THE OCTAS PROJECT, THE GEOID, THE MEAN SEA SURFACE AND AND THE MEAN DYNAMIC TOPOGRAPHY

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ABSTRACT

The OCTAS project, Ocean Circulation and Transport Between North Atlantic and the Arctic Sea, funded by the Norwegian Research Council, is a multidisciplinary project combining geodesy, satellite altimetry and oceanography. The main objective is to enhance the Norwegian capacity in Earth observation technologies through determining the ocean circulation and transport by using satellite techniques in combination with geodesy. The primary study area is the Fram Strait between Svalbard and Greenland.

A vital objective is the determination of a high precision gravimetric geoid for the OCTAS study area. This requires an error free high quality gravimetric dataset. The process of establishing such a data set by adjusting older marine data through comparison with modern airborne and marine gravity data sets is described. Combining this updated gravity data set with data from the CHAMP and GRACE satellites an OCTAS geoid has been computed. The updated gravity field and the derived geoid may be used in validating the GOCE products.

The challenges and efforts undertaken in deriving a high precision mean sea surface in a region with an abundance of sea ice and limited number of altimetric satellites is described. The derived geoid and mean sea surface is combined to form the mean dynamic topography, MDT. These MDT's are assessed by intercomparing with oceanographically derived MDT models.

The status and an overview of the project is given including identification of challenges that must be addressed in order to achieve the project objectives.

Key words: Geoid; Mean Sea Surface; Mean Dynamic Topography.

1. INTRODUCTION

The OCTAS project, Ocean Circulation and Transport Between North Atlantic and the Arctic Sea, is one of many projects that have been greatly influenced by the EU financed AGMASCO project [1], Airborne Geoid Mapping System for Coastal Oceanography. An important part of this project was the development of a system for measuring airborne gravity [2]. The experiences from this project were used at Kort- og Matrikel-styrelsen, now the Danish National Space Center, to derive a Danish airborne gravity system with some Norwegian support, primarily by having access to the LaCoste & Romberg Air and Sea Gravity Meter, S-99, belonging to the University, but also some software support. This system was successfully tested in 1998 with surveys both on Greenland and Svalbard. The Norwegian measurements were financed by the Norwegian Company Norsk Hydro and the Norwegian Mapping Authority, NMA [3]. Later Norwegian surveys in 1999 and 2001, also in the Svalbard region, have been supported by the Norwegian Petroleum Directorate and NMA.

The experiences from these surveys were of vital importance to the discussions that led to the Norwegian DYNTOP, North Atlantic Dynamic Sea Surface Topography and Operational Ocean Circulation Models, application to the Norwegian Research Council in 2000. Despite favorable reviews, no project approval was given. The ideas from DYNTOP were however used as input in the process that lead to the successful EU project GOCINA, Geoid and Ocean Circulation in the North Atlantic, and the still ongoing Norwegian research project OCTAS.

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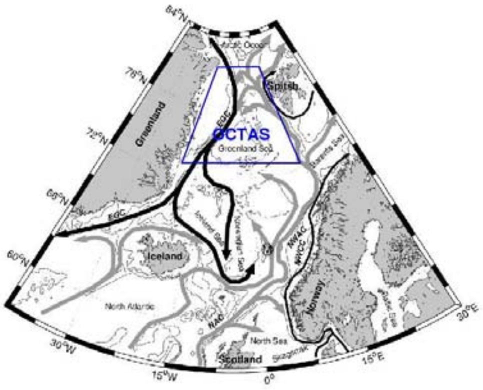

Figure 1. The Octas Study Region

2. PROJECT DETAILS

OCTAS is a 4 year project financed by the Norwegian Research Council. It is a twin project to the EU project GOCINA, which was finalized fall 2005. The OCTAS project has been running since January 2003 and has been extended by half a year till the end of June 2007. A vital part of the project is to increase and extend the existing expertise and to enhance the Norwegian capacity in Earth observation technologies. 4 PhD students were planned to be part of the project. Due to practical problems only 2 PhD students have been working on the project. The 2 remaining PhD positions have been replaced by temporary positions as post docs and/or researchers. The main objective of the project is to establish improved knowledge of ocean circulation and transport by utilizing space techniques in combination with geodesy and to study the impact this will have on ocean modeling. To obtain this, several different tasks have to be undertaken with their separate objectives.

