface heights above geoid using geoid model
3) Adjust for geoid, GPS, laser and sea-surface errors by adjusting smooth "lowest level" curve to results.

This can be combined into equation 4, that describes the recovery of the freeboard height, F:

$$F = h_{GPS} - H_{laser} - N - \Delta h \qquad (4)$$

Here h_{GPS} is the height of the aircraft above the WGS84 reference ellipsoid determined by GPS, H_{laser} the laser range corrected for roll and pitch from INS, and N the geoid height taken from a geoid model derived from previous KMS airborne gravity surveys. Δh are deviations of the sea surface from the geoid caused by errors on the geoid model and changes in the sea surface topography due to tides and permanent sea surface topography. Also included in Δh are errors from possible laser offsets and misalignments and GPS errors. Δh is removed by filtering. The filtering is done by fitting a second order polynomial to the minimum values of the dataset since these minimum values corresponds to open water or newly refrozen areas. Final freeboard heights are found by subtracting the filter from the heights above the geoid.

Fig. 9 shows an example of the recovery of the sea-ice freeboard heights for a 250 km long track. The top black curve is freeboard heights after filtering, the bottom grey curve is heights before filtering and the bottom black curve is the filter polynomial.

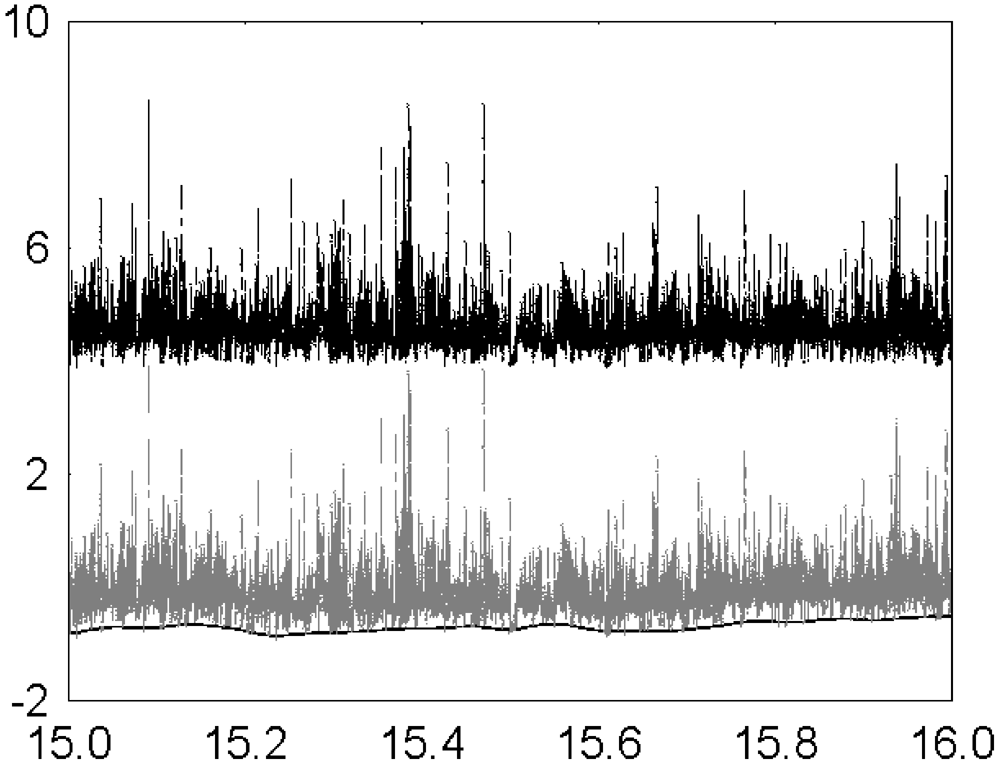


Fig. 9. Sea-ice freeboard heights, top: before (shifted by 4 m on the y-axis); Bottom: after filtering; bottom black curve shows the lowest-value filter

The sea-ice freeboard heights are converted into ice thickness using an assumption of equilibrium on scales longer than typical ice flow size (50-200 m). The principle is outlined in Fig. 10 and equation 5.

$$T = K * F \qquad with \qquad K = 1 + \frac{\rho_i h_i + \rho_s h_s}{h_i(\rho_w - \rho_i) + h_s(\rho_w - \rho_s)} \qquad (5),$$

with parameters as shown in Figure 10.

K=5.89 is used for this data set and is based on a model by Wadhams et al. (1992). This value for K is valid from April 30 to May 31. The presence of snow on the sea-ice is a major uncertainty for the k-factor, and the accuracy of the method cannot be fully utilized until improved models of snow depth can be obtained.

T is found for 4 km along track averages and shown in Figure 11 as a weighted mean gridded surface. This is only sensible since data from adjacent tracks are obtained within a few days. One should keep in mind the spatial variations of the drift velocities in the surveyed areas, which ranges from 15 cm/sec. in the Fram Strait decreasing to zero near Alert.

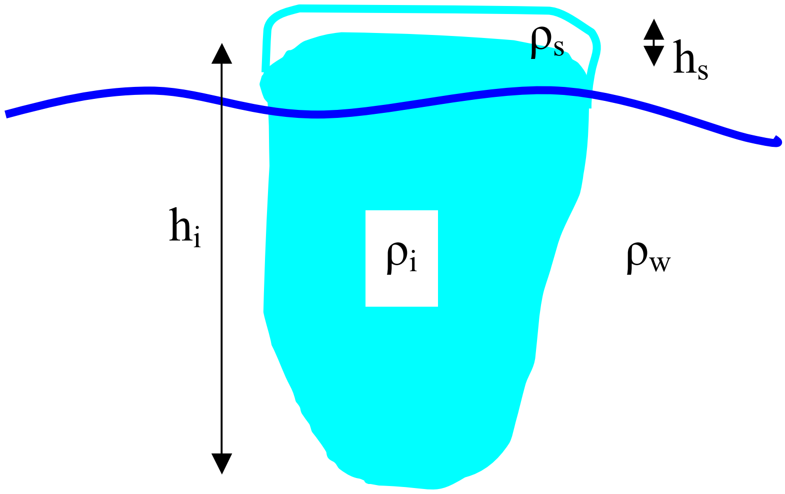


Fig. 10. Sea ice thickness determination principle

Fig. 11 displays the results of the sea-ice thickness determination from ESAG-2002 laser data. The missing tracks (compared to Fig. 1) are mainly due to fog and haze.

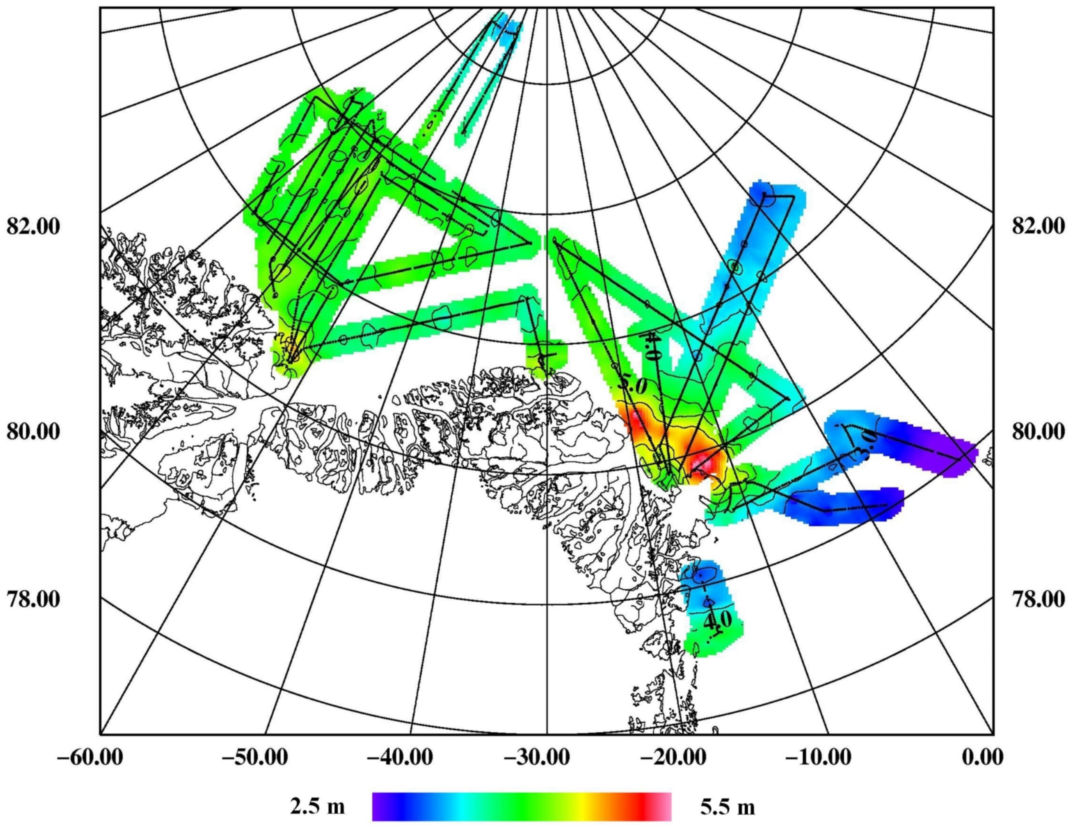
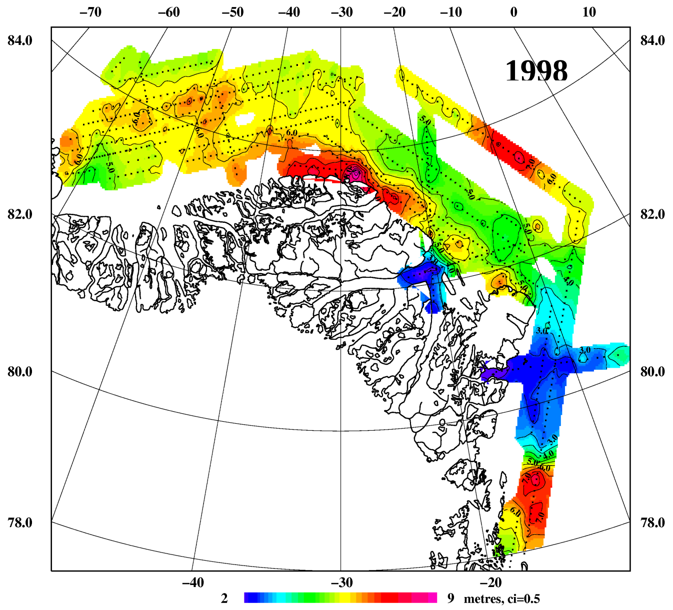


Fig. 11. Ice thickness for May 2002, based on ESAG-2002 data.

In June 1998 and May 2001 ice thickness data were collected using the same methods as piggy-back operations for airborne gravity. Fig. 12 shows the results for the different years, with gridding by weighted mean interpolation. The maps are showing the thick ice in the Lincoln Sea, North-West of Greenland, and the relatively thinner ice in the Fram Strait region, East of Green-land. A direct trend from year to year is difficult to quantify due to the seasonal variations in ice thickness and the limited coverage of the airborne tracks.



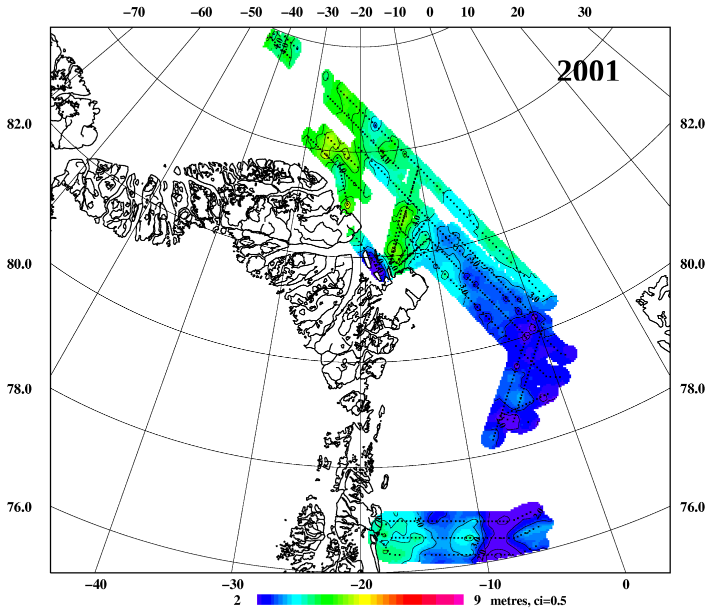


Fig. 12. Ice thickness maps from laser altimetry 1998 and 2001.

5. RIEGL SCANNING LIDAR SWATH ICE DATA

The swath lidar data provide approximately 200 samples of ice heights across the flight direction at a rate of 40 Hz. This results in ice freeboard heights at a resolution of approx. 1.5 m in a 300 m wide swath (equal to the flight altitude) along the flight direction, by similar principles as the processing of laser altimeter data.

The KMS Riegl Q140 laser scanner (lidar) data was logged as hourly files on a stand-alone laptop computer. The lidar files are time tagged by a 1 pps signal from the AIR1 GPS receiver, with start time of the scans given by the operator as a file name. Due to some instrument problems the Riegl files has the risk of 1-sec time shifts, which may occur during the hourly files. It is therefore recommended to avoid such shifts by processing the Riegl data in small batches, no longer than a few minutes (this also limits the very voluminous data!).

Raw lidar files are stored with names referring to the time they were started. The details of the logged lidar data can be found in Appendix II.

The raw lidar files may be converted into elevations above the sea surface by the following programs:

1) READSCAN – reads the raw lidar file, and produce ice-surface heights, using an optional geoid model. Note: The raw lidar files are in three possible formats: two binary and a text format. Great care should be excised in reading the files. Generally files with “.2dd” termination are binary. further information see the header of the ‘readscan.for’ file.

2) FITLIN – this program will fit a minimum surface to a laser swath data, providing (approximate) freeboard heights.

The program “PSE” may produce plots of the freeboard heights, either in lat/lon or as strips of data with along-track time as y-coordinate and a corresponding x-track time.

Sample input file for the READSCAN software:

```
201000.2dd            ! scan file
gpsegi.pos            ! a GPS-INS position file with attitude info
egm96n.gri            ! a geoid model (GRAVSOFT grid)
scan.out              ! output file
vert.out              ! vertical output file
17 26 00              ! scan start time; hr min sec
17.700 17.800         ! wanted time interval in dechr2
-90 90 -90 90         ! geographic limits
1 1 t t t t t         ! nave ithin lbin lnew lpr lcalib, lgeo
0.0 -0.35 1.42        ! ant offset a3 (-3.26 0.52 1.77 ant offset a1)
0.55 -1.35 1.80 0.0   ! pitch0 roll0 hdg0 and time offset (sec)
10  2  195            ! minamp, min scanang, max scanang
t                     ! true bin header
10                    ! min. range (m)
```

The boresight/offset angles have been determined during the test flight over the buildings in Kangerlussuaq April 29th. Before flight, the corners at the roof of a box-shaped buliding were surveyed in order to calibrated the offset angles between the INS and the laser scanner. By flying in a four-leaf clover figure over the building the angles can be well determined. This is not yet automated and very much research in progress.

