GRAVITY AND GEOID IN THE ARCTIC REGION
– THE NORTHERN POLAR GAP NOW FILLED

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ABSTRACT

The GOCE satellite gravity field mission will leave “polar gaps”, and to fill-in these gaps terrestrial and airborne gravity data are essential. The Arctic Gravity Project has recently completed the compilation of a gravity field on a 5’x5’ grid of the entire Arctic region north of 64°N. The project incorporated major new airborne surveys of the US Naval Research Laboratory, Scandinavian, German and Russian sources, as well as extensive surface data coverage for the Russian sector of the Arctic Ocean. Other data sources included submarine data that provided detail over many of the high frequency features in the Arctic, and enhanced satellite altimetry over ice-covered areas. In the paper we describe briefly the data, the principles of the compilation, and a premliminary analysis of the ArcGP grid products based on GRACE and ICESAT data. The Arctic Gravity Project includes free-air gravity anomalies, updated elevation and bathymetry data, and a precise geoid.

1 INTRODUCTION

The gravity field of the Arctic Ocean region is of importance for global gravity field models, for geology and tectonics, as well as for navigation and orbit determination. For the GOCE gravity field mission the determination of spherical harmonic gravity field models will be affected by the lack of satellite coverage around the poles, with the effects of the polar gap showing up as relatively large errors in the zonal coefficients. With GRACE gravity field data only providing the longer wavelengths of the polar gravity field, there is a special room for terrestrial gravity observations to augment the satellite data. In this paper we show how a successful international cooperation, combined with dedicated airborne gravity surveys, have produced a virtually complete coverage of the northern polar gap; for the southern gap (Antarctica) a coordinated international effort with airborne gravity surveys would be a natural effort to be undertaken in the coming years, with events like the planned launch of GOCE 2006 and the International Polar Year 2007 serving as obvious drivers in time.

Ongoing gravity activities over many years have resulted in a nearly complete coverage of the Arctic with gravity field data. In recent years major airborne and surface survey activities have been carried out in the High Arctic and Greenland, US nuclear submarines have criss-crossed under the ice on scientific cruises, and Russia has continued a decade-long program of surface and airborne gravity measurements. In 1998 the Arctic Gravity Project was started as an international initiative under the International Association of Geodesy, involving scientists from all arctic countries, as well as other countries with major gravity data collection activities in the Arctic. The aim has been taken to compile all available and releasable gravity data into a 5' x 5’ uniform, public-domain gravity grid, and the compiled gravity grids, along with a geoid model and updated topography, was released in December 2002, see the ArcGP website at http://164.214.2.59/GandG/agp/index.htm

2 ARCTIC GRAVITY DATA COMPILATION

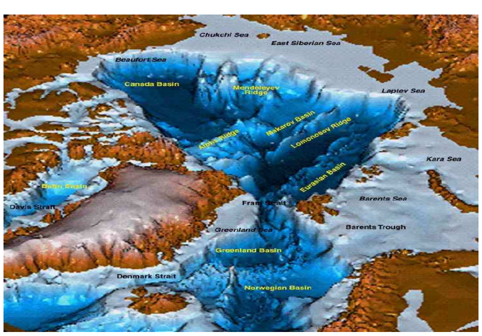

Fig. 1. Arctic Ocean Bathymetry

The Arctic Region has been in focus of various bathymetric and gravimetric activities since the early 1990’s. The development of a modern bathymetric database of the Arctic was initiated in 1997 under the auspices of the International Hydrographic Office (IHO), with the goal that a bathymetric database north of 64°N would be compiled (Fig. 1). The Arctic Gravity Project followed closely in the footsteps of this cooperation, and have secured the release of gridded data products of major classified data sets from as well US as Russian sources, with the final goal to be the compilation of a public-domain 5’x5’ free-air and Bouguer gravity databases above 64° North including the Arctic Ocean, Greenland, and the margins of North

