The BGR Aerogravity system: Results from a survey of the German Bight (North Sea)

Ingo Heyde, Federal Institute for Geosciences and Natural Resources (BGR), Germany

This paper was prepared for presentation during the 11th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, August 24-28, 2009.

Abstract

The Federal Institute of Geosciences and Natural Resources (BGR) has carried out a multitude of gravity surveys onboard marine research vessels since the 1960s. Since 1984 these measurements are performed with the KSS31 gravity meter system. This system has been modified and complemented during the last years for use in aerogravity surveys as well.

In May 2007 the first aerogravity campaign was carried out with this updated system. Gravity data of the main part of the German exclusive economic zone in the North Sea were obtained. During 17 flights 32 northwest-southeast running profiles with a spacing of 5 km and 11 tie profiles with a spacing of 20 and 30 km respectively were surveyed. The total profile length added up to 10500 km. The standard survey altitude was 1000 ft above sea level. Depending on the wind speed and direction the survey ground velocity ranged between 170 and 230 km/h.

To obtain the free air gravity anomalies several reductions to the measured gravity data had to be applied. For this purpose the flight trajectories were determined with high accuracy. Kinematic GPS data of 3 antennae were recorded and combined with the data of an inertial navigation system. One GPS base station was operated at the airfield. Additional base station data were obtained as necessary from the Land Survey Offices of Schleswig-Holstein and Niedersachsen.

The measured free-air gravity anomalies have an accuracy of about 4 mGal with a spatial resolution of 5 km half-wavelength. Comparative marine gravity measurements were carried out in the same area with the same gravity meter system during a BGR cruise with R/V FRANKLIN in June/July 2007. Aero- and ship based data agree closely. The combined data sets result in a free-air gravity anomaly map of the German EEZ in the North Sea.

Introduction

A gravity sensor which is mounted on a moving platform measures the sum of the gravity and the inertial accelerations of the system motion. During aerogravity surveys the inertial accelerations can be 1000 times higher than the gravity effect of different geological units. The inertial accelerations can be deduced from the movement of the aircraft. Therefore it is necessary to measure the flight trajectory with a non-inertial satellite navigation system like the GPS. The navigation data are also indispensable to calculate further corrections to determine the free-air gravity anomalies from the measured gravity sensor data.

Since 1984 marine gravity measurements at BGR are performed with the KSS31 gravity meter system manufactured by Bodenseewerk Geosystem GmbH. The KSS31 is considered to be the best sea gravity meter world wide. The system was updated to the KSS31M by Bodensee Gravitymeter Geosystem GmbH (BGGS), the successor company of the Bodenseewerke in 2001. This modified and complemented system can be used for aerogravity surveys. Due to the experiences of test flights in 2003 and 2005 (Heyde und Kewitsch, 2006) the system was improved concerning the recording of the platform movements and an INS system was added to enhance the quality of the GPS data and to record the flight attitude. In May 2007 the first major aerogravity campaign was carried out to test the performance of the updated system and its capability to deliver accurate data for aereal mapping. Gravity data of the main part of the German exclusive economic zone in the North Sea were obtained.

The aerogravity system

The complete aerogravity system consists of the gravity sensor, navigation system and data recording and processing unit. The system is shown in Fig. 1.

Fig. 1 Aerogravity system consisting of the KSS31M gravity meter (platform with sensor and electronics rack), GPS instrumentation, INS unit and laptop.

While the sensor of the KSS31M is based on the Askania type GSS3 sea gravimeter designed by Prof. Graf in the 60ties, the development of the horizontal platform and the corresponding electronic devices took place at the Bodenseewerk Geosystem in the second half of the

70ties. The KSS31M system consists of two main assemblies: the gyro-stabilized platform with gravity sensor and the data handling subsystem. The system was modernized and modified in 2001 by BGGS. The modifications affected mainly the control electronics and the power supply and resulted in a considerable loss of volume and weight of the system. The sensor itself and the gyro-stabilized platform have not been changed up to now.

The gravity sensor consists of a tube-shaped mass that is suspended on a metal spring and guided frictionless by threads. It is non-astatized and particularly designed to be insensitive to horizontal accelerations. This is achieved by limiting the motion of the mass to the vertical direction. Thus it is a straight line gravity meter avoiding cross coupling effects of beam type gravity meters. The measuring range of the sensor amounts to 10000 mGal with a drift rate of less than 1 mGal/month. The sensitivity is 0.01 mGal and the accuracy in static operation is ±0.02 mGal. In dynamic operation and without special data processing the accuracy ranges from ±0.5 mGal (vertical accelerations < 0.15 m/s²) and ±2 mGal (vertical accelerations 0.8 – 2 m/s²). The system can be operated during accelerations of up to 4 m/s². The leveling subsystem consists of a platform stabilized in two axes by a vertical electrically erected gyro. The stabilization during course changes can be improved by providing the system with online navigation data. This control works fine for shipborne measurements. For airborne surveys the platform errors are significant and have to be measured.