Sample input data for FITLIN (May 9):

```
scan.out         ! input file
scan.dat         ! output file for plotting
0.002 0.5 t      ! dtmin, rejl, lcut
```

The figures 13-15 below show a number of examples of scanner data as plotted with pse. Work is ongoing to derive statistical properties of the ice thickness data. The lidar scanner also has an amplitude channel. This may occasionally provide a clear resolution of structures in thin new ice.

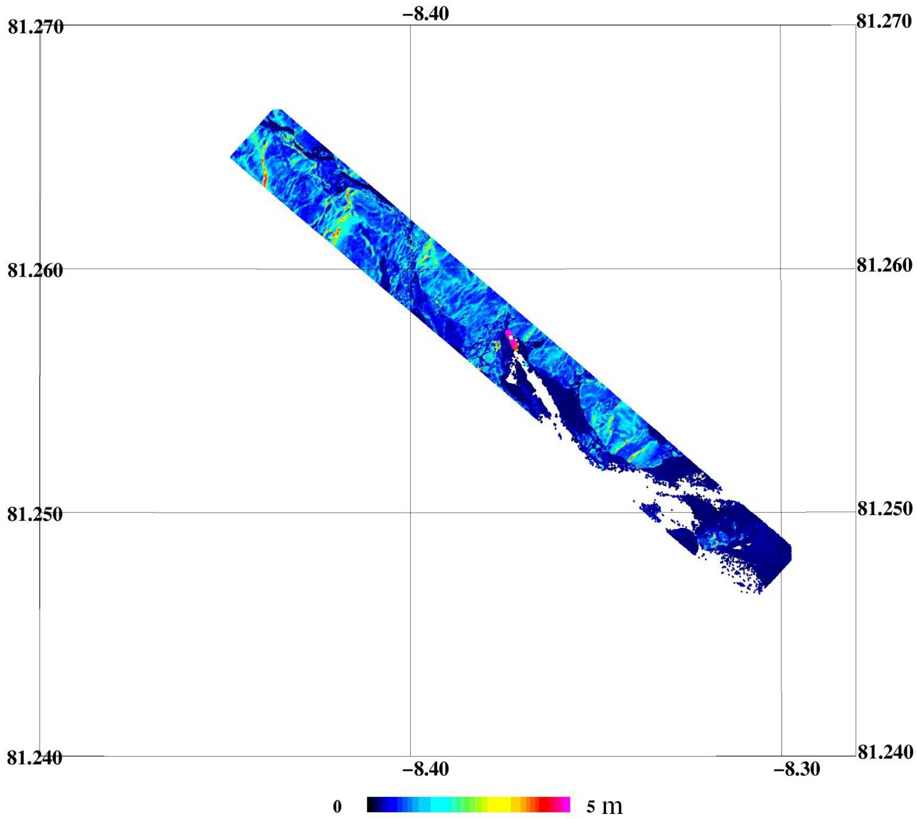


Fig. 13. May 9 – ODEN overflight (ice thickness).

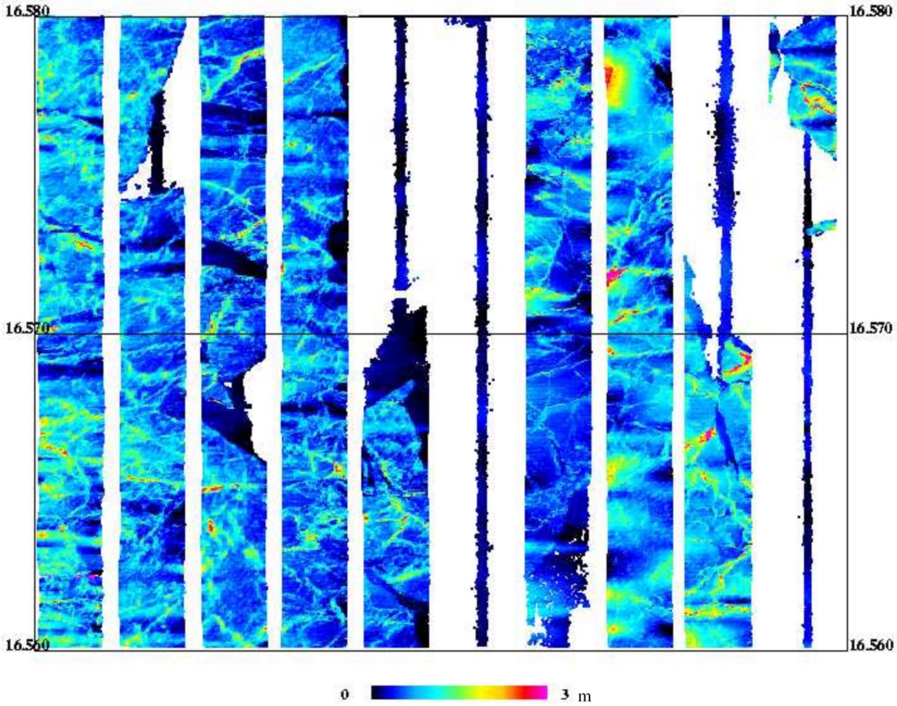


Fig. 14. Example of 12-minute lidar sequence freeboards (Fram Strait, May 9, starting at 16.56 dechr). Strips are continuous from left to right. Open-water stretches are seen as narrow return band.

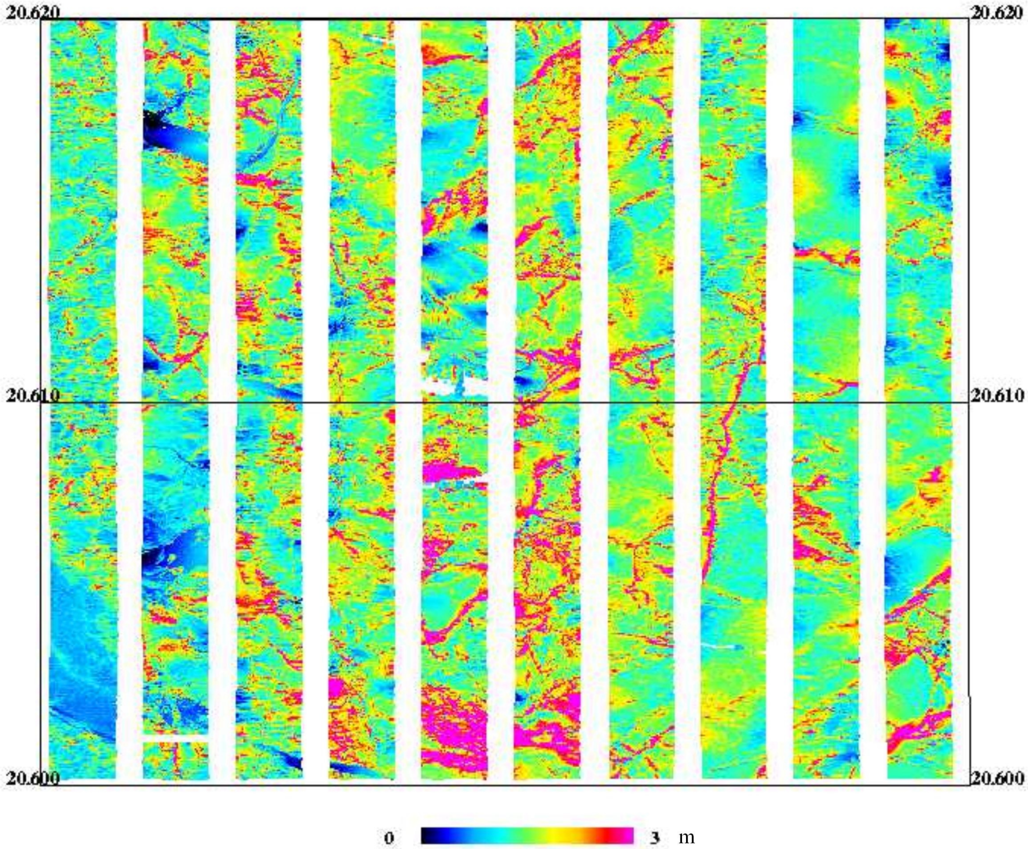


Fig. 15. Sea-ice freeboard heights in compact ice area north of Alert (May 15, 12 min from decimal hour 20.60).

6. AUXILLARY COMPARISON DATA: ICE DRILLING AND SHIPBORNE VIDEO

On-board video:

Approximately 30 1hr DV-tapes were recorded using a video camera looking out the right-hand side window of the aircraft. Five examples of video clips in mpeg-format are given on the final result CD.

Table 4. Approximate latitude/longitude of video sequences, Lincoln Sea

File name	Approximate lat/lon (DD MM.M)
e1755.mpg	84 15.7 N 44 23.6 W
gf1520.mpg	86 05.3 N 52 21.3 W
gf1647.mpg	85 00.7 N 48 41.4 W
gf1736.mpg	83 59.8 N 62 20.8 W
i1828.mpg	86 58.2 N 55 15.2 W

The comparison of lidar scenes and video has not yet been performed.

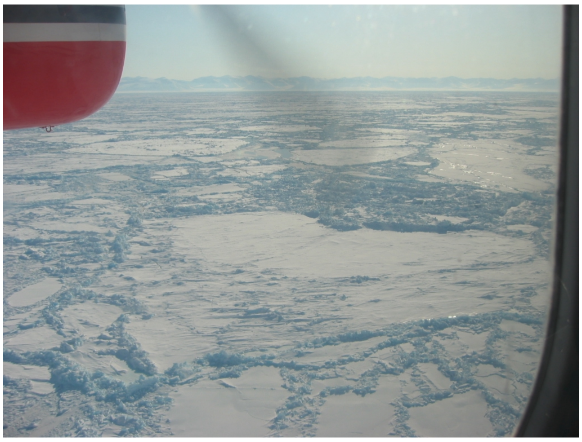
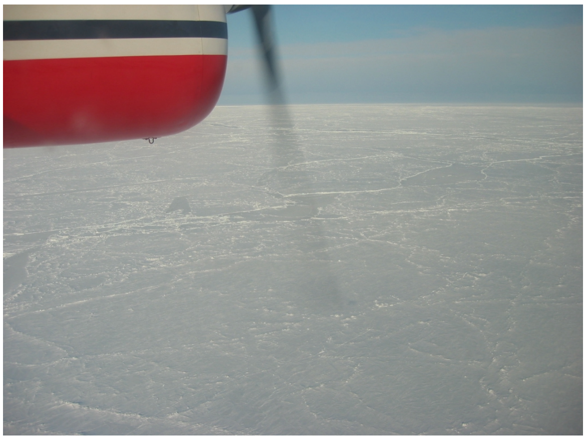
 

Fig. 16. Left: Typical thick sea-ice. May 10 flight off the north tip of Greenland (coastline in background) Right: Typical thinner sea-ice further north in Polar Sea (May 12 north pole flight).

Ice thickness and density:
Limited reference measurements of sea-ice thickness, snow density and thickness were taken off Station Nord (on fast ice) and off Alert (on polar pack ice floes). The results are summarized in Table 6.

The measurements off Alert have a reasonably good agreement with the lidar scanner results, cf. Fig. 18.

Table 6. Ice thickness measurements off Station Nord and Alert
(F is freeboard height, K freeboard to thickness conversion factor)

	Lat N	Lon W	Snow depth (m)	Snow +ice (m)	Snow density (g/cm**3)	F (m)	K
St. Nord	81 37.08	16 44.88	0.95	2.40	0.35	0.79	3.0
(fast ice)	81 38.22	16 49.86	0.68	2.21	0.30	0.64	3.5
Alert	82 32.01	62 09.64	0.50	4.50	0.32	0.77	5.8
(polar pack)	82 32.12	62 07.63	0.48	3.30	0.35	0.62	5.3
	82 32.25	62 05.28	0.35	3.00	0.35	0.51	5.9
	82 32.25	62.06.96	0.60	4.10	N/A	0.77	5.3
	82 32.26	62 07.25	0.70	5.10	0.35	0.93	5.5
	82 30.07	62 08.22	0.50	6.10+	N/A	(0.93)	(6.6)
Alert average			0.52	4.35+	0.34	0.71	5.6

Fig. 17. Ice drilling off Alert and Station Nord

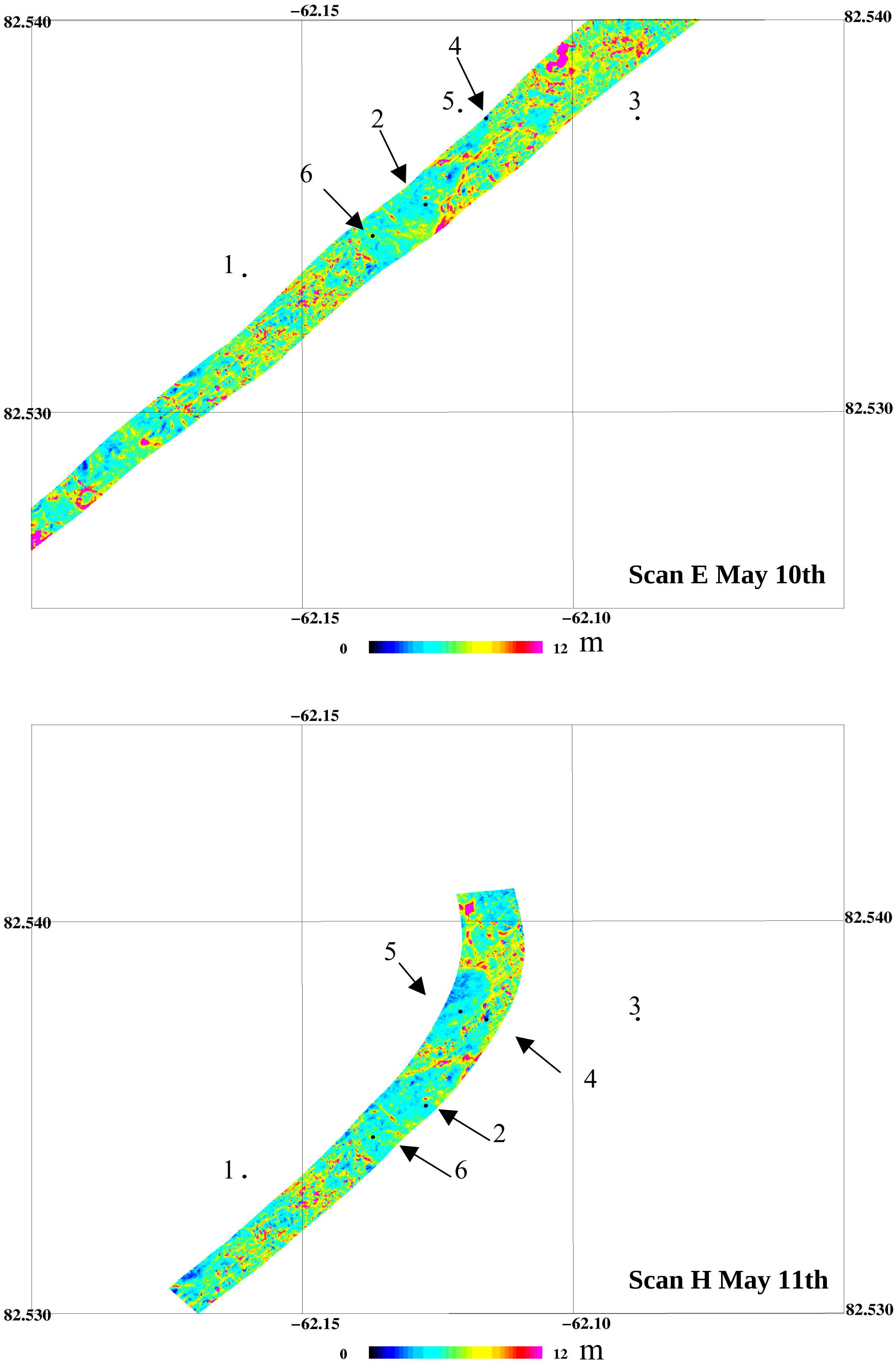


Fig 18. Comparison of laser scanner and measured thickness off Alert.