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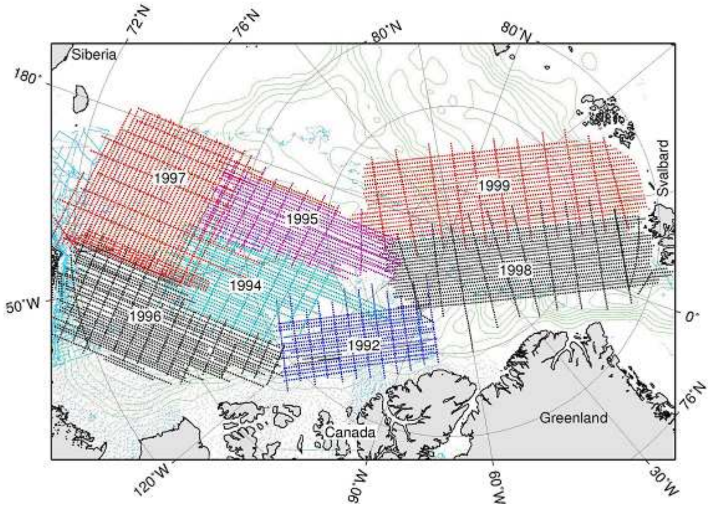


Fig. 2. NRL long-range airborne surveys of the Arctic Ocean

America and Russia. Iceland and Greenland hanve been included in the compilation even though their southern extent is below 64°N. The National Imagery and Mapping Agency (NIMA) would act as the data repository for the project and perform the gravity compilation activities in close cooperation with ArcGP working group members.

The gravity data available for the compilation included surface (ground, helicopter, and marine), airborne, and submarine data, each with special error characteristics in terms of both accuracy and resolution. Some data, especially from Russia, was presented in the form of grids derived from digitized gravity maps. Along with these data types, satellite altimetry has been used over some ice-free and ice-covered areas up to the limits of ERS-1 coverage at 81.5°N [1].

Of especial importance for the filling of the high arctic polar gap has been long-range airborne gravity surveys using kinematic GPS techniques. The airborne gravity holdings in the Arctic are currently the predominant data source over the Arctic Ocean and Greenland, and are primarily the result of surveys by the US Naval Research Lab [2], cf. Fig. 2. The NRL Arctic Ocean surveys followed the pioneering successful aerogravity coverage of Greenland by high-altitude surveys 1991-92 [3]. In addition airborne gravity surveys by Russian, Canadian, and Danish/Norwegian sources have been utilized. Generally the airborne gravity accuracy has improved signifiantly since the early 1990's, with best recent surveys having a typical accuracy of 1.5-2 mGal r.m.s., at a resolution of 6-15 km depending on aircraft speed [4,5].

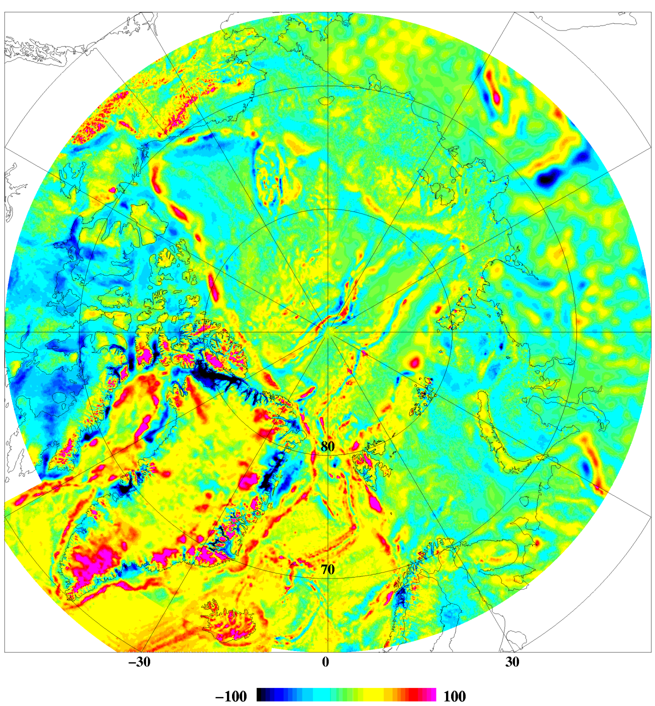


Fig 3. Arctic Gravity Project free-air gravity anomalies (unit: mgal).

