# *AIRBORNE GRAVITY AND GEOID SURVEYS IN THE ARCTIC AND BALTIC SEAS*

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## ABSTRACT

A major airborne gravity survey programme has been done 1998-2000 over the Greenland continental shelf, Svalbard and the Baltic Sea. The surveys have been sponsored by national survey authorities of the region, NIMA and oil companies. A primary motivation for the surveys have been to provide data for improved geoid computations. The gravity surveys in the Arctic contributes to the ”Arctic Gravity Project”, an Arctic-wide compilation effort to produce a public-domain gravity grid for all regions north of 64°N by 2001. All gravity surveys have been done using the KMS aerogravity system set-up in a Twin-Otter aircraft, based on a Lacoste and Romberg primary gravity sensor, lately augmented with a Honeywell H-764G strapdown INS unit. GPS positioning of the aircraft is carried out relatively to several base stations and quality checked/augmented by laser altimetry over the sea. Processing of the Lacoste data include platform off-level errors, cross-correlation techniques for calibration and non-linear response terms. Results show no bias offsets or drifts even for long flights without crossovers, illustrating the force of spring gravimeters compared to stand-alone strapdown systems. Consistent r.m.s. error estimates for our surveys range from 1.5 to 2 mGal, for both internal and external comparisons. This translates into relative geoid accuracies in the 5-10 cm range, dependent on track spacing. Around the Baltic Sea, where independent geoid data exist from GPS-levelling, the new airborne geoid changed the existing geoid models by up to 30 cm in the open sea, with no major changes inland, confirming consistency between surface and airborne data.

## BACKGROUND OF THE AIRBORNE GRAVITY SURVEYS

A number of field campaigns of airborne gravity surveys have been done on a yearly basis since 1998, consisting of low-level flights around the coasts of Greenland, Svalbard and the Baltic Sea. All measurements have been done with the same airplane, a DHC-6 Twin-Otter (OY-POF), a general-purpose charter airplane of Greenlandair, Nuuk. The measurements have been ”low and slow”, mostly flown at 500 ft a.s.l. and 135 knot airspeed, giving accurate high-resolution measurements with essentially no need for analytical downward continuation.

*Fig. 1. Twin-Otter at Danmarkshavn*

The measurements around Greenland have been done to complement the on-shore gravity coverage, mostly established by KMS by helicopter-based conventional gravimetry in the years 1991-97, to provide data for regional geophysics, to improved data for global geopotential models, and for improved geoid determination. The surveys are covering a relatively narrow band along the Greenland coasts, to provide gravity data bridging across the inner continental shelf areas, where data from satellite altimetry are less reliable than in the open sea. In North and North-East Greenland wider shelf areas have been surveyed (Forsberg et al., 1999); these are regions north of the coverage of the ERS radar altimetry, or areas covered by near-permanent sea-ice. The 1998-2001 KMS Greenland surveys complement the 1991-92 high-altitude Greenland Aerogeophysics Project (Brozena, 1991), which provided a complete coverage of the interior of Greenland, and contributes to an ongoing effort to map the gravity and geoid of the entire Arctic region (”Arctic Gravity Project”, cf. www.nima.mil/gandg/agp). Economic support for the Greenland surveys have been provided by NIMA.

The same hardware setup has been used around the Svalbard archipelago, to improve the gravity coverage here, in a cooperative effort with Statens Kartverk, Norway and University of Bergen, with additional support from Norwegian oil companies (Oliedirektoratet and Norsk Hydro). Some of the lines across Svalbard were flown at higher elevations (6000 ft) to clear the topography. Downward continuation of these flights has not yet been done, and the cross-over error estimates are thus less accurate since they are affected by this.