Ship-borne video – icebreaker "Oden"

ODEN carried out an oceanographic cruise in the Fram Strait and Greenland Sea in the period May 1 to June 8. With the helpful support from the crew of ODEN, an automated KMS web cam system was mounted on the bridge, taking pictures of the sea-ice at 20 sec interval, 24 hr a day, during the cruise. The images allow the occasional measurement of ice floe thickness and snow cover depth for ice floe fragments accidentally turned vertical during ice breaking. Approximately 4 GB of jpeg-imagery is available on CD-ROM archive, which can be provided on request. Fig. 20 shows the actual sailed track of Oden. Navigation data and auxiliary meteorological data have been prepared by the Oden crew, allowing geocoding of the data.

Fig. 19. Overflight of Oden icebreaker, May 6.

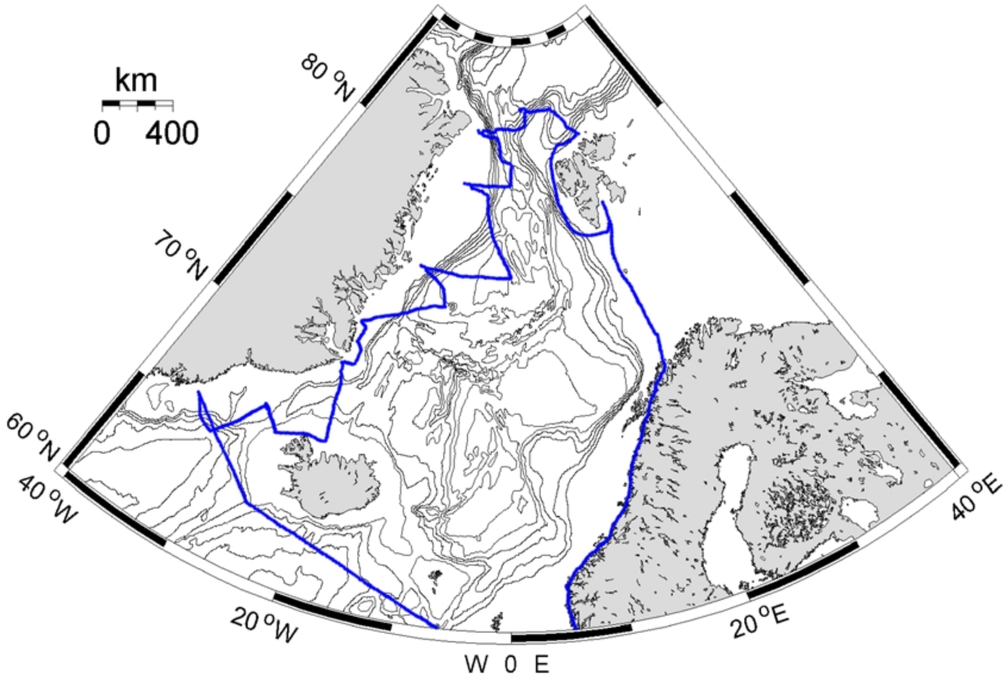


Fig. 20. ODEN cruise tracks, May 2002. 20 sec. web cam data available throughout cruise.

Fig. 21. Some examples of ODEN web cam images. Scale-stick is 2 m.

The thickness of ice floes, occasionally turned vertical, can be estimated by comparing to the 'scale-stick' mounted on the side of the icebreaker, see figure 21. Each mark on the stick corresponds to 50 cm. 10 % are added to the thickness estimates to account for the distance between the stick and the ice surface. Available thickness estimates from the imagery close to the aircraft tracks are shown in Fig. 22. The large differences are caused by the fact that the icebreaker only sail through the absolute thinnest parts of the ice cover, open or newly refrozen leads and thin ice. A few estimates of snow depth have also been obtained from the images giving a mean snow depth of 32 cm near the May 6th over flight of Oden.

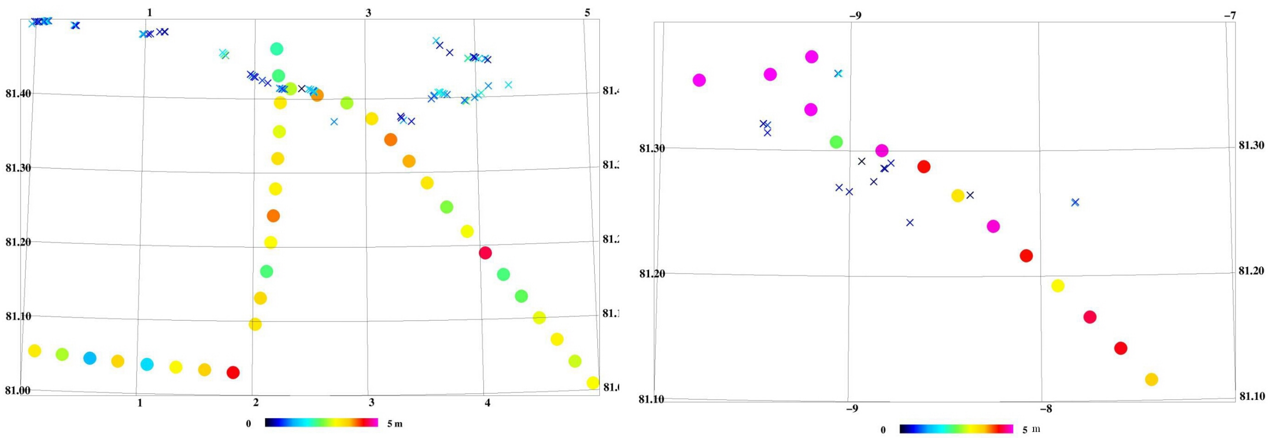


Fig. 22. Bullets: 4 km along track ice thickness estimates from laser altimetry.
X'es: Ice plus snow thickness from Oden web cam images. Left: May 6th, right: May 9th.

7. CONCLUSIONS

The ESAG-2002 field campaign for airborne gravity and lidar measurements was highly successful, with nearly complete recovery of gravimetry, and a fairly good recovery of laser altimetry, given the cold weather, frequent fog and some aircraft problems.

The data material is very rich, and the final scientific processing of lidar data is far from over.

The ESAG-2002 has filled one of the last voids of the Arctic Ocean from a gravity data point of view, and the gravity data have been used in the Arctic-wide gravity compilation under the IAG "Arctic Gravity Project". The data of this project will limit the "polar gap" problem of the future GOCE gravity mission.

8. REFERENCES

Brozena, J.M., Peters, M.F., and Salman R., 1997: *Arctic airborne gravity measurement program*. Proc. International Symposium on Gravity, Geoid and Marine Geodesy, Tokyo, Sept. 1996, Springer Verlag IAG series 117.

Forsberg, R., K. Keller, S. M. Jacobsen: *Laser Monitoring of Ice Elevations And Sea-Ice Thickness in Greenland.* International Archives of Photogrammetry, Remote Sensing and Spatial Information Systems, vol. XXXIV no. 3/W4, pp. 163-169, 2001.

Forsberg, R., A. V. Olesen, K. Keller: *Airborne gravity survey of the North Greenland continental shelf.* In: Sideris, M. G. (ed): Gravity, Geoid and Geodynamics 2000, International Association of Geodesy Symposia, vol. 123, pp. 235-240, Springer Verlag, 2001.

Forsberg, R., A. V. Olesen, K. Keller, M. Møller, Arne Gidskehaug, D. Solheim: *Airborne Gravity And Geoid Surveys in the Arctic And Baltic Seas.* Proceedings of International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation (KIS-2001), Banff, June 2001, pp. 586-593.

Harlan, R. B.: *Eotvos corrections for airborne gravimetry*. J. Geophys. Res., 73, 4675-4679, 1968.

Hvidegaard, S. M. and R. Forsberg, *Sea-ice thickness from airborne laser altimetry over the Arctic Ocean north of Greenland.* Geophys. Res. Lett., 29 (20), 2002

F.G. Lemoine, S.C. Kenyon, J. K. Factor, R. G. Trimmer, N.K. Pavlis, D.S. Chinn, C.M. Cox, S.M. Klosko, S. B. Luthcke, M.H. Torrence, Y.M. Wang, R.G. Williamson, E. C. Pavlis, R.H. Rapp, and T. R. Olson, *The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96*, NASA/TP-1998-206861, Goddard Space Flight Centre, Greenbelt, Maryland, July 1998.

Kenyon, S. and R. Forsberg: *Arctic Gravity Project – a status.* In: Sideris, M. G. (ed): Gravity, Geoid and Geodynamics 2000, International Association of Geodesy Symposia, vol. 123, pp. 391-395, Springer Verlag, 2001.

Olesen A V, R Forsberg, A Gidskehaug: *Airborne gravimetry using the LaCoste & Romberg gravimeter – an error analysis*. In: M.E. Cannon and G. Lachapelle (eds.). Proc. Int. Symp. on Kinematic Systems in Geodesy, Geomatics and Navigation, Banff, Canada, June 3-6, 1997, Publ. Univ. of Calgary, pp. 613-618, 1997.

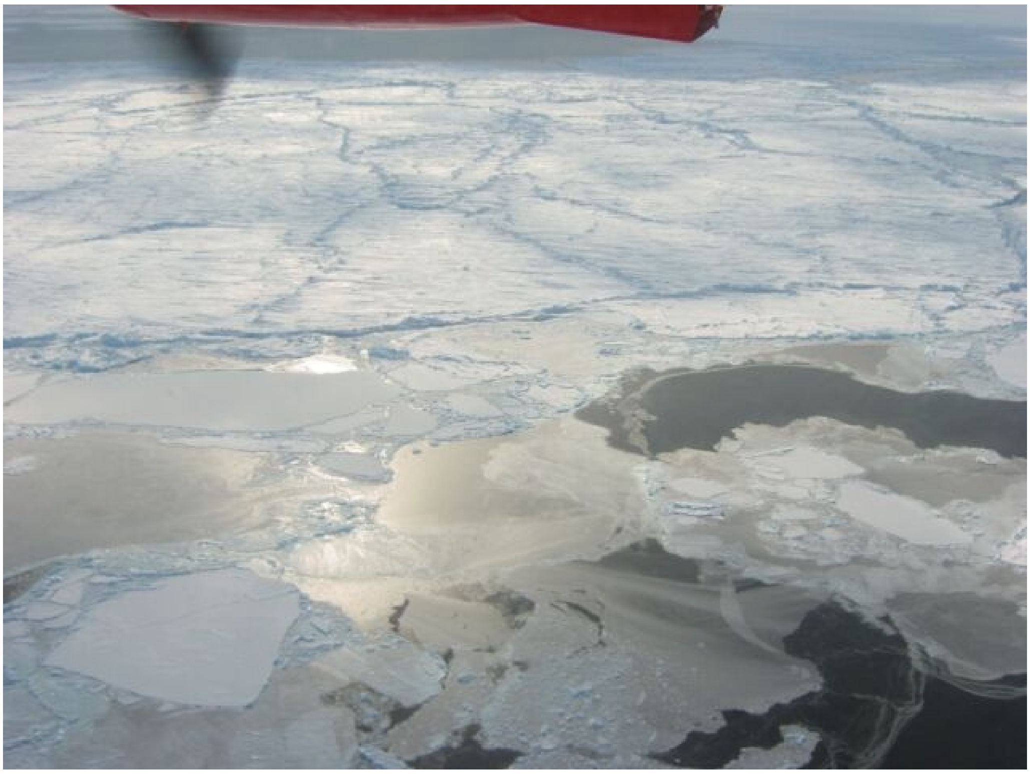
Valliant, H: *The LaCoste & Romberg air/sea gravimeter: an overview*. In: CRC Handbook of Geophysical Exploration at Sea, Boca Raton Press, 1991.

APPENDIX I – Progress Report #2 Field Operations.

ESAG-2002

European airborne gravity and lidar survey in the Arctic Ocean

Progress Report 2
Data acquisition report
June 2002



by

R. Forsberg, S. M. Jacobsen, K. Keller, A. Olesen
National Survey and Cadastre (KMS)
Denmark

Kort & Matrikelstyrelsen
National Survey and Cadastre - Denmark

esa

INTRODUCTION

The ESAG-2002 airborne gravity and lidar campaign of the European Space Agency (ESA) and Kort og Matrikelstyrelsen (National Survey and Cadastre of Denmark, KMS) have been carried out with success in the period April 26 – May 17, 2002. The airborne survey was done using a chartered Air Greenland Twin-Otter aircraft (OY-POF), operating primarily from military airfields at Station Nord (Greenland) and Alert (Canada).

The ESAG-2002 campaign had the following aims:

- To acquire high-accuracy airborne gravity measurements of the Arctic Ocean, in support of ESA's GOCE mission, filling in voids in the existing gravity coverage in the polar region and providing control ties to older gravity surveys in the region.
- To acquire scanning laser ranging (lidar) data over the sea-ice north of Greenland, as a means of measuring ice thickness, to provide background data in preparation for the ESA CryoSat mission.

In addition to these objectives some ground truth ice thickness measurements were carried out on the sea ice off Station Nord and Alert, and an automated web cam system was operated on the Swedish ice breaker "Oden", during a simultaneous oceanographic cruise in the Fram Strait and Greenland Sea.

In general all objectives of ESAG-2002 were met, the actually flown tracks were close to the planned pattern, and reasonably good weather conditions meant that most of the tracks had successful laser data acquired. The typical weather for ESAG-2002 was blue skies or thin, high clouds, with a temperature between –10 and –20 C. Some fog and low cloud patches were encountered, with total loss of useful laser data.

Flying north to the ESAG-2002 operations area in the Polar Sea, laser tracks were flown over selected areas of the East Greenland ice sheet margins (Isortoq region west of Kulusuk; Geikie Ice Cap south of Scoresbysund). In the Isortoq region 3 aircraft landings were made for snow pit measurements of accumulation and snow physics; in addition an automated climate station was installed. This part of the survey was done in cooperation with the glaciological group at GEUS (Greenland Geological Survey, Copenhagen), and was funded by a national CryoSat research grant.

After the ESAG-2002 campaign in the Arctic Ocean, the aircraft and KMS scientists continued to Canada for an airborne gravity survey of Foxe Basin, done in the period May 22-June 4. The FOXE-2002 project was done in order to cover the largest gap in gravity coverage of the Canadian Arctic, taking advantage of the ESAG-2002 aircraft installation and logistics. The FOXE-2002 campaign was supported by the Geodetic Survey Division (National Resources, Canada), and by the National Imagery and Mapping Agency (NIMA), USA.

This report outlines the operations and the data collected for ESAG-2002. Raw formatted data will be delivered on a set of CD-ROMs to ESA by September 2002; final report will be available by the end of the year.