Long-wavelength errors in airborne gravity are a potential problem due to inherent ulinearities in the platform tilt corrections in the airborne gravity [6], and can be further aggrevated by aliasing from cross-over adjustements frequently used. In addition uncertainties in reference gravity ties and other errors necessitates a "draping" approach where more accurate data are used as "reference" to tie in less accurate data. Table 1 shows an example of comparison of different data sources in the Arctic Ocean region from Greenland over Svalbard to Frans Josef Land (Russia). Due to the homogenous nature of the errors of each individual survey the use of long-wavelength gravity field information from GRACE should significantly improve the possible biases in the airborne data.

The final combination of all data from airborne, submarine and surface/map data was done using least-squares collocation gridding/draping methods. Over Greenland and Svalbard high-altitude airborne gravity data from NRL and KMS were downward continued to the geoid. Only over Siberia (east of 60°E) and for a few minor data voids in the Arctic Ocean were EGM96 used for grid cell fill-ins. The final Arctic Gravity Project gravity grid, released Dec. 2002 and available at the ArcGP web site, is shown in Fig. 3.

Table 1. Comparison of difference airborne gravity surveys and satellite altimetry in eastern Arctic Ocean areas

Difference (mgal)	*Mean*	*Std. Dev.*
NRL-KMS airborne gravity (North Greenland shelf)	-2.5	5.6
NRL-SK/KMS airborne gravity (Svalbard region)	-0.4	4.3
KMS-PMGE(Russia) airborne data (Frans Joseph Land)	3.6	4.6
AWI-KMS airborne (Greenland/Fram Strait)	-1.5	7.5
AWI-NRL airborne (Fram Strait)	-6.9	5.5
ERS satellite altimetry (BGI) – KMS airborne	-1.4	12.2
ERS satellite altimetry (Laxon/McAdoo) – KMS airborne	-1.1	15.3

3 GEOID MODEL FOR THE ARCTIC

Geoid models are determined from the available airborne and surface gravimetric data using a remove-restore technique, where the reference field (EGM96) is removed from the free-air gravity data, and subsequently restored in the final geoid. The gravity to geoid conversion of the residual gravity signal is done by spherical FFT, using the bandwise approach derived in [7], where the geoid signal is obtained by a number of bandwise Fourier transformations of form

$$N = \Im^{-1}[\Im(S)\,\Im(\Delta g \sin\phi)] \qquad (1)$$

where $\Im$ is the two-dimensional Fourier transform, N the geoid, Δg the gravity anomaly, ϕ the latitude, and S the classical Stokes' function. For the practical computations a modified Stokes' function

$$S'(\psi) = \sum_{l=N}^{\infty} \frac{2l+1}{l-1} w_l P_l(\cos\psi) \qquad (2)$$

is used. This allows only the shorter- and medium wavelengths of the geoid to be determined (with EGM96 for $l > 36$), with the reference field geoid in principle determining the longest wavelengths. Fig. 4 shows the computed geoid model of the Arctic, similarly available from the ArcGP web site.

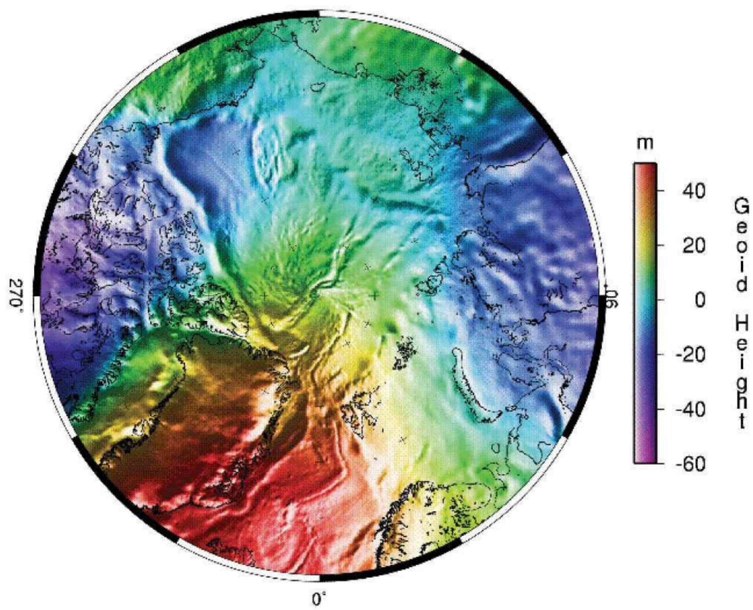


Fig. 4. Shaded relief geoid model of the Arctic region. Unit: m.