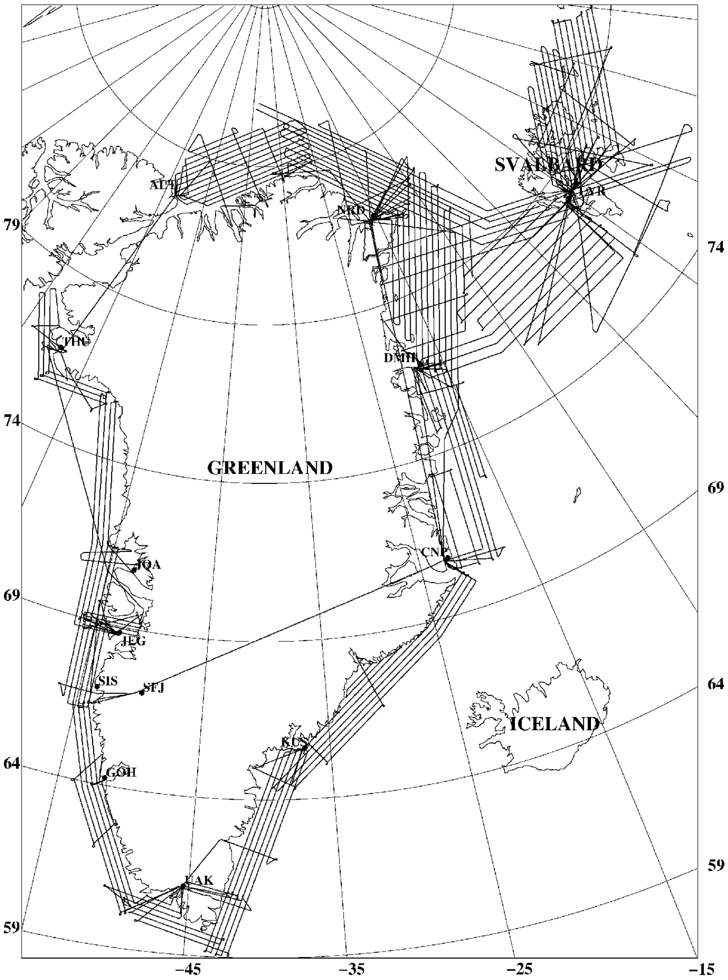

*Fig. 2. Greenland and Svalbard aerogravity tracks 1998-2001*

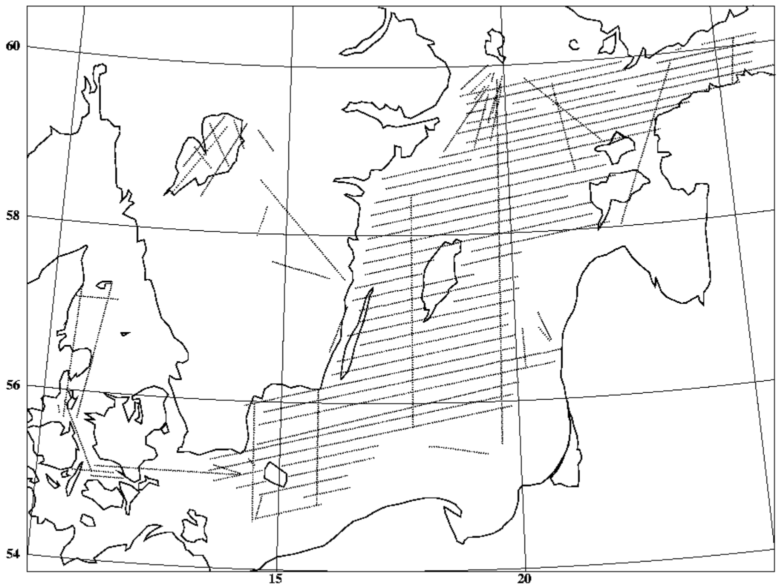

*Fig. 3. Processed gravity tracks, Baltic Sea survey 1999*

The airborne gravity survey of the Baltic Sea was done in 1999, taking advantage of a logistic possibility to take the Greenlandair Twin-Otter south. The Baltic Sea gravity survey filled up the last major gravity data void in the Nordic/Baltic region, and was especially done with the purpose of providing data for improved geoid determination of the Nordic/Baltic region. The airborne survey, and ground GPS and gravity support, was carried out in close cooperation with the Finnish Geodetic Institute (FGI), The National Land Survey of Sweden (LMV), and the geodetic survey authorities of Estonia, Latvia and Lithuania. Economic support was provided by FGI, LMV and KMS, and the Geological Survey of Sweden.