Air Greenland Twin-Otter at Station Nord

SUMMARY OF KMS OPERATIONS

April 26-29	Installation of scientific equipment in Air Greenland hangar at Kangerlussuaq, Greenland. Test flight. Set up of GPS reference stations at Kangerlussuaq and Kulusuk. Personnel: K. Keller and R. C. Andersen (KMS), C. E. Bøggild (GEUS), S. M. Jacobsen (from April 30).
April 29-30	Lidar survey of East Greenland ice sheet margin, Kulusuk region. Ice sheet landings in different elevations for snow pit measurements. Automated climate station set out by helicopter, aircraft landing not possible.
May 1	Return to Kangerlussuaq for gravimeter repair. C. E. Bøggild returns to Copenhagen, with Kulusuk GPS reference station. O. Meyer (University of Bergen, Norway) in Greenland for gravimeter repair.
May 2-3	Flight from Kangerlussuaq to Station Nord, with stop-over at Constaple Pynt airport. Laser survey of Geikie ice cap (repeat of earlier surveys 1996-1998). Laser survey of Greenland ice sheet margin and new islands off 79-glacier enroute. Science crew: K. Keller, S. Jacobsen (KMS), and Roger Haagmans (ESTEC).
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. Test flight and check of gravimeter in Svalbard. R. Forsberg and A. Olesen (KMS) join survey; K. Keller and R. Haagmans leaves.
May 10-16	Operations from Canadian Forces Station Alert. All lines flown as planned, in spite of aircraft generator fault, which resulted in aircraft non-availability for 2 days.
May 17	Flight from Alert to Thule Airbase via Nares Strait

	Planned gravity/lidar profile over Greenland ice sheet margins could not be done due to clouds. End of ESAG-2002.
May 18-22	Aircraft service at Thule Air Base (100 hr service and removal of skis), weather-bound.
May 23	Start FOXE-2002 airborne gravity survey from Hall Beach, Repulse Bay and Cape Dorset, Nunavut, using same science equipment as during ESAG-2002.
June 4	End of FOXE-2002. Aircraft return to Kangerlussuaq, Greenland Scientific equipment dismounted.

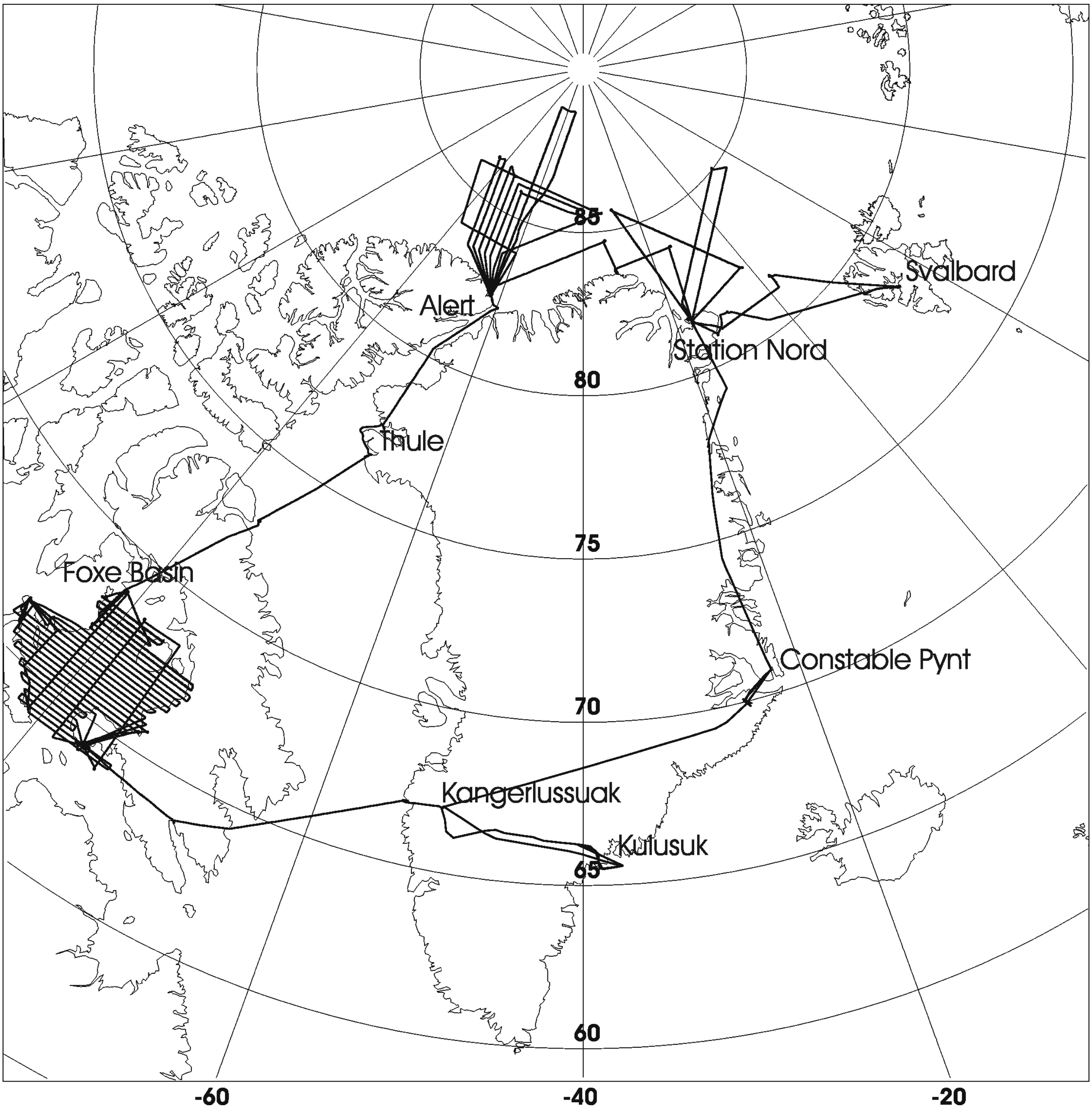


Figure 1a. Actually flown tracks of ESAG-2002 and FOXE-2002

Fig. 1 shows the actually flown aircraft tracks. Most ESAG-2002 flights were flown at 1000 ft elevation, with a few lower flights due to low clouds and fog. A total of 160 flight hours was flown on ESAG-2002, FOXE-2002 and transfer flights.

The ESAG-2002 track pattern was modified somewhat relative to the original proposal, in order to limit the lengths of some of the flights, to satisfy operational constraints. Also, due to the initial delays the flight pattern sequence was changed, so that all flight from Station Nord were done separately from the Alert flights, in order to secure a timely overflight of the icebreaker “Oden” and receive a new set of gravimeter spare parts in Svalbard. The tracks between Station Nord and Svalbard were shifted south to match the actual position of Oden, which had selected a more southerly traverse profile due to heavy ice conditions.

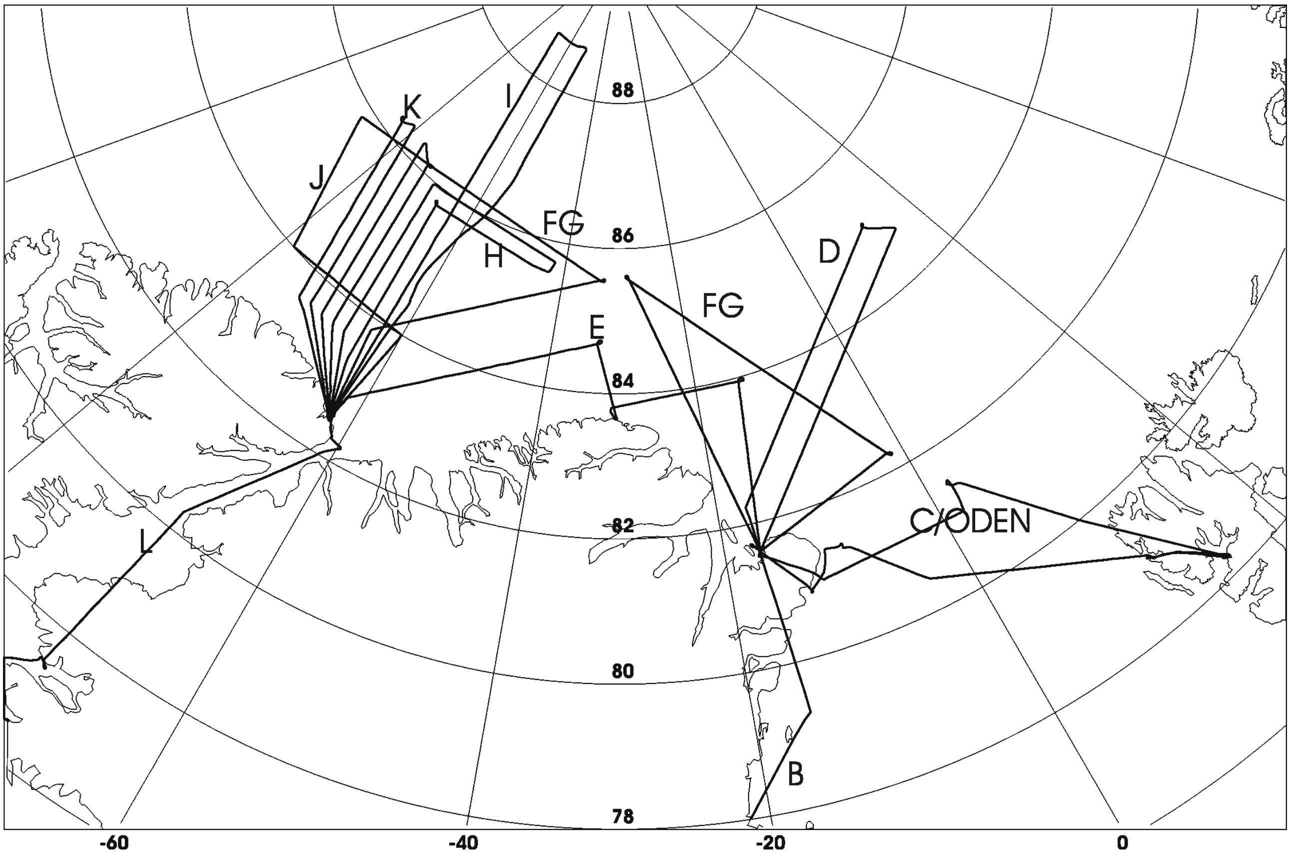


Figure 1b. ESAG-2002 flights with track names, cf. Table 1.

Table 1. Flights of ESAG-2002 by Julian day and date

Date/JD	From/to	Track	Take off UTC	Landing UTC	Airborne	Operator
April 29 / 119	SFJ-SFJ	test	1131	1200	0 h 29 min	KRK
April 29 / 119	SFJ-KUS	X	1426	1818	3 h 52	KRK
April 30 / 120	KUS-KUS	X+landing, Y1 X4 X5 KUS	1041 1514 1830 2058	1149 1532 1846 2122	1 h 08 0 h 18 0 h 16 0 h 24 =2 h 06	KRK
May 01 / 121	KUS-SFJ	Z	1108	1347	2 h 39	KRK
May 02 / 122	SFJ-CNP	A	1052	1550	4 h 58	KRK
May 03 / 123	CNP-CNP	Geikie	0859	1143	2 h 44	KRK
May 03 / 123	CNP-NRD	B	1256	1850	5 h 54	KRK/SMJ
May 04 / 124	NRD-NRD	D	1248	1801	5 h 13	KRK
May 05 / 125	No flight					
May 06 / 126	NRD-NRD	F-G	0324	0917	5 h 53	KRK/SMJ
May 06 / 126	NRD-LYR	ODEN	0947	1351	4 h 04	KRK
May 07 / 127	No flight					
May 08 / 128	Test flight		1354	1502	1 h 08	AVO
May 09 / 129	LYR-NRD	ODEN	1431	1822	3 h 51	AVO
May 10 / 130	NRD-ALT	E	1411	1917	5 h 06	RF
May 11 / 131	ALT-ALT	H	1459	2025	5 h 26	AVO/SMJ
May 12 / 132	ALT-ALT	I	1420	2043	6 h 23	RF
May 13 / 133	POF to Thule for generator repair					
May 14 / 134	POF back from Thule					
May 15 / 135	ALT-ALT	F-G	1242	1827	5 h 45	AVO/SMJ
May 15 / 135	ALT-ALT	K	1943	0021	4 h 38	RF
May 16 / 136	ALT-ALT	J	1219	1756	5 h 15	AVO/SMJ
May 17 / 137	ALT-THU	L(Nares Str.)	1248	1639	3 h 51	RF/SMJ
Total					79 h 15	

Generally all instruments worked satisfactorily, although problems with synchronization drift of the airborne gravimeter LCR S-99 (owned by the University of Bergen, Norway) continued throughout the field season. Some short-term problems with freeze-up of computers and laser scanner were also encountered, especially if the temperature in the aircraft dropped too low during night. The scientific equipment was kept above freezing on ground by a hot-air blower and by heating on auxiliary power (230/110 V).

The gravimeter synchronization drift (i.e., difference between logged and manually read spring tension) was likely due to a sticking mechanical gear in the spring tension servo system. The problem could not be fixed in the field, in spite of shipment of new spare parts from the manufacturer in Texas (ZLS corporation) and assistance from University of Bergen. Since the error only affected the computer logging of data, and not the function of the gravimeter itself, an operational routine was implemented where the science equipment operator would manually read spring tension on the LCR counter as well as the logged spring tension values at very frequent intervals (2-5 min) throughout the flights, quite a demand during the typical 5-6 hour flights. The drift was subsequently modeled by an ad-hoc developed software (“lcrsync”), which transformed the raw gravimeter data into synchronized (correct) data. This software error fix seemed to work well, in spite of large synchronization drifts (up to 100 mGal per flight, depending on turbulence and direction of flights). The r.m.s. noise due to the synchronization modeling is estimated to be well below 1 mGal r.m.s., and should only affect the shortest wavelengths.

A generator fault on the aircraft occurred on the return flight from the longest flight north of Alert (May 12 – northernmost flight to 89 N). The generator fault meant the loss of all power to the scientific equipment, loosing more than half of the gravity and lidar data on the return leg of the flight. It was decided *not* to refly the missing part of the leg, since good data had been acquired on the way out, and older Canadian gravity data were available for most of the lost profile. The loss of aircraft power also meant loss of aircraft navigational aids; it is apparent from Fig. 1 that the aircraft went off course from the planned track after the power failure (a small hand-held GPS unit was eventually used to navigate back to Alert over the featureless ice pack).

Aircraft interior during May 15 flight to 89 N; spare drum of fuel carried for security

OVERVIEW OF RECORDED DATA

1. GPS

Kinematic GPS is the key positioning method for the aircraft. GPS dual-frequency phase data were logged at 1 Hz using 1-2 reference ground receivers at one or more reference sites, and 3 aircraft receivers (Trimble, Ashtech and Javad types).

The aircraft GPS receivers are named AIR1 (Trimble), AIR2 (Ashtech) and AIR3 (Javad). AIR1 and AIR2 share the forward GPS antenna; AIR3 the aft GPS antenna. Antenna offsets were

Table 2a. ESAG-2002 GPS and aircraft data files.