Up to the expected launch of GOCE in 2007 the gravimetric geoid is not known with sufficient accuracy to allow full use of the massive sea surface height information, which several satellite altimetry missions have regularly provided since the early 90-ies, in global analysis of the ocean circulation.

In a few marine regions in the world sufficient in-situ information about the Earths gravity field exists to compute a more accurate geoid. The region covering the Northern North Atlantic and the Nordic seas between Greenland, Iceland, Norway and the UK, is one of these regions. The gravity coverage do however vary some and especially in the northern North Atlantic it would have been advantageous with access to more high quality gravity data.

One of the OCTAS objectives is to determine an accurate geoid in the Fram Strait and the adjacent seas, see Fig. 1. Together with the results obtained by the EU-funded project GOCINA, where in a similar approach an accurate geoid was determined for the region between Greenland and the UK, this will create a platform for validation of future GOCE Level 2 data and higher order scientific products. The new and accurate geoid is used together with an accurate Mean Sea Surface (MSS) to determine the Mean Dynamic Topography (MDT) through the simple equation

$$MDT = MSS - Geoid. \tag{1}$$

Another major goal of OCTAS is to use this new and accurate MDT for improved analysis of the ocean circulation. The ocean transport through the Fram Strait is known to play an important role in the global circulation. Water from the North Atlantic Current flows into the Nordic seas and feeds the formation of heavy bottom water that returns back into the Atlantic Ocean. Recent results have shown that changes in this bottom water transport may cause the inflow of water to slow down or change into another stable circulation mode over a few decades. Such a change with even a possible shut down of the heat transport towards high latitudes would have a huge impact on the North European climate. The OCTAS project attempts to elucidate the role of the water exchange between the Arctic and Greenland Seas in this process.

The work-plan is broken down into six distinct tasks of which each is associated with a Work Package, see Fig. 2 for an overview of the work packages:

- **Task 1:** To determine a regional high-accuracy gravimetric geoid.
- **Task 2:** To determine a regional high-accuracy MSS.
- **Task 3:** To determine a regional best possible MDT using in-situ hydrographic data and ocean modeling.
- **Task 4:** To provide detailed assessment of the geoid, the MSS, and the MDT.
- **Task 5:** To integrate the three techniques for improved (optimal) estimation of the geoid and the MDT.
- **Task 6:** To investigate the impact of the improved MDT on the ocean circulation estimation.

The primary study region as shown in Fig. 1, is the Fram Strait and the adjacent seas to the North and South. The circulation pattern in the Nordic Seas is schematically illustrated in the figure. Dark arrows mark the cold and fresh water path, while gray marks the relatively warm and saline path.

3. AIRBORNE GRAVITY SURVEY

In a joint cooperation between GOCINA and OCTAS new airborne gravity data was collected during summer 2003 in the Northern North Atlantic. In Fig. 3 the OCTAS

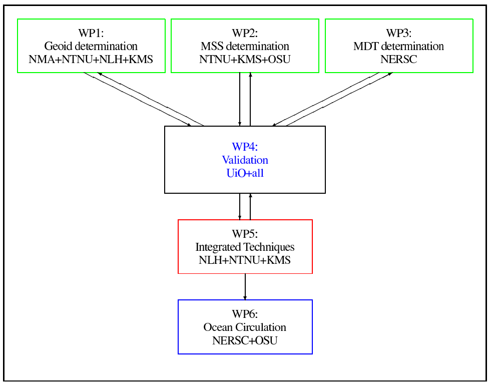

Figure 2. Linkage of the work packages

part of the airborne measurement campaign is visible. For information about the airborne gravity data collected by GOCINA, see e.g. [4].

The airborne survey was carried out with an aircraft equipped with GPS receivers, laser altimetry, Inertial Navigation Systems (INS), and a modern LaCoste & Romberg marine gravimeter. The OCTAS measurement was done around Greenland, Svalbard, Jan Mayen and along the Norwegian coast.