Table 1 outlines the field seasons, and the processed tracks are shown in Fig.2 and Fig. 3. Numerous GPS base stations on ground have been used as references for the flights. Especially in central and southern Greenland ionospheric conditions have been bad at times, making the use of multiple base GPS stations indispensable. The use of many flight operation bases made logistics at times a quite complicated affair, facilitated, though, by the compact and light-weight KMS aerogravity hardware setup. This allows additional payload to be carried along with survey flights, and thus minimizes ferry flights. In the Baltic Sea logistics were further complicated by having to deal with the airspace of seven independent countries, all full of military and restricted air space!

Use of the free space in the aircraft, allowed us to make joint side-by-side flight tests with strapdown inertial gravimetry equipment: in 1998 for a 3-day flight programme in Disko Bay with the University of Calgary/Intermap system (Glennie et al., 2000), and in 1999 by the Ohio State University (vector) gravimetry INS for flights east of Svalbard.

*Table 1. KMS airborne gravity field surveys using OY-POF*

| Field season | Area | Main base airfields | Other piggy-back projects |
|---|---|---|---|
| June 1998 | North Greenland<br>Svalbard | Ilulissat, Alert, Station Nord<br>Longyearbyen | UoC inertial gravimetry, Disko Bay |
| Aug-Sep 1999 | NE Greenland<br>Svalbard-Frans Josef Land<br>Baltic Sea | Station Nord, Danmarkshavn<br>Longyearbyen<br>Mariehamn, Oscarshamn, Rønne | Ohio State inertial vector gravimetry, Svalbard |
| August 2000 | SE and W Greenland | Constable Pynt, Kulusuk, Narsarsuaq, Aasiat, Thule | Ice-penetrating radar |
| April/May 2001 | N Greenland, Fram Strait | Station Nord, Longyearbyen | Laser scanner |

## THE KMS AEROGRAVITY HARDWARE SYSTEM

The KMS airborne gravity system is based on a ZLS-modified Lacoste and Romberg gravimeter (S-99, owned by University of Bergen), where the basic correction for non-gravitational and Eotvos effects is provided by kinematic long-range carrier-phase GPS positioning. The S-99 gravimeter has proven as an extremely stable and realiable field instrument, with typical bias drifts less than 1 mGal per month, thus making this type of system especially useful for geoid determination in previously unsurveyed areas, compared to the bias-drift problems encountered in strapdown inertial gravimetry. The LCR gravimeter is a damped-platform type instrument, used with a 4-minute horizontal accelerometer feed-back period, after initial coarse levelling after turns, for details see Valiant (1991).

*Fig. 4. Cabin set-up: extended-range ferry tank (left), rack and aluminum cage with gravimeter.*

The KMS gravimeter assembly is heritage from the AGMASCO project (Forsberg et al, 1996; Bastos et al., 1997). The gravity sensor is flown in an aluminum protective cage. The aircraft power converter and system control are in the KMS system mounted in a single rack, together with GPS units and a data logger. Numerous GPS receivers are usually flown (Asthech, Trimble and Javad type), fed by beam-splitter on two antennas (forward and aft). Aircraft attitude is provided by a custom-made strapdown inertial measurement unit, consisting of 3 Litef fibre-optics gyros and 3 Schaewitz accelerometers. The rack system and IMU have been custom-build by a small Danish engineering company (Greenwood Engineering). Since 2000 a medium grade integrated INS/GPS (Honeywell H764G) have been flown as well, with the aim to provide improve attitude as well as gravity recovery redundancy. The KMS aerogravity system is usually operated by a single person in flight, and a total field crew of 2-3 geodesists make for small and efficient surveys.