JD/DATE	Air1	Air2	Air3	LCR	Datalog	EGI	SFJ (Trim)	KUS (Jav)	CNP (Jav)	NRD (Trim)	NRD2 (Jav)	ALT (Trim)	ALT2 (Ash)	THU (Jav)	LYR (Jav)
119/29 Apr test	X		X		X	X	X								
119/29 Apr	X		X		X	X	X								
120/30 Apr	X		X		X	X	X	X							
121/1 May	X		X		X		X	X							
122/2 May	X	X	X		X	X	X								
123/3 May	X	X	X		X	X	X		X						
123/3 May	X	X	X	B	X	X	X		X						
124/4 May	X	X	X	X	X	X	X			X					
125/5 May				B			X			X					
126/6 May!	X	X	X	X	X	X	X			X	X				
127/7 May				B			X			X	X				
128/8 May	X	X	X	X	X	X	X			X	X				X
129/9 May	X	X	X	X	X	X	X			X	X				X
130/10 May	X	X	X	X	X	X	X				U				
131/11 May	X*	X	X**	X	X	X	X					X	X		
132/12 May	X	X	X	X	X	X	X					X	X		
135/15 May	X	X	X	X	X	X	X					X	X		
135/15 May	X	X	X	X	X	X	X					X	X		
136/16 May	X	X	X	X	X	X	X					X	X		
137/17 May	X	X	X	X	X	X	X							X	

! 2 flights, data in one file
* Stopped before landing
** Not started until last part of flights
U Receiver under the way from St. Nord to DK
B Base-reading only

unchanged from earlier KMS installations on OY-POF. Data were logged internally in receivers during flights, and downloaded upon landing on laptop computers. Nearly all data were recovered; only a few files were missing or incomplete due to operator errors or other malfunctions.

Reference GPS stations were mounted on roofs or on tripods in the field; the reference points were generally not marked. The reference positions of the GPS reference stations will be done relative to IGS international network; this will ensure GPS coordinates consistent with the global ITRF-2000 coordinate system at an accuracy level of a few cm.

Table 2 shows the GPS reference and aircraft data files recorded during ESAG-2002. At present one GPS reference file from Station Nord (providing the sole reference for the Nord-Alert flight on May 10) is still missing (awaits GPS receiver shipment to KMS on first southbound regular flight from Station Nord).

Table 2b. GPS reference stations used for ESAG-2002.

Location	Name – site
Kangerlussuaq	SFJ - meteorological hut. Trimble
Kulusuk	KUS - temporary station in Kulusuk airport, Javad
Constape Pynt	CNP – antenna on roof of Personnel Building, Javad
Scoresbysund	SCO1 - KMS permanent GPS station in Scoresbysund
Station Nord	NRD1 - antenna on roof of building 7, Trimble NRD2 - antenna on roof of building 22 (“Polar 2”) , Javad.
Svalbard	LYR - antenna on Norsk Polar Institute building roof, Svalbard airport, Javad.
Alert	ALT1 - antenna on Hilton building roof (Trimble; same as 1995 and 1998 site) ALT2 - antenna on tripod behind fuel tanks, Alert (Ashtech)
Thule Air Base	THU - antenna on metal rod off Greenland home rule housing building, Javad THU3 - KMS permanent GPS station

GPS reference at Station Nord

2. Attitude: Honeywell INS and Greenwood IMU

A Honeywell medium-grade inertial navigation system H764-G "EGI" was used throughout the flights to record inertially integrated position, velocity and attitude information. Data were logged on a laptop PC in binary format through a 1558 mil-spec communications bus. Both free-inertial and GPS-integrated inertial data were logged on many flights. Data volume per flight was typically 50-100 MB.

Raw inertial data was also logged from a strap-down Inertial Measurement Unit (IMU), made by Greenwood Engineering, Denmark, logging on a special rack PC along with gravimetry and single-beam laser altimetry. The IMU data consists of averaged, uncalibrated gyro and accelerometer output at 18 Hz rate in a custom text format. The IMU data are essentially back-up for the EGI.

Both EGI and IMU output data were nearly 100% recovered. Test computations of roll and pitch showed that the systems worked without problems. Data were written onto CD's on a daily basis, cf. Table 2 and 3. Fig. 2 shows height, roll and pitch of a small part of a typical flight.

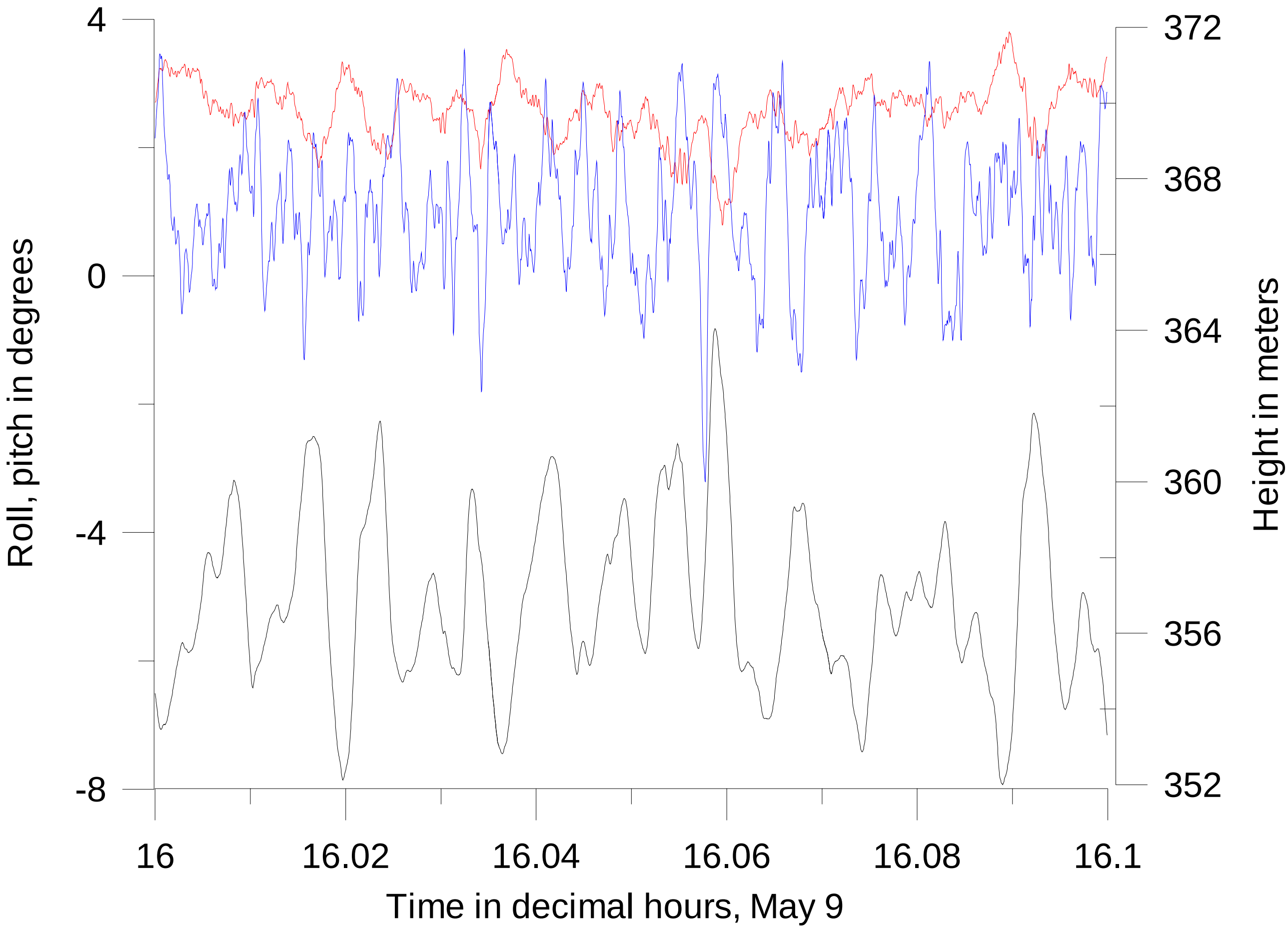


Figure 2: Example of aircraft height (from GPS) in black, roll (blue) and pitch (red) both from EGI. The regular phugoid motion is due to aircraft and autopilot characteristics, and provides strong constraints for time-correlation of data streams to check time offsets.

3. Gravimetry

Airborne gravity measurements and stabilized platform data from the S-99 were logged in Ultrasys 1 Hz format on the stand-alone gravimeter control laptop, as well as on the Greenwood data logger. Raw unsynchronized data were written on CD's, cf. Table 2 and 3 (LCR is the Ultrasys data). The synchronized data are derived in connection with processing on a line-by-line basis. A selected part of the gravity lines were quality controlled by computation of gravity anomalies on preliminary GPS solutions (for an example see Figure 3), and correct performance of the instrument verified.

4. Log file

An operator log file was maintained on a daily basis, including the readings of gravimeter synchronization. The log files are included on the CD's. All times are given in UTC (the survey spanned 5 local time zones).

5. Laser altimeter data

Data from a single-beam Optech rangefinder infrared laser unit was logged on the Greenwood data logger at 50 Hz. The unit only provided useful data for less than half of the tracks, due to low fog, cold, or open water. The 1000 ft flight elevation is close to the maximum range of the unit. Since the scanning lidar has better nadir performance, the laser altimeter is mainly considered a back-up unit. The files logged are shown in Table 2a (Datalog). Synchronization of the laser altimeter data is provided by GPS time tags, logged from the Trimble AIR1 GPS unit.

Table 3. Overview of data placement in CD-ROM archive

Aircraft data: AIR1, AIR2, AIR3, Datalog, LCR and EGI	
CD number	Julian day
A1	119, 120
A2	121, 122
A3	124
A4	126
A5	126
A6	128
A7	129, 130
A8	131
A9	132, 135a
A10	135b, 136, 137
Reference GPS data	
CD number	Stations
R1	ALT1, ALT2, CNP, KUS, LYR
R2	NRD1, NRD2
R3	SFJ
R4	SFJ
R5	THU, THU3

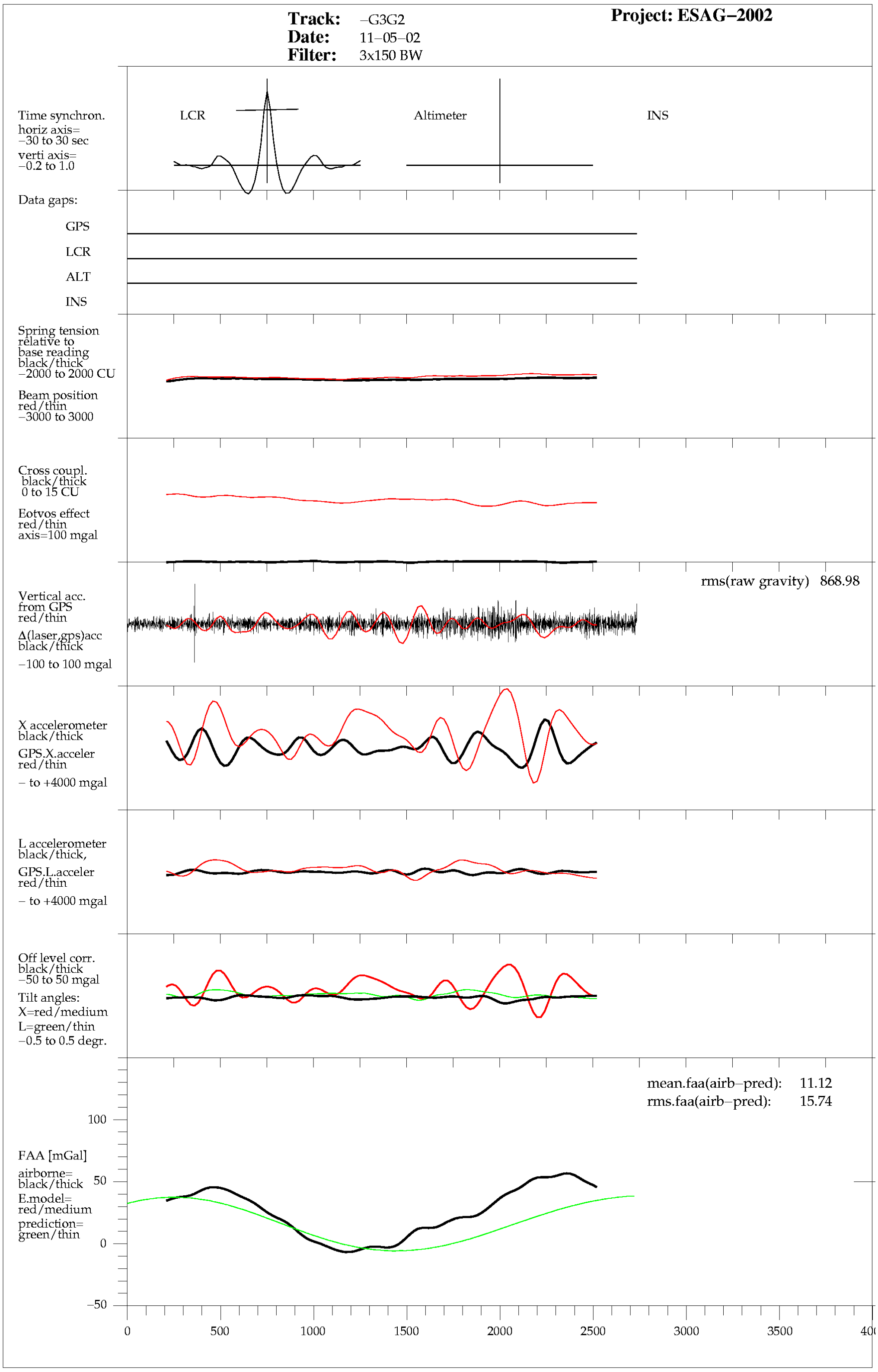


Figure 3. Standard graphics output from the gravity processing program. Line G3G2. The middle panel indicates very smooth flight conditions for this line. The lower panel shows filtered airborne gravity estimates (black) and EGM96 values (green) along the line.

6. Scanning lidar

The KMS Riegl laser scanner (lidar) data was logged as hourly files on a stand-alone laptop computer. The lidar files are time tagged by a 1 pps signal from the AIR1 GPS receiver, with start time of the scans given by the operator as a file name. Table 4 below shows the logged lidar data. Nominally files cover about 1 hr of data, at 40 scans/second. During changeover between files 1-2 min of data are typically lost. No data was taken in fog. Files were logged in either text or binary formats, yielding files size of 100-300 MB. Data were written directly on CD's after the flights. The lidar data are processed my merging with GPS positions and attitude data. Figure 4 shows an example of the lidar ice surface height data.