The supplementary GOCINA survey was along a band from Greenland over Iceland and Faeroe-Shetland to Norway. The main objective of these surveys was to tie in as many possible different marine surveys as possible by performing crossover computations and adjustments as well as to fill in some data voids in the gravity coverage.

A total of 9222 measurements divided into 35 profiles of airborne gravity tracks have been processed. An internal cross over computation (airborne gravity data only) show an RMS of 1.6 mGal, while compared to the marine data give an RMS of 4.51 mGal, see Table 1.

	N	Mean	Min	Max	RMS
Internal	15	0.71	-2.87	3.79	1.58
Marine	548	0.44	-27.44	20.54	4.51

Table 1. Statistics of the cross over computations with marine gravity data and with itself. Values in mGal

4. MARINE GRAVITY ADJUSTMENT

The main marine gravity data sets used in this study have been acquired from BGI, NGDC, NMA, and from several oil companies. The data set was recently augmented with the airborne gravity survey described in section 3.

Marine gravity measurements are, in principle, very precise, but despite this they should be used with care when computing the geoid. Some of the problems relate to measuring gravity on an imperfectly stabilized platform.

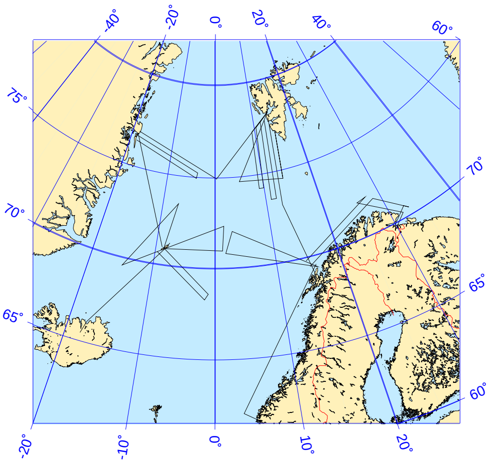

Figure 3. OCTAS Airborne Survey, 2003

Others are due to systematic instrument errors, loosing reference to an absolute gravity datum and uncertainties in the navigation system, in terms of course, speed, and position errors, affecting the Eötvös correction. [5] review these problems in depth, see also [6].

Marine gravity data have been measured for quite some time. A lot of the measurements were done in the pre GPS area and by companies mostly interested in the relative variation of the gravity signal. Precise navigation is mandatory when determining the Eötvös correction. Likewise a proper tie to onshore existing land gravity data is of vital importance for the determination of the geoid. Most surveys have been performed by measuring along lines or tracks with a few supplementary tracks crossing these in order to get an assessment of the quality of the data by investigating the cross over differences. Several datasets may have a small internal cross over difference, but an offset when compared with the true gravity value. The idea of the airborne gravity survey was to create a reference gravity field for adjustment of existing marine gravity data through cross over computations and adjustment.

The simple method would be to identify a bias for different surveys. A refinement of this would be the method developed by the University of Edinburgh. This involves pre-processing the raw gravity data followed by network adjustment. Pre-processing aims to reduce the dynamical errors associated with course changes, smooth out high-frequency noise, and remove spikes and gross blunders. Network adjustment aims to remove the systematic effects of datum offsets, different gravity reference systems and drift in the gravity meter zero.

The basic component of our pre-processing algorithm is the *line-segment*. A line-segment is a component of a survey where the ship's course is adequately straight. Point-to-point vectors are compared with chosen criteria for breaking surveys into line-segments: a break can be triggered by a large change in course azimuth or an excessive gap between points. For each line-segment, we represent the long-track free-air anomaly as well as the eastings and