To obtain the best navigational results NovAtel OEM4 L1/L2 GPS receivers were used, both as base and as kinematic receivers. During the campaign a GPS base station at the airfield of Wilhelmshaven-Mariensiel was operated. Two rover receivers each equipped with its own GPS antenna were run in the airplane. Additionally a NovAtel SPAN system was installed. It consists of a DL4Plus (OEM4 L1/L2) GPS receiver and an IMU-G2 inertial unit containing 3 accelerometers and 3 high precision ring laser gyros (Honeywell HG1700 AG58). The two components are integrated through receiver firmware that combines the GPS and inertial data to provide a joint solution (Kennedy et al., 2007). The evaluation of the navigation data was carried out by post-processing. Post-processing offers the advantage that further information concerning precise satellite ephemeris and above all one or more static reference stations can be considered. The DGPS software used was Inertial Explorer (version 7.70) from Waypoint Inc. It integrates rate data from six degrees of freedom IMU sensors with GPS data processed with an integrated GPS post-processor.

For the registration of analogue voltage signals a multimeter is used, which is controlled by a laptop. The software LabVIEW7.1 is used for data acquisition and processing. A second laptop was operated for flight guidance and management. Its display was duplicated to a second screen for the pilot.

System installation

The flights were carried out with an Aero Commander 680 FL of Air Tempelhof Fluggesellschaft mbh & Co. KG (Fig. 2). The aircraft, usually used for aerial photography, was very appropriate for the survey. The installation of the instruments in the cabin is shown in Fig. 2.

GPS aero antennas were installed on the hull above the gravity sensor, on the right wing and on the right of the horizontal tail. During post-processing it turned out that the GPS data of the 3rd antenna were consistently of lower quality than the other two because the number of received satellites was reduced due to shadowing effects of the empennage. Thus only the data of two rover receivers were considered for the data processing.

Fig. 2 Aero Commander 680 FL of Air Tempelhof (above). System installation in the aircraft cabin is shown below.

Aerogravity survey of the German Bight

The flights were performed in May 2007 from the airfields Wilhelmshaven and Husum. During 17 flights 32 northwest-southeast running profiles with a spacing of 5 km and 11 tie profiles with a spacing of 20 and 30 km respectively were surveyed (Fig. 3). The total profile length added up to 10500 km. Subtracting data during and after turns as well as during bad flight conditions, data along a profile length of 9000 km were useable. The standard survey altitude was 1000 ft above sea level. Depending on the wind speed and direction the survey velocity ranged between 170 and 230 km/h. One GPS reference station was run in Wilhelmshaven. Additional reference data were bought after the campaign from the Land Survey Offices of Niedersachsen and Schleswig-Holstein.

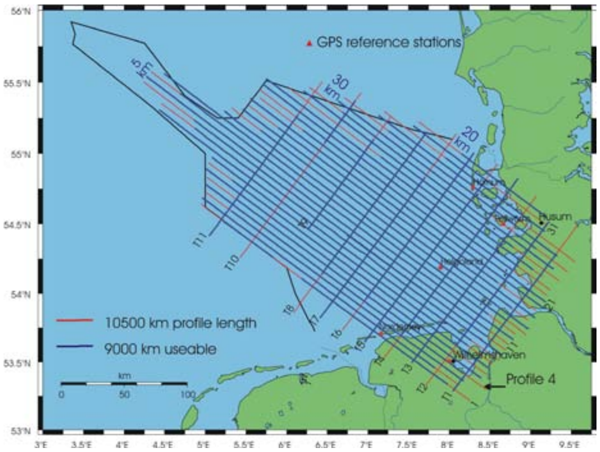

Fig. 3 Map of the profiles flown during the campaign.

Data processing

To obtain the gravity variation, the following corrections have to be determined:

►Eoetvoes correction
►Correction of the inertial vertical accelerations
►Platform error or Harrison correction

The gravity variation in the flight altitude is the principal measured variable in an aerogravity survey. However, the preferable result for geophysical applications are free-air gravity anomalies. They are to be obtained by applying the following reductions to the gravity variation:

►Normal gravity reduction
►Free-air reduction

The Eoetvoes correction, the normal gravity and the free-air reduction can be calculated directly from the positions and velocities, which were obtained by DGPS/INS post-processing. For the Eoetvoes correction formula the flight altitude is considered (Harlan, 1968). The normal gravity is calculated according to the GRS 1980 (Moritz, 1984). The inertial vertical acceleration is determined by gradient calculation of the vertical velocity. For the Harrison correction the error angles and the horizontal and vertical accelerations of the platform are used.