For ocean and ice sheet applications an Optech laser altimeter is used to map surface heights, whenever conditions permit (low fog is frequent in the Arctic). Over the ocean the laser may be used as an independent source of vertical acceleration source, with a fit to GPS accelerations after filtering typically better than 1 mGal r.m.s. (Olesen et al., 1997). Since 2001 a Riegl 60° swath scanning laser has also been added to the system, and used for ice sheet elevation and sea-ice freeboard and thickness measurements. On occasions an ice-sounding 60 MHz radar has also been added to the system (courtesy the Technical University of Denmark), with a simple dipole antenna fitted to a tie-down hole through the aircraft tail, cf. Lintz et al. (2000).

## DATA PROCESSING

The principle of airborne gravity is to measure the total acceleration by a gravimeter, and subtract the non-gravitational accelerations as determined by GPS. The fundamental equation for the free-air anomaly Δg is

$$\Delta g = y - h'' - \delta g_{eotvos} - \delta g_{tilt} - y_0 + g_0 - \gamma_0 + 0.3086\,(h - N) \qquad (1)$$

where y is gravimeter reading, h´´ the GPS acceleration, $\delta g_{eotvos}$ the Eotvos correction (computed by the formulas of Harlan, 1968), $y_0$ the gravimeter base reading, $g_0$ the apron gravity value,. $\gamma_0$ normal gravity, h the GPS ellipsoidal height, and N the geoid undulation (EGM96 used throughout). The platform off-level correction $\delta g_{tilt}$ due to non-level measuring system is expressed as

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

where 'a' and 'A' denote GPS horizontal kinematic aircraft accelerations and horizontal specific forces measured by the accelerometers, respectively. Because of the potential for high amplitudes in the horizontal accelerations, and the small difference between accelerations from accelerometer and GPS measurements, the 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, based on the frequency dependent behaviour of the platform, and a similar method has also been used for calibration of the dynamic beam scale factor, cf. Olesen et al (1997).

Reference gravity values were determined by land gravimeter ties to absolute reference points, with the measured apron value corrected for the height of the aircraft. A number of airborne system gravity basereadings were made over the field season, ensuring a smooth drift function of the airborne gravimeter could be determined.

Kinematic GPS solutions were generally made in pairs to different base stations and aircraft antennas using commercial software (mainly "GPSurvey"). Problems in GPS solutions were rectified by occasional use of INS vertical acceleration and/or laser data. All GPS base station coordinates were tied into the ITRF94 reference system.

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 in the data, and to remove the high frequency noise masking the gravity anomaly signal. Especially the nonlinear terms, mainly represented by the tilt correction, are sensitive to the initial filtering. In the Greenland surveys all data were filtered with a symmetric 2nd order Butterworth filter with a half power point at 200 seconds, corresponding to a resolution of 6 km (half-wavelength). The impulse response and spectral behaviour of the used filter are shown in Fig. 5.

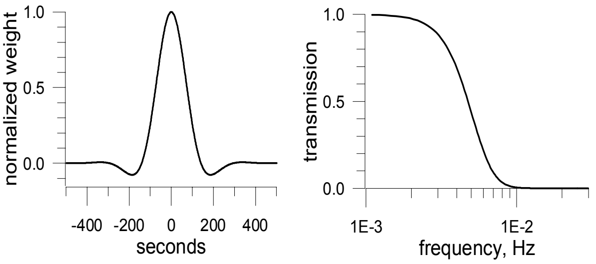

*Fig. 5. Normalized gravity processing filter response (left) and transfer function (right)*

## EVALUATION OF THE AIRBORNE GRAVITY

The gravity data may be internally evalutated by a cross-over adjustment, and by comparisons to independent surface data. In all field seasons several high-quality ground data sets were available for comparison, either in the form of gravimeter measurements on sea-ice (north of Greenland), or recent, well-calibrated and accurate marine gravimetry from commercial Nunaoil seismic surveys in Greenland. In the Baltic Sea a 1997 marine gravity cruise across the southern Baltic by the University of Bergen ship R/V Håkon Mossby provide high-quality independent marine ground truth data, along with ocean-bottom gravimetry data off Poland, Latvia and Estonia.