4 ARCTIC GRAVITY PROJECT COMPARISON TO NEW GRACE AND ICESAT DATA

Since the Dec. 2002 release of the ArcGP grids, the release of GRACE gravity field models, as well as some very limited ICESAT laser altimetry, allows a first investigation of possible biases and errors in the ArcGP grid. A new composite GRACE-EGM reference gravity field model was constructed by merging the GGM01C GRACE geopotential model with EGM96, with a linear transition of coefficients from GRACE to EGM96 in the spherical harmonic band range 80-90. Table 2 shows the comparison of the ArcGP gravity anomalies to EGM96 as well as the GRACE-EGM composite model.

Table 2. Comparison of differences between ArcGP free-air anomalies and referernce fields

Difference (mgal)	***Mean***	***Std. Dev.***
ArcGP free-air anomalies	3.4	27.5
Difference ArcGP minus EGM96	-0.3	19.8
Difference ArcGP minus GRACE-EGM composite model	0.1	16.8

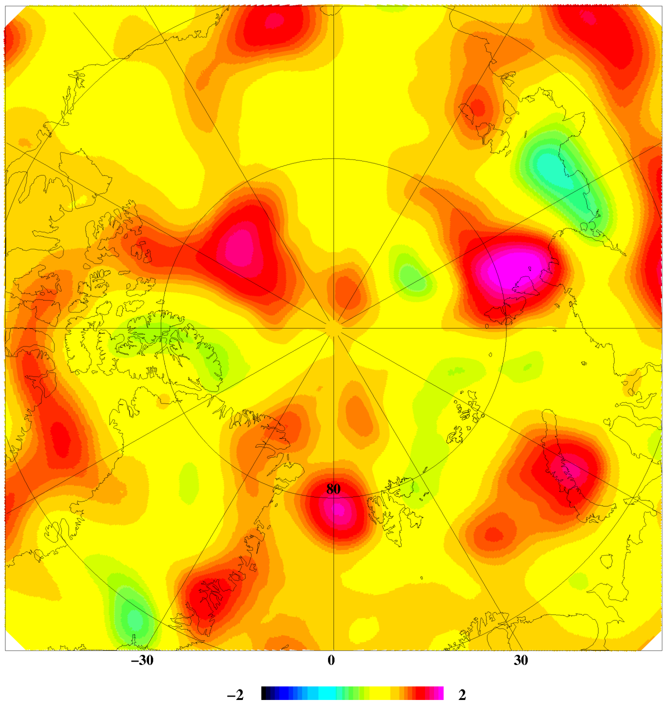
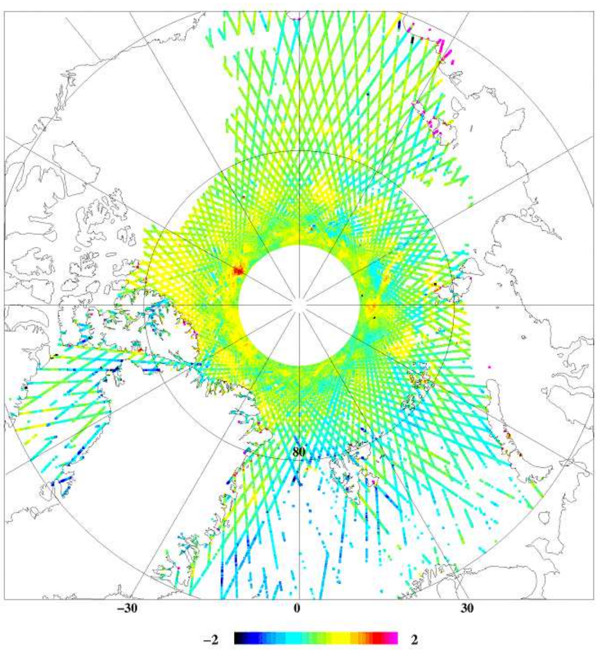


Fig. 5. Difference of geoids using EGM96 and GRACE reference (m).