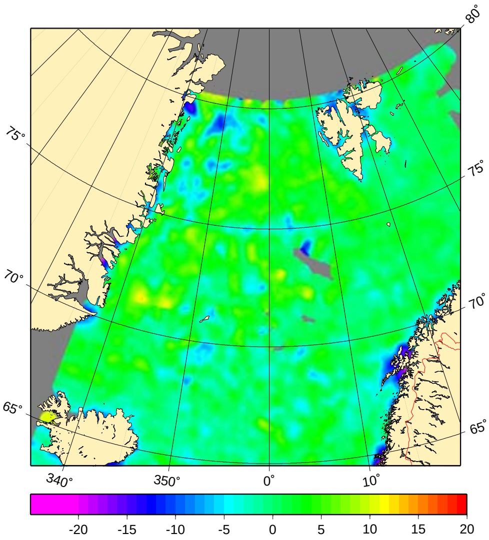

Figure 4. KMS02 free-air anomalies minus marine gravity data (mgal)

northings defining the ship's position, by a continuous function. Chebyshev polynomials represent our best estimate for the true shape of the gravity anomaly profile and smooth out point-to-point noise. Statistics derived from the residuals between the fitted curve and the point data are used to estimate the stationary random component of the data errors. The subsequent network adjustment is to suppress the remaining systematic errors.

The network adjustment model fit an independent datum shift parameter to each survey or survey leg. For any survey with sufficient number of crossing points to remain stable with a second free parameter, the model will include drift rate. The adjustment estimated these model parameters by minimizing the cross over errors, weighting the observed free air anomaly at the crossing according to the standard deviation of the polynomial curve fit for that line-segment in the least square sense.

For the approximately 45000 cross-over points in the northern Atlantic Ocean, network adjustment reduces the standard deviation of the cross-over errors from 4.13 mGal to 1.64 mGal. Similarly the difference between KMS02 altimetry anomalies and shipborne and airborne data improved, with the adjustment reducing the standard deviation of the differences from 8.15 to 6.07 mGal. The difference between KMS02 based free-air anomalies and marine free-air anomalies before and after adjustment are shown in Fig. 4 and Fig. 5 respectively. The difference, Fig. 6 shows that the network adjustment has contributed in the adjustment of a number of surveys that have a datum shift due to a bad harbor ties.

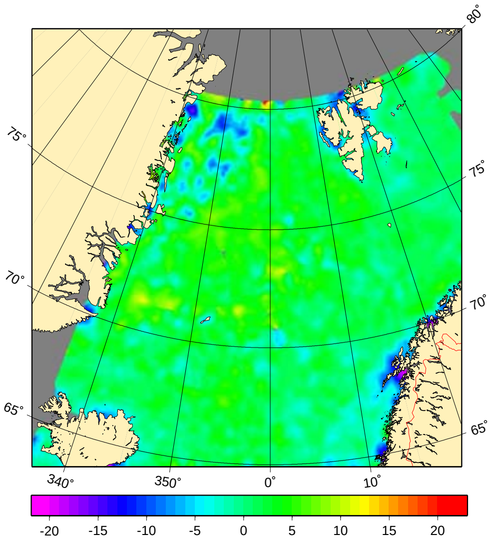

Figure 5. KMS02 free-air anomalies minus adjusted marine gravity data (mgal)

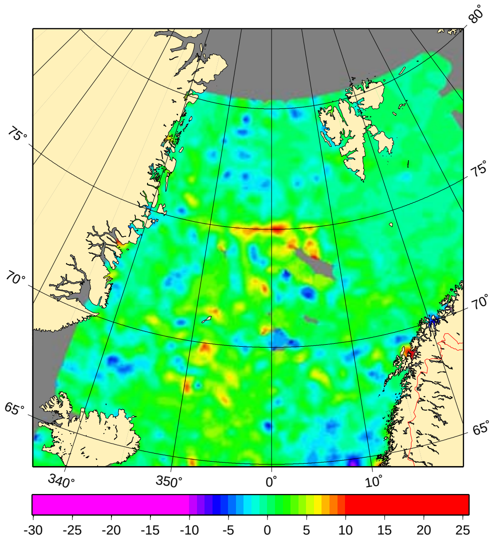

Figure 6. Difference of non-adjusted and adjusted marine gravity data (mgal)

5. COMPUTATIONAL METHODS

In OCTAS we have looked into different ways of computing the MDT. The "OCTAS method" is by combining the gravimetric geoid with the MSS and determine the MDT through equation 1.

Secondly, the MDT may be computed directly from different types of observation data using estimations techniques such as LSC, Least Square Collocation.