Table 2 shows that the cross-over errors are at a level between 2 and 3 mGal r.m.s., which, assuming random errors, corresponds to a gravity error of 2 mgal (x-over error/√2) or better. It should be noted that no cross-over adjustment have been applied to the data, as experience have shown that such an adjustment can actually degrade the data (in spite of improvements in r.m.s. x-over error statistics, cf. Forsberg et al, 1999), since any cross-over adjustment by nature distributes point errors at crossings into along-track corrections (e.g., biases and tilts), and thus provides an avenue of short-period random errors leaking into longer wavelengths.

Table 3 shows the comparisons of the airborne data to the independent surface data, without any correction for downward continuation. It is seen that the comparison to the independent data support the 2 mGal r.m.s. error estimate found in the x-over analysis (allowing for errors in the ground truth data), and that the airborne data appears to have little or no bias error. The data are therefore very useful for geoid determination, where biases have an especially large impact, due to the inherent low-pass filtering nature of geoid determination.

*Table 2. Internal airborne track cross-over differences.*

| Unit: mGal | No of crossings | Without cross-over adjustment | |
|---|---|---|---|
| | | R.m.s. | Abs. max |
| Disko Bay 1998 | 15 | 2.6 | 5.2 |
| North Greenland 1998 | 69 | 2.6 | 6.0 |
| North-East Greenland 1998/99 | 77 | 2.8 | 8.4 |
| SE and W Greenland 2000 | 97 | 2.8 | 9.3 |
| Svalbard 1999 (some flight level differences) | 21 | 3.4 | 9.8 |
| Baltic Sea 1999 | 126 | 2.0 | 8.4 |

*Table 3. Comparisons between surface gravity data and final airborne data*

| Unit: mGal | Mean diff. | R.m.s. |
|---|---|---|
| *Greenland:*<br>Disko Bay – 1998 survey | -0.5 | 3.1 |
| Lincoln Sea sea-ice data – 1998 | -0.1 | 2.4 |
| Station Nord sea-ice profile – 1998 | -0.8 | 1.7 |
| NE Greenland (Nunaoil data) – 1998/99 | 0.2 | 2.4 |
| Nunaoil data off W and SE Greenland – 2000 | 0.3 | 1.6 |
| *Baltic Sea:*<br>Marine data by R/V Håkon Mossby | 0.5 | 1.9 |
| Latvia/Estonia ocean-bottom gravimetry | 0.0 | 1.2 |
| Polish ocean-bottom gravimetry grid | 1.1 | 1.9 |

## GEOID FROM AIRBORNE GRAVITY DATA

The geoid is determined from the airborne data by conventional methods of physical geodesy. With gravity errors at 2 mgal, typical relative geoid errors are at the 0.5-1 ppm level, or 5-10 cm for 10 km track spacing, as based on experience from land geoid computations and collocation error studies. To illustrate the impact of the airborne data on the geoid, a geoid computation have been done for the Baltic region, comparing the previous “best” geoid (NKG96, cf. Forsberg et al., 1996) to a new geoid including the airborne data, computed by the exact same methods.