Table 2 shows that it appears that the ArcGP grid is nearly bias-free, and that the GRACE information has yielded an improved estimation of the longer wavelengths of the field. To illustrate the changes in the long wavelengths, Fig. 5 shows the difference between the Dec. 2002 ArcGP geoid, and a new geoid using the GRACE-EGM96 composite model. The deviations both highlight some data voids and some data problem areas.

The geoid models may be directly evaluated by ICESAT laser altimetry data, covering the Arctic Ocean up to 86°N. Limited data for a single 8-day repeat period (March 2003) have been used for this study. The measured heights of the ice surface of the Arctic Ocean includes the geoid height, as well as ocean tides (generally small in the Arctic Ocean), and the ice free-board heights. The latter are typically on average a near-constant 30-50 cm when averaged on spatial scales of 10's of km, depending on ice thickness.

Fig 6a shows the location of the Icesat laser tracks, as well as the difference between the measured mean ice surface and the GRACE-improved ArcGP geoid. It is seen that a quite reasonable fit is obtained, except for an area at approx. 85°N 135°W, exactly corresponding to a void in the NRL airborne gravity data (Fig. 2). By assuming the Icesat mean sea-surface to represent the geoid, the gravity anomalies may be recovered by inverse Wiener filtering FFT methods [8]. Fig 6b shows the results of the gravity anomalies determined by the Icesat data only, using the GRACE-EGM96 combination model as reference field. Compared to recent KMS airborne gravity data north of Greenland this data shows an agreement of 10 mgal r.m.s., and may thus be



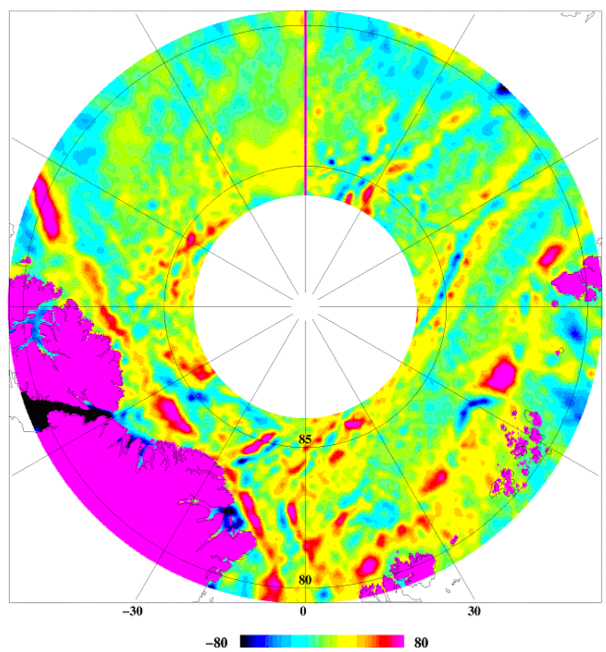


Fig 6a (left): Location of used Icesat data and the difference between the surface heights and the ArcGP geoid model (unit m).
Fig 6b (right): Free-air gravity anomalies from Icesat data and the GRACE-EGM reference field (unit mgal)

used to improve the ArcGP gravity data in the data voids. In spite of the very limited amount of Icesat data used (a single 8-day repeat), it is surprising how well the main tectonic features of the Arctic Ocean are resolved with these data. That implies that the ArcGP grid can be improved with Icesat, especially in the data voids and when more data are released.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

The Arctic Gravity Project has been highly successful in making a nearly complete gravity grid of the Arctic Ocean and adjacent land areas. Gravity data provided to date for the Arctic Gravity Project has been quite accurate and is the result of improved navigation solutions for GPS and research into better modeling and processing techniques for airborne, marine, ground, and submarine collections. The ArcGP data shows a good agreement with new GRACE gravity field models. The geoid derived from the Arctic gravity grid should be useful in e.g. defining mean-sea surfaces to serve as references for the measurement of ice free-board heights by satellite laser or radar.

With the recent availability of satellite data from GRACE and ICESAT, as well as new detailed gravity information just made available by Russian sources for Siberia, it is planned shortly to update the ArcGP gravity grid and geoid model.

With the northern polar gap of GOCE now filled with ArcGP data, an effort should be undertaken to make a similar compilation and dedicated airborne gravity surveys of the Antarctic polar gap. Such an effort would, however, be quite a challenge given the much more challenging logistics in Antarctica compared to the Arctic.

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