Table 4. Lidar data by date and start/stop times

JD/Date	File name	2dd format	Start (dechr)	Stop	Comments
119 – April 29	112300.2dd	T	11.383	11.587	SFJ test
	113930.2dd	T	11.658	12.004	SFJ test
	145330.2dd	T	14.892	15.232	XY, SFJ-KUS
120 – April 30	104400.2dd	T	10.733	11.023	XY until landing
	110700.2dd	T	11.117	11.718	
121 – May 1	113000.2dd	T	11.500	11.790	Z, KUS-SFJ
	115200.2dd	T	11.867	12.850	
	125700.2dd	T	12.950	13.791	
122 – May 2	111700.2dd	T	11.283	12.253	A, SFJ-CNP
	121700x.2dd	T	12.283	12.676	scandisc
	125900.2dd	T	12.983	13.819	
	135000.2dd	T	13.833	14.808	
	144930.2dd	T	14.825	15.889	
123 – May 3	093330.2dd	T	9.558	10.623	Geikie
	1038300.2dd	T	10.633	11.207	
	145340.2dd	T	14.894	15.711	B, CNP-NRD
	154400.2dd	T	15.733	16.717	
	164400.2dd	T	16.733	17.720	
	174400.2dd	T	17.733	18.266	
124 – May 4	124530.2dd	T	12.758	12.836	D, NRD-NRD
	130100.2dd	T	13.017	14.092	
	140630.2dd	T	14.108	15.025	
	150230.2dd	T	15.042	16.047	
	160400.2dd	T	16.067	17.599	
	173800.2dd	T	17.633	18.035	
126 – May 6	031600.2dd	T	3.267	3.468	FG, NRD-NRD
	033700.2dd	T	3.617	4.848	
	045130.2dd	T	4.858	5.867	
	055530.2dd	T	5.892	6.842	
	065200.2dd	T	6.867	7.844	
	075130.2dd	T	7.858	8.781	
	084900.2dd	T	8.817	9.193	
	094930.2dd	T	9.825	11.204	C, NRD-LYR
	111300.2dd	T	11.217	11.911	
	115520.2dd	T	11.922	13.471	
	133000.2dd	T	13.500	13.946	
128	141740.2dd	F	14.294		syncseq not ok!
	143900.2dd	T	14.650	14.918	Kongsvegen/ Sveabreen
129 – May 9	143830.2dd	F	14.633	15.037	LYR-Nord, 1000 ft
	161030.2dd	F	16.167	17.865	
	175900.2dd	T	17.983	18.351	

130 – May 10	145210 152800 155230 162600 165130 171830.2dd 180930.2dd 185700.2dd	Text – cd1 Text – cd3 Text – cd2 Text – cd4 Text – cd3 T – cd4 T – cd1 T – cd2	14.868 15.467 15.875 16.433 16.858 17.308 18.150 18.950	15.322 15.774 16.277 16.738 17.191 18.133 18.917 19.279	Nord-Alert
131 – May 11	145830.2dd 153530.2dd 164700.2dd 174630.2dd 184630.2dd 194630.2dd	T F T T T T	14.975 15.592 16.783 17.775 18.775 19.775	15.337 16.768 17.759 18.756 19.761 20.447	Alert H-route
132 – May 12	153900.zip 163630.2dd 173100.2dd	Text T T	15.650 16.608 17.517	16.368 17.502 18.539	Alert I-route
135 – May 15 first flight	124530.2dd 133700.2dd 143000.2dd 152130.2dd 160200.2dd 170130.2dd 181500.2dd	T - cd1 T - cd2 T - cd2 T - cd2 T - cd1 T - cd1 T - cd1	12.758 13.616 14.500 15.358 16.033 17.025 18.250	12.965 13.480 15.341 16.018 17.008 17.997 18.442	Alert G-route
135 – May 15 second flight	193900.2dd 201530.2dd 212000.2dd 222300.2dd 232600.2dd	T T T T T	19.650 20.258 21.333 22.383 23.433	20.040 21.314 22.361 23.419 24.355	Alert K-route
136 – May 16	122600.2dd 132630.2dd 142730.2dd 152300.2dd 163700.2dd 172300.2dd	T – cd2 T – cd1 T – cd1 T – cd2 T – cd4 T – cd3	12.433 13.441 14.458 15.383 16.616 17.383	13.425 14.439 15.369 16.603 17.361 17.957	Alert J-flight
137 – May 17	124500.2dd	T	12.753	12.987	Alert-Thule

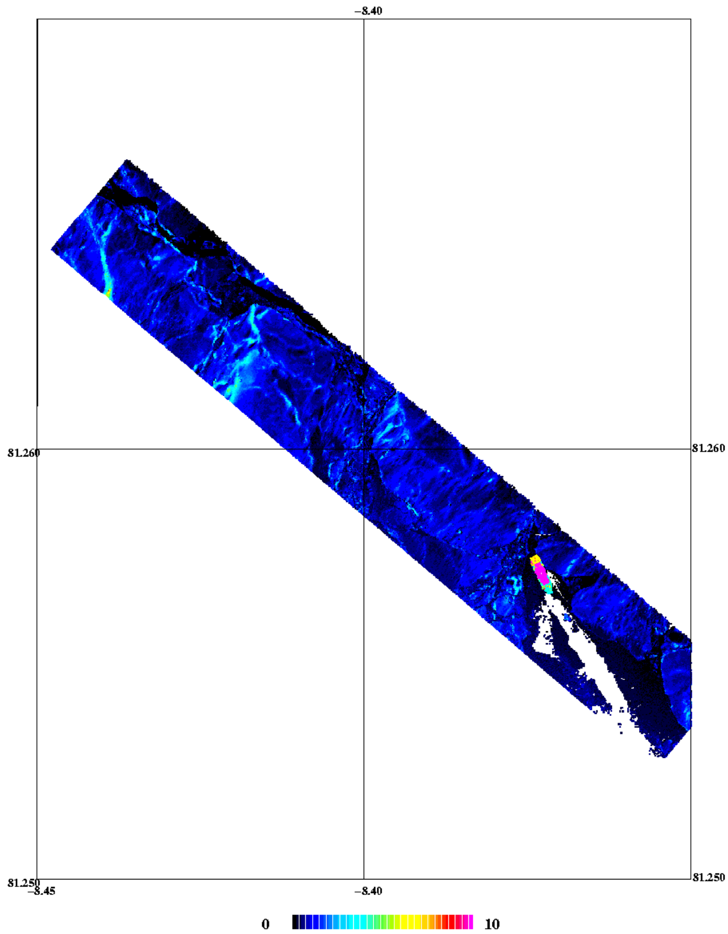


Figure 4. Example of lidar ice height data (ellipsoidal heights), overflight of ODEN May 9

7. Auxiliary data: Airborne video

Digital video was shot from a right-mounted camera mounted with a roughly 45-degree look angle from the side of the aircraft. The DV tapes hold about 1 hr, and only a part of the flights were recorded to limit the data volume. Table 5 shows the video recorded time intervals. The video data can be “grabbed” to mpeg-files on request for specific time intervals, and some video over typical areas have been converted. It is otherwise not planned to copy the videotapes as part of the ESAG-2002 raw data delivery.

Table 5. Side-looking video data on DV tape available for ESAG-2002

Tape	JD	Date	Start *	Stop	Comments
1	120 122	April 30 May 2	11:12 14:45	11:25 15:41	From Kulusuk over ice boarder Track A (A4-A5), Geikie top at 36:27
2	123	May 3	9:59	11:01	Geikie
3	123	May 3	14:59	16:00	Track B (B1-B2)
4	123	May 3	17:15	18:19	Tobias Island (Track B until coast)
5	124	May 4	13:14 14:12	13:37 14:52	Track D
6	124	May 4	16:02	17:04	Track D
7	126	May 6	3:49	4:53	Track F (NRD-F1+)
8	126	May 6	4:57	5:54	Track F (F1-F2)
9	126	May 6	6:00	7:03	Track F (F1-F2+)
10	126	May 6	7:09	8:12	Track F (F2-NRD)
11	126	May 6	10:14 11:16	10:15 12:17	NRD-Oden-LYR Oden: 11:37-11:38
12	129	May 9	14:42 15:55 16:26 16:35	15:03 16:02 16:11 16:58	LYR-Oden-NRD, beginning is from land/glacier
13	129 130	May 9 May 10	17:02 14:25	17:50 14:39	LYR-Oden-NRD Track E
14	130	May 10	15:03	16:06	Track E
15	130	May 10	16:20	17:21	Track E
16	130	May 10	17:33	18:36	Track E
17	132	May 12	14:45	15:48	Track I
18	132	May 12	15:48 16:59	16:20 17:39	Track I
19	132	May 12	17:43 18:14 19:20	18:08 18:39 19:25	Track I
20	135	May 15	13:37	14:40	Track G, F
21	135	May 15	14:46	15:55	Track G, F
22	135	May 15	16:03	17:06	Track G, F
23	135	May 15	17:13 18:15	17:56 18:34	Track G, F Tape ends on ground
24	135	May 15	20:43	21:46	Track K
25	135	May 15	22:17	23:19	Track K
26	136	May 16	14:54	15:57	Track J
27	137 142	May 17 May 22	14:46 14:04	14:51 14:59	Track L, from inside the aircraft Davis Strait

* The clock on the video was synchronised with the GPS receiver within a few seconds

8. Auxiliary data: Imagery from Swedish icebreaker "ODEN"

ODEN carried out an oceanographic cruise in the Fram Strait and Greenland Sea in the period May 1 to June 8. With the helpful support from the crew of ODEN, an automated KMS web cam system was mounted on the bridge, taking pictures of the sea-ice at 20 sec interval, 24 hr a day, during the cruise. The images allow the occasional measurement of ice floe thickness and snow cover depth for ice floe fragments accidentally turned vertical during ice breaking. Approximately 4 GB of jpeg-imagery is available on CD-ROM archive. Fig. 5 shows the actual sailed track of Oden. Navigation data and auxiliary meteorological data have been prepared by the Oden crew, allowing geocoding of the data.

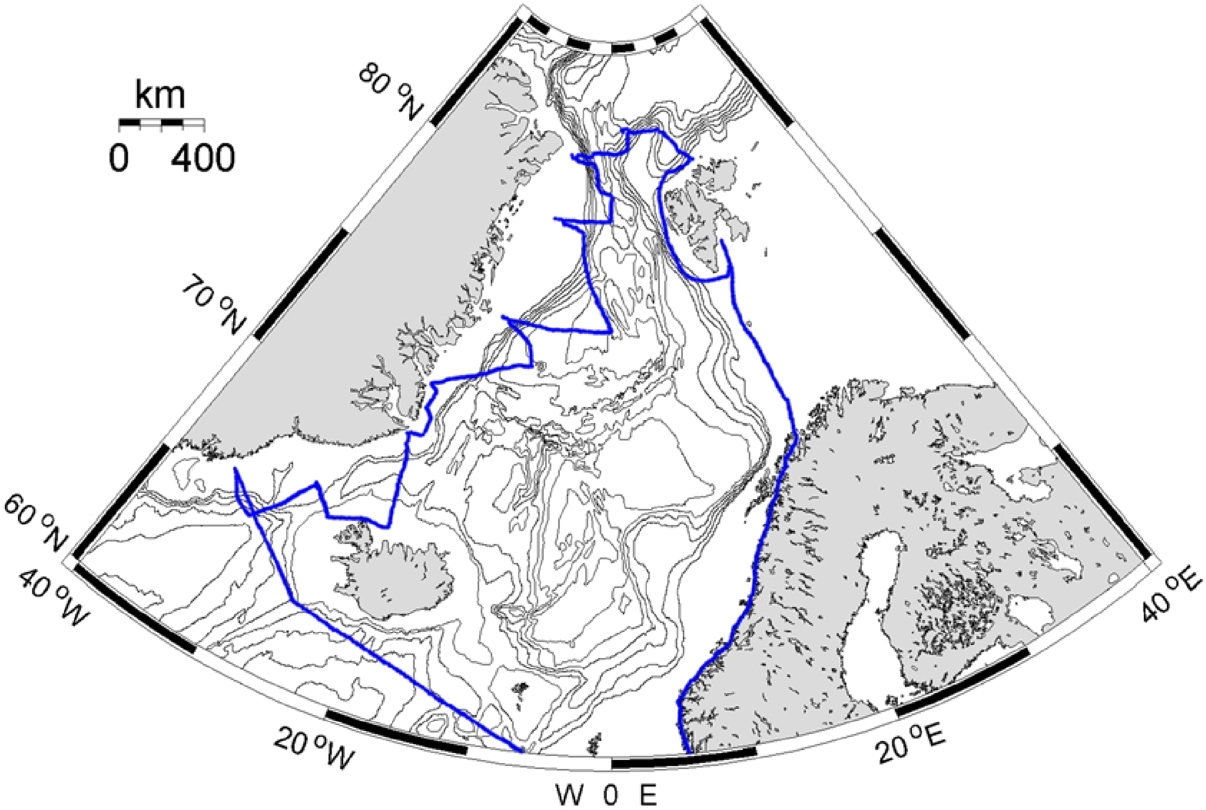


Figure 5. ODEN cruise tracks, May 2002. 20 sec web cam data available throughout cruise.

Oden in the pack ice of Fram Strait (May 6 overflight)

Example of ODEN web-cam image. Ship-mounted reference ruler bands 50 cm wide.

9. Other data – gravity ties and ground truth ice thickness measurements

The airborne gravity measurements are relative, and must be tied into a global reference gravity system by relative gravimeter ties (linking gravity value at an aircraft parking spot to the absolute reference values). A LCR land gravimeter was used to obtain apron gravity values from nearby absolute or first-order KMS gravity stations. The accuracy of the gravity reference value transfer (0.05 mGal) is superior to the noise of the airborne gravity measurement.

Limited reference measurements of sea-ice thickness, snow density and thickness were taken off Station Nord (on fast ice) and off Alert (on polar pack ice floes). The results are summarized in Table 6.

Table 6. Ice thickness measurements off Station Nord and Alert
(F is freeboard height, K freeboard to thickness conversion factor)

	Lat N	Lon W	Snow depth (m)	Snow+ice (m)	Snow density (g/cm**3)	F (m)	K
Station Nord	81 37.08	16 44.88	0.95	2.40	0.35	0.79	3.0
(fast ice)	81 38.22	16 49.86	0.68	2.21	0.30	0.64	3.5
Alert	82 32.01	62 09.64	0.50	4.50	0.32	0.77	5.8
(polar pack)	82 32.12	62 07.63	0.48	3.30	0.35	0.62	5.3
	82 32.25	62 05.28	0.35	3.00	0.35	0.51	5.9
	82 32.25	62.06.96	0.60	4.10	N/A	0.77	5.3
	82 32.26	62 07.25	0.70	5.10	0.35	0.93	5.5
	82 30.07	62 08.22	0.50	6.10+	N/A	(0.93)	(6.6)
Alert average			0.52	4.35+	0.34	0.71	5.6

Gravity reference measurement next to aircraft (Repulse Bay, Foxe Basin, Canada)


Ice drilling off Station Nord

CONCLUSIONS

The ESAG-2002 airborne gravity and lidar data survey was highly successful, with close to 100% data recovery. Only few tracks did not yield useful laser data due to fog and low clouds. Auxiliary data including airborne video and ship-borne web cam ice images may further enhance the usefulness of the laser data, and aid in understanding radar remote sensing signatures.

The ESAG-2002 airborne gravity survey have filled an important gravity void in the Arctic Ocean, and will allow an intercomparison of older US, Canadian and German gravity surveys in the region, in order to detect possible systematic long-wavelength errors, which might degrade polar gap supplementary data for GOCE.

Data processing is currently underway, and final results expected by the end of 2002.

APPENDIX II – Raw Data Acquisition Report.

ESAG-2002

European airborne gravity and lidar survey in the Arctic Ocean

Raw data report
September 2002

by

R. Forsberg and S. M. Hvidegaard
National Survey and Cadastre (KMS)
Denmark

Kort & Matrikelstyrelsen
National Survey and Cadastre - Denmark

INTRODUCTION

The ESAG-2002 airborne gravity and lidar campaign of the European Space Agency (ESA) and Kort og Matrikelstyrelsen (National Survey and Cadastre of Denmark, KMS) have been carried out in the period April 29 – May 19, 2002). The airborne survey was done using a chartered Air Greenland Twin-Otter aircraft (OY-POF), operating primarily from military airfields at Station Nord (Greenland) and Alert (Canada).