5.1. Geoid determination

Gravity data used in the geoid computation are a combination of adjusted marine data, new and old airborne measurements, land data in Scandinavia and data from the ArcGP. Voids in the data distribution were patched with satellite altimetry gravity data (KMS02).

The gravity data set is a combination of Bouguer anomalies on land and free-air anomalies at sea. We are using the remove-restore technique in combination with the RTM method [7].

The reduced anomalies are obtained using a Bouguer plate approximation

$$\Delta g_{\mathrm{red}} = \Delta g + 2\pi G\rho h_{\mathrm{ref}} - \Delta g_{\mathrm{ggm}}, \qquad (2)$$

where h_{ref} is a smooth reference surface of resolution approx. 50 km and Δg_{ggm} is the global geopotential model. The reduced gravity data Δg_{red} is gridded and Faye anomalies, Δg_{faye}, are obtained after restoring the RTM terrain effect $2\pi G\rho(h - h_{\mathrm{ref}})$. The residual quasigeoid is estimated using multi-band spherical 2D-FFT [8]

$$\zeta_{\mathrm{res}} = F^{-1}[F(\Delta g_{\mathrm{faye}})F(S^{\tau}(\psi))] \qquad (3)$$

where F and F^{-1} are the Fourier and the inverse Fourier transform, respectively.

$S^{\tau}(\psi)$ is the Wong-Gore modified Stokes' function with truncation degree τ given as [9]

$$S^{\tau}(\psi) = \sum_{n=\tau}^{\infty} \frac{2n+1}{n-1} P_n(\cos\psi) \qquad (4)$$

where P_n is Legendre polynomials. As Eq. (4) indicates the Wong-Gore modification gives a kernel function taking summation only from τ to infinity. The long wavelength part of the signal is thereby removed, and the changing of τ compares to some degree to the selection of different capsizes.

Restoring the GGM gives the quasigeoid,

$$\zeta = \zeta_{\mathrm{res}} + \zeta_{\mathrm{ggm}} \qquad (5)$$

Over sea, or where height equals zero, the quasigeoid ζ equals the geoid, N.

6. LSC

Considering only geodetic measurements, MDT is simply given by subtracting MSS and the geoid.

$$MDT = MSS - N + \epsilon \qquad (6)$$

where ϵ is noise. The data coverage however, especially gravity data, is not complete, so more advanced combination methods may be needed.

LSC is a well known technique to combine different geodetic measurements, e.g. gravity anomalies, the geoid and altimetry sea surface heights. The measurements are associated with the anomalous gravity potential T of the Earth through linear functionals.

$$\Delta g = L_{\Delta g}(T) = \frac{\partial T}{\partial r} - 2\frac{T}{r} \qquad (7)$$

$$N = L_N(T) = \frac{T}{\gamma} \qquad (8)$$

The signal x (e.g. the geoid) is given by the formula

$$x = C_x^T (C + D)^{-1} y \qquad (9)$$

where C_x is the covariance function between the observations and the signal, C is the covariance function between the observations and D is the covariance function for the measurement noise. The a posteriori error covariance between two estimated quantities is given by

$$c_{\hat{xx'}} = c_{xx'} - C_x^T (C + D)^{-1} C_x \qquad (10)$$

6.1. Covariance functions

The covariances are obtained using kernel functions. The kernel associated with the gravity field is derived using the spherical harmonic expansion of T (the anomalous gravity field) and some a priori variances. The covariance between T in the points P and Q depend only on the spherical distance between them, and are thus independent of location and azimuth (i.e. a homogeneous and isotropic kernel). More details in [10]. Applying the linear functionals yield the expressions of the covariances

$$C_{NN} = \sum_{i=2}^{\infty} \left(\frac{1}{\gamma}\right)^2 \sigma_i^{TT} P_i(\cos\Psi) \qquad (11)$$

$$C_{\Delta g \Delta g} = \sum_{i=2}^{\infty} \left(\frac{i-1}{R}\right)^2 \sigma_i^{TT} P_i(\cos\Psi) \qquad (12)$$

$$C_{N\Delta g} = \sum_{i=2}^{\infty} \left(\frac{i-1}{R\gamma}\right) \sigma_i^{TT} P_i(\cos\Psi) \qquad (13)$$

The covariance function of the MDT is expressed, similar to the gravity field, as

$$C_{\zeta\zeta} = \sum_{i=1}^{\infty} \sigma_i^{\zeta\zeta} P_i(\cos\Psi) \qquad (14)$$

6.2. Covariance function modeling

In LSC it is very important to take the full signal/error content into account. This means that the covariance function models should agree with the empirically determined characteristics in the local area, such as the variance and the correlation length.