The NKG96 and the new geoid have been computed by remove-restore techniques, with the geoid signal constructed by subdividing it into three parts

$$N = N_1 + N_2 + N_3 \qquad (3)$$

where the first part comes from a spherical harmonic expansion complete to degree and order 360 (EGM96), the second part from the topography, and the third part from the contributions of "residual" gravity (i.e., gravity anomalies minus the global field contribution and gravimetric terrain effects). Terrain effects have been removed in a consistent “RTM” terrain data reduction scheme using rectangular prisms as basic integration element. Residual gravity anomalies are converted into residual height anomalies by spherical FFT (Strang van Hees, 1990). The method in principle evaluates Stokes’ integral

$$N_3 = \frac{R}{4\pi\gamma} \underset{\sigma}{\ } \Delta g_3 S(\psi) d\sigma \qquad (4)$$

through a series of band wise two-dimensional FFT operations of form

$$N_3 = S_{ref}(\Delta\varphi, \Delta\lambda) * [\Delta g_3(\varphi, \lambda)\sin\varphi] = F^{-1}[F(S_{ref})F(\Delta g\sin\varphi)] \qquad (5)$$

where $S_{ref}$ is a (modified) Stokes' kernel function, and * and F the two-dimensional convolution and Fourier transform, respectively, for details see Forsberg and Sideris (1993). In the actual implementation of the method, the data are gridded by least-squares collocation, and a 100% zero padding is used to limit the periodicity errors of FFT. The total number of grid points transformed is 1600 x 1280.

The difference between the old NKG96 geoid, and the new geoid with airborne data, is shown in Figure 6. Some major differences up to 30 cm are seen off the coast of Estonia, and up to 20 cm off Gotland and Bornholm. Overall the geoids are quite similar, though, and on land significant differences are found only in a few coastal regions. For the geoid on land, only Estonia showed significant improvement, with the fit to national GPS-levelling data improving from 6 to 4 cm r.m.s. across the country with the new computation. Tide gauges on both sides of the sea from the “Baltic Sea Level Project” fit to 10 cm r.m.s. in both solutions, with a major uncertainty in levelling datum connections. The old NKG96 geoid was thus apparently quite good, likely due to the use of a special ERS-1 altimetry gravity solution, draped to existing ocean-bottom and land gravimetry. The ERS-1 gravity data fit the airborne data at the 6 mGal r.m.s. level, and the satellite-derived gravity anomalies are thus quite accurate (a consequence in part of the lack of tides in the Baltic, and the use of a model of the known quasi-stationary sea surface topography in the NKG96 computation, cf. Forsberg et al., 1997).

## CONCLUSIONS

A major gravity survey campaign, with a total of nearly 600 flight hours, has been done 1998-2001 by KMS. An accuracy of 2 mGal or better has repeatedly been obtained, as evidenced by cross-over statistics and comparisons to independent data, with best results in the Baltic Sea where GPS has the least ionosphere problems. The platform gravimeter system have proven itself to be highly reliable, stable, and thus very suitable for geoid determination and mean anomaly recovery for global models in unsurveyed areas.

## REFERENCES

Bastos, L., S. Cunha, R. Forsberg, A. Olesen, A. Gidskehaug, U. Meyer, T. Boebel, L. Timmen, G. Xu, M. Nesemann, K. Hehl: An Airborne Geoid Mapping System for Regional Sea-surface Topography: applications to the Skagerrak and Azores areas. In: Forsberg (Ed.): Geodesy on the Move, IAG proceedings 119, pp. 30-36, Springer Verlag, 1997.

Brozena, J. M.: The Greenland Aerogeophysics Project: Airborne Gravity, Topographic and Magnetic Mapping of an Entire Continent. In: Colombo (Ed.): From Mars to Greenland:

Charting Gravity with Space and Airborne Instruments, IAG Proceedings Series 110, pp. 203-214, Springer Verlag, 1991.

Forsberg, R., J. Kaminskis and D. Solheim: Geoid of the Nordic and Baltic Region from Gravimetry and Satellite Altimetry. In: J. Segawa, H. Fujimoto and S. Okubo (ed.): Gravity, Geoid and Marine geodesy. IAG Symposium Series 117, pp. 540-547, Springer Verlag, 1996.

Forsberg, R., K. Hehl, L. Bastos, A. Gidskehaug, U. Meyer: Development of an Airborne Geoid Mapping System for Coastal Oceanography (AGMASCO). In: Segawa et al. (eds.): Gravity, Geoid and Marine Geodesy, IAG proceedings 117, pp. 163-170, Springer Verlag, 1996.