The ESAG-2002 part of the airborne gravity and sea-ice lidar survey was part of a larger project with Greenland ice sheet laser mapping, and airborne gravity in Foxe Basin, Canada.

Summary of operations

April 26-29 Installation of scientific equipment in Air Greenland hangar at Kangerlussuaq, Greenland. 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.
Flight from Kangerlussuaq to Station Nord, with stop-over at Constaple Pynt airport.
Laser survey of Geikie ice cap (repeat of earlier surveys 1996-1998).
Laser survey of Greenland ice sheet margin and new islands off 79-glacier enroute.
May 4-10 First ESAG-2002 gravity flights from Station Nord.
Overflights of Swedish ice breaker "Oden" on May 6 and May 9 in Fram Strait.
Test flight and check of gravimeter in Svalbard.
May 10-16 Operations from Canadian Forces Station Alert. All lines flown as planned, in spite of aircraft generator fault, which resulted in aircraft non-availability for 2 days.
May 17 Flight from Alert to Thule Airbase via Nares Strait.
Planned gravity/lidar profile over Greenland ice sheet margins could not be done due to clouds. End of ESAG-2002, aircraft continues to Canada.

The details of the field operations and science background may be found in the report "Progress report #2", dated June 2002. This report briefly describes the raw GPS, gravity, INS, laser altimeter and scanning lidar data. It is not the intention with this report to give a full description of the raw data files; users must refer to original documentation of manufacturer's manuals. KMS can help to provide this information on request.

The raw data are provided to ESTEC on 47 CD-ROM's (table with content of all CD-ROMs can be found in bottom of this report), collected in 3 folders marked with ESAG-2002. A CD-ROM with prototype KMS software and pictures from the field survey is enclosed, too. The KMS software include the following Fortran programs on CD-ROM P1:

LCRSYNC – program to synchronize gravity readins from LCR raw files.
READEGI – to read Honeywell H764G INS data and output pitch, roll and other quantities.
READLAS – reads "Greenwood" data logger time tag and laser altimeter files
RIEG2TXT – read Riegl Q140 binary lidar scanning data
READSCAN – read Riegl lidar data, GPS and attitude data, and output ground laser points.

The software is provided as-is, with no guarantee of any kind for results. The programs are part of a larger suite of programs under continuing development. The software, will, however be useful to anybody trying to read the raw data.
In addition are included on the CD P1:

PHOTOS – directory with digital photos during survey. Times are in UT.
VIDEOCLP – 5 selected video clippings from the sea-ice north of Greenland and Alert. The video-clips are names with track names and UT start times. All clips are of about 1 min. length.
LOGFILES – daily survey log files, including necessary information for "lcrsync"

The data of CD-ROMs are stored on a Julian Date (JD) basis.

Table 1. Flights of ESAG-2002 by Julian day and date.

Date/JD		Track	Off bloc	Take off UTC	Landing UTC	On bloc	Airborne	Operator
April 29 / 119	SFJ-SFJ	test	1124	1131	1200	1204	0 h 29 min	KRK
April 29 / 119	SFJ-KUS	X	1420	1426	1818	1822	3 h 52	KRK
April 30 / 120	KUS-KUS	X+landing, Y1 X4 X5 KUS	1034	1041 1514 1830 2058	1149 1532 1846 2122	1153 1538 2124	1 h 08 0 h 18 0 h 16 0 h 24 =2 h 06	KRK
May 01 / 121	KUS-SFJ	Z	1100	1108	1347	1350	2 h 39	KRK
May 02 / 122	SFJ-CNP	A	1040	1052	1550	1559	4 h 58	KRK
May 03 / 123	CNP-CNP	Geikie		0859	1143	1146	2 h 44	KRK
May 03 / 123	CNP-NRD	B	1250	1256	1850	1855	5 h 54	KRK/SMJ
May 04 / 124	NRD-NRD	D	1243	1248	1801		5 h 13	KRK
May 05 / 125	No flight							
May 06 / 126	NRD-NRD	F-G		0324	0917		5 h 53	KRK/SMJ
May 06 / 126	NRD-LYR	ODEN	0940	0947	1351	1407	4 h 04	KRK
May 07 / 127	No flight							
May 08 / 128	Test flight			1354	1502		1 h 08	AVO
May 09 / 129	LYR-NRD	ODEN		1431	1822		3 h 51	AVO
May 10 / 130	NRD-ALT	E		1411	1917		5 h 06	RF
May 11 / 131	ALT-ALT	H		1459	2025		5 h 26	AVO/SMJ
May 12 / 132	ALT-ALT	I		1420	2043		6 h 23	RF
May 13 / 133	POF to Thule for generator repair							
May 14 / 134	POF back from Thule							
May 15 / 135	ALT-ALT	F-G		1242	1827		5 h 45	AVO/SMJ
May 15 / 135	ALT-	K		1943	0021		4 h 38	RF

	ALT							
May 16 / 136	ALT-ALT	J		1219	1756		5 h 15	AVO/SMJ
May 17 / 137	ALT-THU	L(Nares Str.)		1248	1639		3 h 51	RF/SMJ
Total							79 h 15	

GPS data files

Kinematic GPS is the key positioning method for the aircraft. GPS dual-frequency phase data were logged at 1 Hz using 1-2 reference ground receivers at one or more reference sites, and 3 aircraft receivers (Trimble, Ashtech and Javad types).

The aircraft GPS receivers are named AIR1 (Trimble), AIR2 (Ashtech) and AIR3 (Javad). AIR1 and AIR2 share the forward GPS antenna; AIR3 the aft GPS antenna.

All GPS data are provided as original formats of the manufacturers. These data can be read by many commercial software packages, or easily converted to RINEX, receiver-independent format by standard routines of the International GPS service

The file names are of the form:

Trimble files: `04391220.dat` – data, receiver no. 0439, JD117
`04391220.eph, .ion, .mes` – supplementary orbit files etc.
Javad files: `air0502a.jps` – Javad file (air = air3)
Ashtech files: `uarr2a02.122` – Ashtech files (JD117, air2),

Note that Ashtech files must be unpacked with Ashtech software to provide b-, e- and s- files, which are more standard formats.
For more details see document: "GPSdata.doc" stored on CD-ROM G1.

Reference GPS stations were mounted on roofs or on tripods in the field; the reference points were generally not marked. The reference positions of the GPS reference stations will be done relative to IGS international network; this will ensure GPS coordinates consistent with the global ITRF-2000 coordinate system at an accuracy level of a few cm.

Table 2a. GPS reference stations used for ESAG-2002.

Location	Name – site
Kangerlussuaq	SFJ - meteorological hut. Trimble
Kulusuk	KUS - temporary station in Kulusuk airport, Javad
Constape Pynt	CNP – antenna on roof of Personnel Building, Javad
Scoresbysund	SCO1 - KMS permanent GPS station in Scoresbysund
Station Nord	NRD1 - antenna on roof of building 7, Trimble NRD2 - antenna on roof of building 22 ("Polar 2") , Javad.
Svalbard	LYR - antenna on Norsk Polar Institute building roof, Svalbard airport, Javad.
Alert	ALT1 - antenna on Hilton building roof (Trimble; same as 1995 and 1998 site) ALT2 - antenna on tripod behind fuel tanks, Alert (Ashtech)

Thule Air Base	THU - antenna on metal rod off Greenland home rule housing building, Javad THU3 - KMS permanent GPS station

Table 2b. Reference GPS coordinates as computed by KMS

Station	Lat	Lon	Ell. height	Comment
SFJ	67 00 21.6517	-50 42 9.6773	72.014	
KUS	65 34 40.5259	-37 9 11.9715	72.042	
NRD1	81 36 5.0977	-16 39 43.5273	70.037	
NRD2	81 35 49.7660	-16 39 24.8776	67.514	
LYR (8/5a)	78 14 51.4679	15 29 35.0743	52.516	*
LYR (8/5b)	78 14 51.4649	15 29 35.0779	52.560	*
LYR (9/5)	78 14 51.4646	15 29 35.0683	52.550	*
ALT1	82 30 41.5574	-62 19 36.3358	56.271	
ALT2	82 30 39.9955	-62 18 55.6712	42.810	
THU	76 32 16.4222	-68 47 48.0292	43.884	*
CNP	70 44 40.2403	-22 38 53.4847	70.770	*

* Only one file used to determine position

LCR gravimeter data

Airborne gravity measurements and stabilized platform data from the S-99 were logged in Ultrasys 1 Hz format on the stand-alone gravimeter control laptop, as well as on the Greenwood data logger.

The data from the LCR instrument are text data including time, spring tension, beam position and horizontal platform accelerations. The data is given in hourly files with a typical file name of the form:

`2002_19.135` - indicates data from JD135 at start time 1900 UT

The raw data are described in full details in the "Ultrasys operations manual" (Ultrasys cooperation). Full description of the function of the LCR air/sea-gravimeter may be found in *Valliant, H: The LaCoste & Romberg air/sea gravimeter: an overview. In: CRC Handbook of Geophysical Exploration at Sea, Boca Raton Press, 1991.*

Raw unsynchronized data were written on CD's, which showed a strong drift. The synchronized data are derived in connection with processing on a line-by-line basis. The need for synchronization (program LCRSYNC) was unique to the KMS 2002 field season, and was due to an error in the LCR instrument (partially faulty stepper motor system); however, the use of software synchronization of frequently read instrument physical spring tension to logged spring tension values provided a fully satisfactory solution, and results are estimated to be accurate at 2 mgal r.m.s., as expected.

Base readings for stationary readings of the instruments at the reference parking spots in the airports are given in the log files and in a separate base reading file. Both files can be found on CD-ROM P1.

Reference gravity values at the aircraft parking spots were measured with relative land gravimeters, relative to the KMS reference gravity network in Greenland, with ties to Canada and Svalbard absolute measurements. The following apron reference values were determined for ESAG-2002 airports – the values refer to ground level:

Table 3. Gravity reference gravity values

Longyearbyen, Svalbard	982962.94 mgal
Station Nord (Garage)	983068.75 mgal
Alert apron (Hilton)	983127.49 mgal

Honeywell INS

A Honeywell medium-grade inertial navigation system H764-G "EGI" was used throughout the flights to record inertially integrated position, velocity and attitude information. Data were logged on a laptop PC in binary format through a 1558 mil-spec communications bus. Both free-inertial (mode 29) and GPS-integrated Kalman-filtered inertial data (mode 17) were logged on some flights; on other flights either mode 17 or mode 29 was logged. The data modes are still being investigated for research in improvement of the airborne gravity data. For roll, pitch and heading determination either mode yield sufficiently accurate results for pointing the laser instruments.

The data from the H764G was logged on a stand-alone laptop, using a custom-developed logging software essentially downloaded operator-wanted "frames" of the basic H764G data available on the 1558 mil-spec data bus. The H764G data were SNU-84 compliant (standard US military navigation packages), for details see the SNU-84 documentation. The details of the packages are described in several voluminous Honeywell manuals, for an overview see Honeywell document DS34200800, St. Petersburg, Florida, August 1998. The main packages logged were the packages 17 and 29, which essentially contains binary packed latitude, longitude, velocities, heights and heading information. An example of reading the data may be seen in READEGI. It should be pointed out that the documentation for the KMS H764G has shown several flaws relative to the physical unit delivered – scale factors for several items were found not to be in accordance with the manual.

The EGI files names are of form:

`EGI-020430-101624.ddk` - Binary EGI files XXXXXX-XXXXXX is year, month, day and the time in UT)

Both free-inertial and Kalman-filtered modes depend on the vertical channel on GPS aiding. On a number of flights the altitude GPS input was erroneously set at wrong levels (either in fixed-height or GPS-estimated heights, ft or meter). The errors will show inertial heights which are consistently too high or too low. These errors do not affect roll or pitch, and it appears that the errors came both from operator errors as well as errors in the EGI control software.

In addition data were also recorded from a Danish-build strapdown IMU system (Greenwood Engineering). These data are experimental and not meant for other users. The Greenwood IMU in principle served as the back-up for the H764G, and may in the future be used to augment the airborne gravimetry processing. The Greenwood logging computer is logging a 1-sec UTC time tag from the Trimble GPS receiver for time base, and is logging LCR data (for backup) and laser altimeter data as well.

Laser altimeter data

Data from a single-beam Optech “Rangefinder” infrared laser unit was logged on the Greenwood data logger at 100 Hz. The unit only provided useful data for less than half of the tracks, due to low fog, clouds, or open water. The 1000 ft flight elevation is close to the maximum range of the unit. Since the scanning lidar has better nadir performance, the laser altimeter is mainly considered a back-up unit. Synchronization of the laser altimeter data is provided by GPS time tags, logged from the Trimble AIR1 GPS unit.

The general format of the Greenwood data logger files are

`92050901.alt` – Laser range (m) and internal computer time
`92050901.gps` – GPS time tags (UTC) and internal computer time
`92050901.ins` – Greenwood INS raw gyro and accelerometer data

In the above, “92” = 2002 (computer clock reset 10 years back to avoid year 2000 bug), date = May 9, 01 = first file of day.

The laser altimeter was roughly mounted to be vertical when airborne. However, precise definition of offset angles must be done by analysis of flights over known surfaces (runways or ice-free sea surface).

Riegl scanning lidar

The KMS Riegl Q140 laser scanner (lidar) data was logged as hourly files on a stand-alone laptop computer. The lidar files are time tagged by a 1 pps signal from the AIR1 GPS receiver, with start time of the scans given by the operator as a file name. In a few cases the timing of the file is not correct, and there is a risk of time offsets (mostly +/- 1 sec). Since 1 sec timing offset corresponds to 60 m on ground, this is easily detected over known features (e.g., runways or topography); it’s more difficult over ocean and sea-ice.

Table 4 below shows the logged lidar data. Nominally files cover about 1 hr of data, at 40 scans/second. During changeover between files 1-2 min of data are typically lost. No data was taken in fog. Files were logged in either text or binary formats, yielding files size of 100-300 MB. Data were written directly on CD’s after the flights. The lidar data are processed my merging with GPS positions and attitude data in the program READSCAN (still under development – may be used as a guide to reading the raw data).

Table 4. Lidar data by date and start/stop times.