The covariance functions for gravity anomalies and geoid heights are modeled using a Tscherning/Rapp degree variance model [11]

$$\sigma_i^{TT} = \begin{cases} \epsilon_i^{GRACE} & i = 2,\dots 90 \\ \epsilon_i^{EGM96} & i = 90,\dots 360 \\ \frac{A}{(i-1)(i-2)(i+4)}\left(\frac{R_B^2}{R^2}\right)^{i+1} & i = 360,\dots \end{cases} \qquad (15)$$

The model is fitted to local empirical covariance values calculated from reduced marine, land and airborne gravity data in a least squares iterative inversion technique [12]. More details in e.g. [13].

The covariance functions for MDT are modeled with Knudsen degree variance model [13]

$$\sigma_i^{\zeta\zeta} = b\left(\frac{k_2^3}{k_2^3 + i^3} - \frac{k_1^3}{k_1^3 + i^3}\right) s^{i+1} \qquad (16)$$

The spectrum of the MDT is assumed to have a decay similar to the geoid. The model is fitted to empirical covariance values determined from synthetic data (MSS - Geoid).

By assuming no correlations between the components in Eq. (6) the covariance function for MSS is given by

$$C_{MSS} = C_N + C_{MDT} \qquad (17)$$

$$D_\epsilon = \sum_i D_i \qquad (18)$$

where D_i are the covariance values associated with the different error components in ϵ. The assumption of no correlation between the gravity field and sea surface heights may not be correct [14].

7. OCTAS MSS

In deriving the first version of the MSS model for the OCTAS study area, ENVISAT (cycles 11-35) and ERS-2 (cycles 1-85) data are used. These data have been extracted from altimetry data base (Stack File) at the Ohio State University. The ENVISAT and ERS-2 satellite should give slightly different sea surface height signal, therefore, a bias of approximately 36 cm to the ENVISAT data is adjusted for. This model, OCTAS06_v1, is illustrated in Figure 7. The resolution of OCTAS06_v1 model is 3 minutes in latitude and 6 minutes in longitudes.

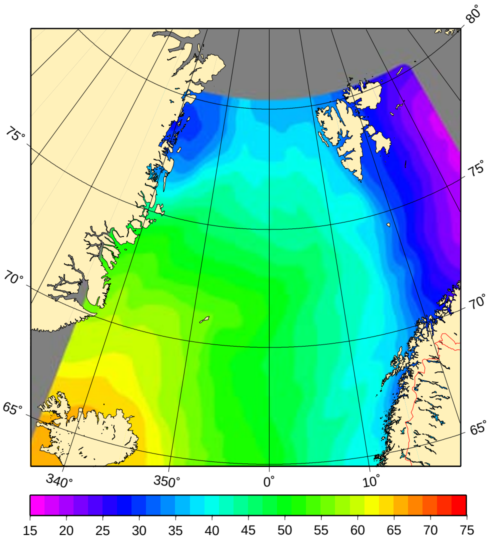

Figure 7. The OCTAS06_v1 MSS model (m)

8. RESULTS

In Fig. 8 a synthetic MDT , derived from a geoid and the OCTAS06_v1 MSS model, is illustrated. The gravimetric geoid was estimated following Sect. 5.1, using, as input data, the adjusted marine gravity measurements, land data, and KMS02 satellite altimetry data (fill gaps in the marine gravity data set). The geoid and MSS model was combined [Eq. (1)] and then low-pass filtered.