Forsberg, R., A. Olesen and K. Keller: Airborne Gravity Survey of the North Greenland Shelf 1998. Technical Report no. 10, Kort og Matrikelstyrelsen, Copenhagen, 34 pp., 1999.

Glennie, C. L., K. P. Schwarz, A. M. Bruton, R. Forsberg, A. V. Olesen, K. Keller: A Comparison of Stable Platform and Strapdown Airborne Gravity. Journal of Geodesy, 74, 2000.

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

Lintz Christensen, E., N. Reeh, R. Forsberg, J. H. Jørgensen, N. Skou, K. Woelders: A low cost glacier mapping system. Accepted for publication, Journal of Glaciology, 2000.

Olesen, A., R. Forsberg and A. Gidskehaug: Airborne Gravimetry using the LaCoste and Romber Gravimeter – an Error Analysis. In: Proc. Int. Symp. On Kinematic Systems in Geodesy, Geomatics and Navigation (KIS-97), Dept. Of Geomatics Engineering, University of Calgary, pp. 613-618, 1997.

Strang van Hees, G.: Stokes formula using fast Fourier techniques. Manuscripta Geodaetica, vol. 15, pp. 235-239, 1990.

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

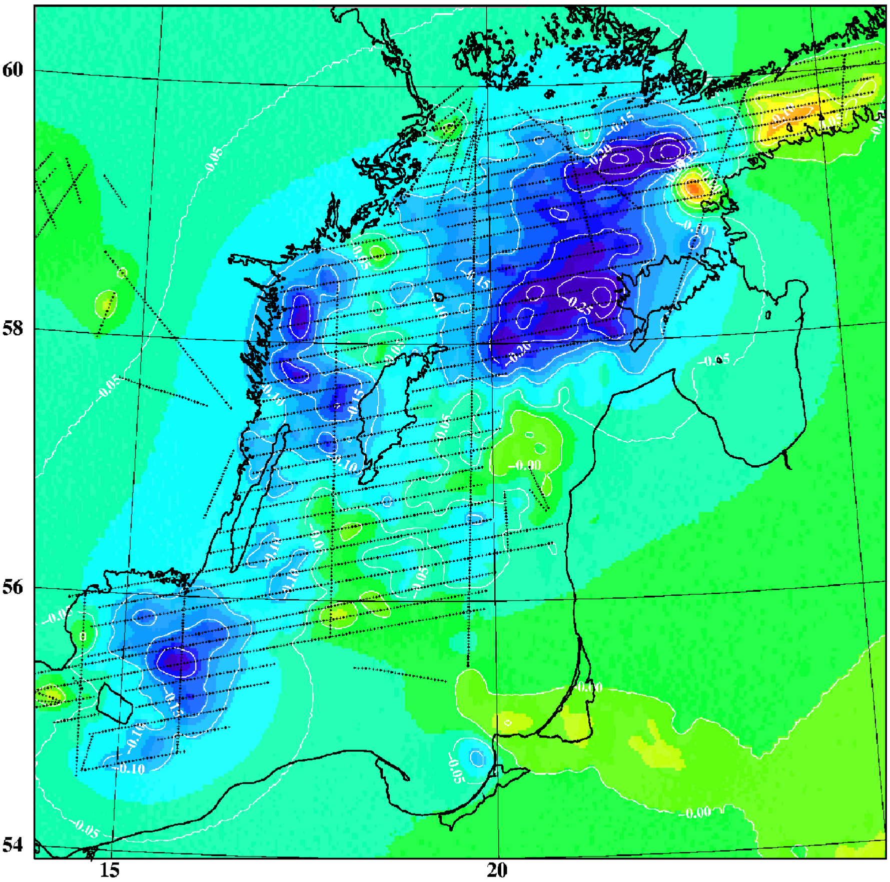

*Fig. 6. Difference between new geoid (with airborne data) and NKG96. Contour interval 5 cm.*