JD/Date	File name	2dd format	Start (dechr)	Stop	Comments

119 – April 29	112300.2dd 113930.2dd 145330.2dd	T T T	11.383 11.658 14.892	11.587 12.004 15.232	SFJ test SFJ test XY, SFJ-KUS
120 – April 30	104400.2dd 110700.2dd	T T	10.733 11.117	11.023 11.718	XY until landing
121 – May 1	113000.2dd 115200.2dd 125700.2dd	T T T	11.500 11.867 12.950	11.790 12.850 13.791	Z, KUS-SFJ
122 – May 2	111700.2dd 121700x.2dd 125900.2dd 135000.2dd 144930.2dd	T T T T T	11.283 12.283 12.983 13.833 14.825	12.253 12.676 13.819 14.808 15.889	A, SFJ-CNP scandisc
123 – May 3	093330.2dd 1038300.2dd 145340.2dd 154400.2dd 164400.2dd 174400.2dd	T T T T T T	9.558 10.633 14.894 15.733 16.733 17.733	10.623 11.207 15.711 16.717 17.720 18.266	Geikie B, CNP-NRD
124 – May 4	124530.2dd 130100.2dd 140630.2dd 150230.2dd 160400.2dd 173800.2dd	T T T T T T	12.758 13.017 14.108 15.042 16.067 17.633	12.836 14.092 15.025 16.047 17.599 18.035	D, NRD-NRD
126 – May 6	031600.2dd 033700.2dd 045130.2dd 055530.2dd 065200.2dd 075130.2dd 084900.2dd 094930.2dd 111300.2dd 115520.2dd 133000.2dd	T T T T T T T T T T T	3.267 3.617 4.858 5.892 6.867 7.858 8.817 9.825 11.217 11.922 13.500	3.468 4.848 5.867 6.842 7.844 8.781 9.193 11.204 11.911 13.471 13.946	FG, NRD-NRD C, NRD-LYR
128	141740.2dd 143900.2dd	F T	14.294 14.650	 14.918	syncseq not ok! Kongsvegen/ Sveabreen
129 – May 9	143830.2dd 161030.2dd 175900.2dd	F F T	14.633 16.167 17.983	15.037 17.865 18.351	LYR-Nord, 1000 ft
130 – May 10	145210 152800 155230 162600 165130 171830.2dd 180930.2dd 185700.2dd	Text – cd1 Text – cd3 Text – cd2 Text – cd4 Text – cd3 T – cd4 T – cd1 T – cd2	14.868 15.467 15.875 16.433 16.858 17.308 18.150 18.950	15.322 15.774 16.277 16.738 17.191 18.133 18.917 19.279	Nord-Alert
131 – May 11	145830.2dd 153530.2dd 164700.2dd 174630.2dd 184630.2dd 194630.2dd	T F T T T T	14.975 15.592 16.783 17.775 18.775 19.775	15.337 16.768 17.759 18.756 19.761 20.447	Alert H-route
132 – May 12	153900.zip	Text	15.650	16.368	Alert I-route

	163630.2dd 173100.2dd	T T	16.608 17.517	17.502 18.539	
135 – May 15 first flight	124530.2dd 133700.2dd 143000.2dd 152130.2dd 160200.2dd 170130.2dd 181500.2dd	T - cd1 T - cd2 T - cd2 T - cd2 T - cd1 T - cd1 T - cd1	12.758 13.616 14.500 15.358 16.033 17.025 18.250	12.965 13.480 15.341 16.018 17.008 17.997 18.442	Alert G-route
135 – May 15 second flight	193900.2dd 201530.2dd 212000.2dd 222300.2dd 232600.2dd	T T T T T	19.650 20.258 21.333 22.383 23.433	20.040 21.314 22.361 23.419 24.355	Alert K-route
136 – May 16	122600.2dd 132630.2dd 142730.2dd 152300.2dd 163700.2dd 172300.2dd	T – cd2 T – cd1 T – cd1 T – cd2 T – cd4 T – cd3	12.433 13.441 14.458 15.383 16.616 17.383	13.425 14.439 15.369 16.603 17.361 17.957	Alert J-flight
137 – May 17	124500.2dd	T	12.753	12.987	Alert-Thule

The software-controllable setup for the 2002 lidar measurements was set up with a scan rate of 40 Hz (across-track), and 208 measurements per scan, yielding a basic binary record of 1664 bytes (8 bytes per measurement, including range, angle and amplitude). The detailed format is described in the Riegl Q140 format. By mistake some flights were accidentally stored in ASCII format, equivalent to the binary format, but taking about the double space. The system also produced binary data occasionally in an unknown format – this format was later recognized as being equivalent to the binary format except for a different (longer) header. The change in formats was due to operator errors (a consequence of some slightly inconvenient naming conventions during start up of the Riegl software).

Sample input file for the preliminary READSCAN software (May 26 overflight of Repulse Bay, Canada):

```
201000.2dd
..\egi\gpsegi.pos   ! a GPS-INS position file with attitude info
scan.out
vert.out
20 10 00        ! scan start time
20.2 20.4       ! wanted time interval in dechr2
0 90 -90 90     ! geographic limits
5 5 t t t t f   ! nave ithin lbin lnew lpr lcalib lgeo
0 0 1.66  0.0   ! ant offset, time offset
-4 -1.3 0       ! pitch0 roll0 hdg0
10  10  19      ! min.amp.  min.scan  max.scan
f               ! lheader  (T/F)
```

The offset angles must, as with the laser altimeter, be determined by calibration over known targets. This is not yet automated and very much research in progress.

To summarize, the contents of all CD-ROMs can be found below.

AIRCRAFT DATA (AIR1, AIR2, AIR3, Datalog, LCR and EGI)*

CD number	Content
A1	Julian day: 119,120
A2	121,122
A3	123
A4	124
A5	126
A6	126
A7	128
A8	129, 130
A9	131
A10	132, 135a
A11	135b, 136, 137

REFERENCE GPS DATA

CD number	Content
R1	ALT1, ALT2, CNP, KUS, LYR
R2	NRD1, NRD2
R3	SFJ
R4	SFJ
R5	THU, SCO1

LIDAR SCANNER DATA

CD number	Content
S1	Julian day 119, 120
S2	121
S3	122
S4	122
S5	123
S6	123
S7	124
S8	124
S9	126
S10	126
S11	126
S12	126
S13	128
S14	129
S15	130
S16	130
S17	130
S18	130
S19	131
S20	131
S21	132
S22	132
S23	135a

S24	135a
S25	135b
S26	135b
S27	136
S28	136
S29	136

PROCESSED GPS DATA

CD number	Content
G1	All days

PROGRAMS TO READ DATA

CD number	Content
P1	Fortran programs, log-files, photos, video-clips, basereadings

*Abbreviations:

AIR1: Forward GPS antenna, Trimble receiver

AIR2: Forward GPS antenna, Ashtech receiver

AIR3: Aft GPS antenna, Javad receiver

Datalog: Greenwood INS, timesync. and single-beam laser altimetry

EGI: Honeywell INS

APPENDIX III – Track plot

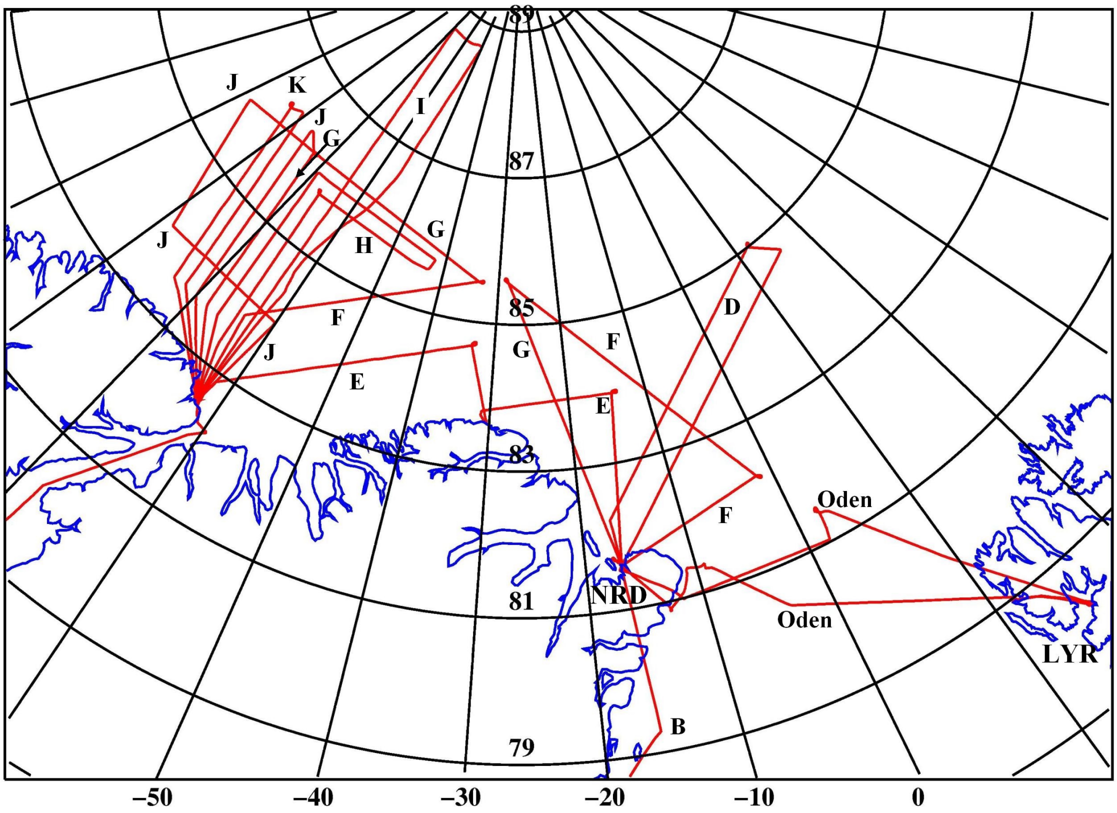


Fig.A3. All flights tracks of the ESAG2002 campaign.

APPENDIX IV – Contents of final results

Contents of “final results” CDs:

SOFTWARE: readscan, fitlin, pse, pse.inp, geoid models
GRAVITY: File with final gravity anomalies
LASERALT: Files and plots
LIDAR: Examples of swath freeboards
VIDEO: 5 mpegs
PRESENTATIONS: Powerpoint presentations material from Dec. 2002
IMAGES: Digital pictures from the ESAG 2002 campaign

APPENDIX V – Table of Contents of CDs

ESAG2002 CD-ROM DATA ARCHIVE

Below is found lists of data from the ESAG2002 campaign. The data is divided into categories AIRCRAFT, REFERENCE GPS, SCANNER and PROCESSED GPS and placed on CD-ROMs named A_, R_, S_ and G_ respectively.

AIRCRAFT DATA (AIR1, AIR2, AIR3, Datalog, LCR and EGI)*

CD number	Content
A1	Julian day: 119,120
A2	121,122
A3	123
A4	124
A5	126
A6	126
A7	128
A8	129, 130
A9	131
A10	132, 135a
A11	135b, 136, 137

REFERENCE GPS DATA

CD number	Content
R1	ALT1, ALT2, CNP, KUS, LYR
R2	NRD1, NRD2
R3	SFJ
R4	SFJ
R5	THU, SCO1

LIDAR SCANNER DATA

CD number	Content
S1	Julian day 119, 120
S2	121
S3	122

S4	122
S5	123
S6	123
S7	124
S8	124
S9	126
S10	126
S11	126
S12	126
S13	128
S14	129
S15	130
S16	130
S17	130
S18	130
S19	131
S20	131
S21	132
S22	132
S23	135a
S24	135a
S25	135b
S26	135b
S27	136
S28	136
S29	136

PROCESSED GPS DATA

CD number	Content
G1	All days

FINAL RESULTS CDs

CD number	Content
F1	SOFTWARE: readscan, fitlin, pse, pse.inp, geoid models GRAVITY: File with final gravity anomalies LASERALT: Files and plots LIDAR: Examples of swath freeboards VIDEO: 5 mpegs PRESENTATIONS: Powerpoint presentations material from Dec. 2002 Images

*Abbreviations:

AIR1: Forward GPS antenna, Trimble receiver
AIR2: Forward GPS antenna, Ashtech receiver
AIR3: Aft GPS antenna, Javad receiver

Datalog: Greenwood INS, timesync. and single-beam laser altimetry
EGI: Honeywell INS

National Survey and Cadastre – Denmark (KMS), Technical Reports

The National Survey and Cadastre – Denmark, Technical Report series is intended as an informal report series, published at irregular intervals. The following reports have so far been published in the series (up to number 3, the reports were named "Geodætisk Institut, Technical Reports", from number 4 through 7, the reports were named "National Survey and Cadastre – Denmark, Geodetic Division, Technical Reports").

1. Jørgen Eeg: *On the Adjustment of Observations in the Presence of Blunders*, 32 pp., 1986.
2. Per Knudsen, C.C. Tscherning and René Forsberg: *Gravity Field Mapping Around the Faeroe Islands and Rockall Bank from Satellite Altimetry and Gravimetry*, 30 pp., 1987.
3. Niels Andersen: *The Structure and Filling of a 19.2 Kilometer Hydrostatic Leveling Tube*, 83 pp., 1988.
4. René Forsberg: *Gravity Measurements in East Greenland 1986-1988*, 32 pp., 1991.
5. Gabriel Strykowski: *Automation Strategy for Repeated Tasks in DOS*, 15 pp., 1992.
6. Simon Ekholm and Kristian Keller: *Gravity and GPS Survey on the Summit of the Greenland Ice Sheet 1991-1992*, 26 pp., 1993.
7. Per Knudsen: *Integrated Inversion of Gravity Data*, 52 pp., 1993.
8. Thomas Knudsen: *Geophysical Use of Geographical Information Systems*, 76 pp., 1996.
9. Simon Ekholm: *Determination of Greenland Surface Topography from Satellite Altimetry and Other Elevation Data*, 23 pp., 1997.
10. René Forsberg, Arne Olesen and Kristian Keller: *Airborne Gravity Survey of the North Greenland Shelf 1998*, 34 pp., 1999.
11. Cecilia S. Nielsen: *Topography and Surface Velocities of an Irregular Ice Cap in Greenland Assessed by the means of GPS, Laser Altimetry and SAR Interferometry*, 81 pp., 2001.
12. Cecilia S. Nielsen: *Estimation of Ice Topography and Surface Velocities Using SAR Interferometry*, 37 pp., 2001
13. Thomas Knudsen (ed): *Proceedings of the seminar on remote sensing and image analysis techniques for revision of topographic databases, Copenhagen, Denmark 2000-02-29*, 119 pp., 2000.
14. Lars Brodersen: *Maps as Communication - Theory and Methodology in Cartography*, 88 pp., 2001.
15. Claus V. Petersen og Simon Ekholm: *Analyse af digitale terrænmodeller beregnet fra satellitbåren SAR interferometrii, Case studies af udvalgte områder i Grønland og Danmark,* 20 pp., 2001.
16. Olwijn Leeuwenburgh: *Combined Analysis of Sea Surface Height and Temperature for Mapping and Climate Studies*, 96 pp., 2001.
17. Călin Arens: *Some examples of topographic applications and accuracy of laser scanning.* 66 pp, 2002.
18. Rene Forsberg, Arne V. Olesen, Kristian Keller and Mads Møller: *Airborne Gravity Survey of Sea Areas Around Greenland and Svalbard 1999-2001,* 55 pp., 2002.
19. Jacob L. Høyer: *On the combination of satellite and in situ observations to detect oceanic processes*, 116 pp, 2002.
20. Thomas Knudsen: *"True" colour presentation of suburban areas from colour-infrared aerial photos*, 51 pp, 2001.
21. R. Forsberg, K. Keller, S. M. Hvidegaard and A. Olesen: *ESAG-2002: European airborne gravity and lidar survey in the Arctic Ocean,* 25 pp., 2002.
22. R. Forsberg, A. Olesen: *Airborne gravity survey of the Foxe Basin, Nunavut,* 13 pp., 2002.

Reports may be ordered from the individual authors at the following address: Kort & Matrikelstyrelsen, Rentemestervej 8, DK-2400 Copenhagen NV, Denmark, Internet: www.kms.dk