The MDT may be estimated directly using LSC, see Sect. 6. The LSC method is quite computer demanding due to matrix inversion, so a smaller area with fewer measurement was selected. The computed MDT, in Fig. 9, is derived from marine, airborne, land gravity data and KMS04 MSS.

The two estimated MDTs, Figs. 8 and 9, show similar major oceanographic features as the OCCAM MDT in Fig. 10. Excluding the areas around the Greenland coast and north of Svalbard, a comparison to OCCAM MDT gives a standard deviation of approximately 10 cm and 15 cm for synthetic MDT and LSC based MDT, respectively.

9. CONCLUSIONS

The marine gravity data in the Northern North Atlantic has been error screened and adjusted using new airborne

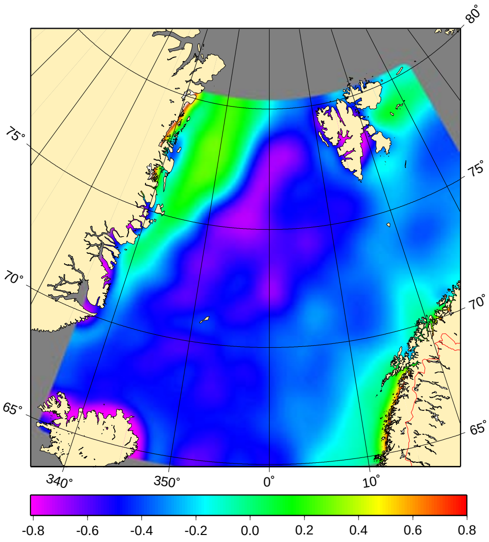

Figure 8. An MDT derived from the OCTAS06_v1 MSS and a geoid model based on adjusted marine gravity data. MDT is low-pass filtered (m)

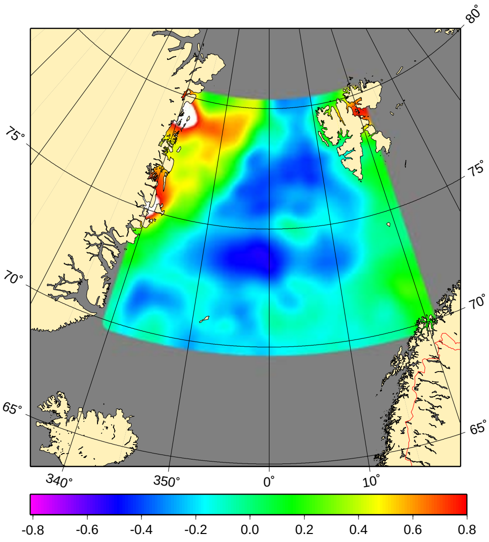

Figure 9. MDT derived from a combination of gravity and MSS data using least square collocation. MDT is low-pass filtered (m)

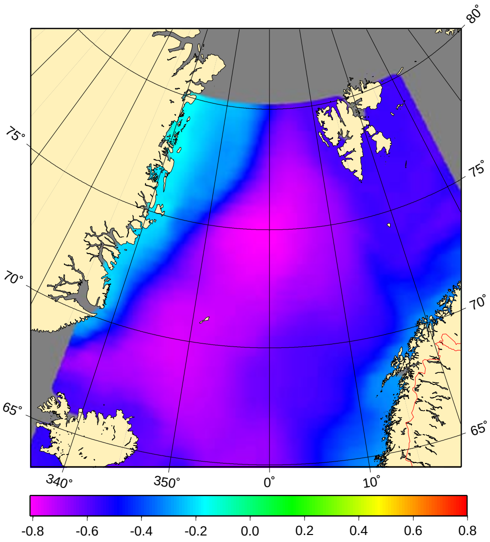

Figure 10. The OCCAM MDT (m)

gravity data.. The standard deviation of the cross-over errors for the marine gravity data was reduced from 4.1 mGal to 1.6 mGal.

Based on adjusted gravity data new geoid model was computed and combined with the first OCTAS MSS model a synthetic MDT was computed. Both the synthetic and the LSC based MDTs give an overall good representation of the major oceanographic features in the Northern North Atlantic, when compared to the OCCAM MDT.

ACKNOWLEDGMENTS

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