Before the values can be applied they have to be low-pass filtered with the so-called sensor copy filter describing the behaviour of the gravity sensor. Fig. 4 shows exemplary the results along the 280 km long SE-NW running profile 4. The variation of the measured gravity and the vertical accelerations correlate directly with the variation of the flight altitude. The variation gets smaller with the reduced thermal above the sea than overland at the beginning of the profile. The amplitudes of up to ±6000 mGal demonstrate the challenge to elaborate from the data geological anomalies with amplitudes of a few mGal only.

Obviously the data have to be low-pass filtered. Good experiences were gained during the first system tests with Bessel filters (Heyde und Kewitsch, 2006).

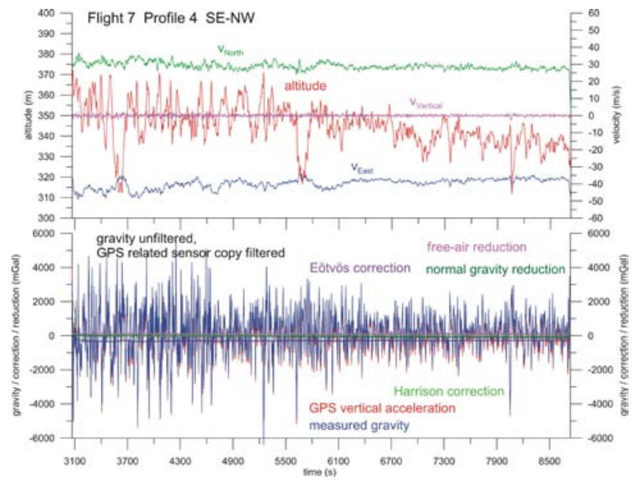

Fig. 4 Flight altitude and velocities along survey profile 4 (above). Measured gravity and calculated corrections and reductions along the profile are shown below.

Fig. 5 shows the results after filtering with a 3rd order Bessel filter with a corner frequency of 471 s. This ensures the presence of data with 200 s period and thus a spatial resolution of about 5 km half-wavelength based on our average flight velocity. Whereas the differences of the further corrections and reductions are below 0.5 mGal using the 4 different navigation data sets, the differences of the vertical acceleration values are considerable higher. In the lower part of Fig. 5 the 4 vertical acceleration data calculated from the navigation data sets are shown together with the measured gravity including all corrections except for the vertical acceleration.

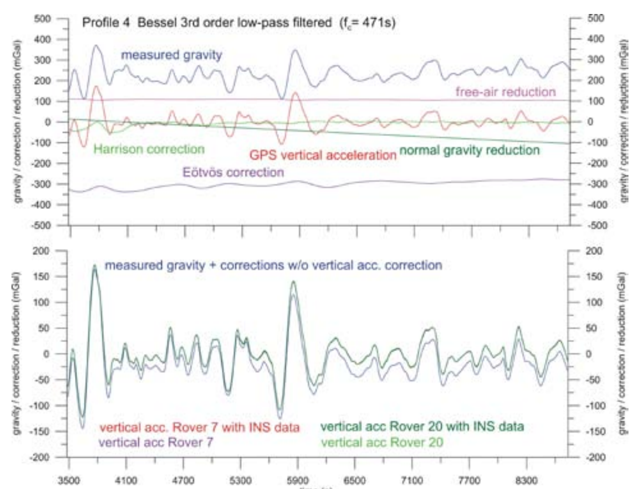

Fig. 5 Low-pass filtered values along profile 4 (above). The comparison of the different DGPS/INS data of rovers 7 and 20 used for the determination of vertical accelerations is shown below.

The differences between the data sets amount to less than 5 mGal on this profile. Along other profiles the differences are significant higher.

Fig. 6 shows the free-air gravity anomalies along profile 4 using the different DGPS/INS data sets for the corrections of the vertical accelerations.

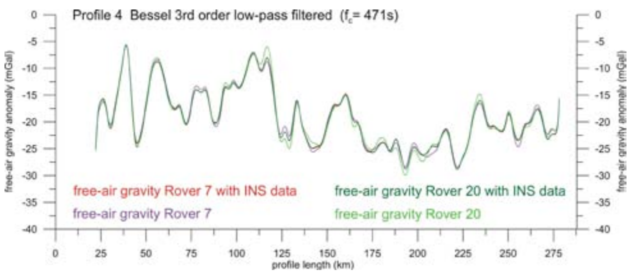

Fig. 6 Free-air gravity anomalies along profile 4 using different DGPS/INS data sets.

Taking the quality of the DGPS/INS solution as decision support which free-air gravity data were favoured, for nearly all profiles the rover 7 with INS data were used. The antenna location and the smallest lever arm both to the gravity sensor and the INS unit resulted in the best navigation data.

Data accuracy

To evaluate the accuracy of the free-air gravity data, the differences at these crossovers were examined. The map of the differences is shown in Fig. 7. There is no pronounced areal distribution and time dependence. Thus no adjustment was applied to the profile data. A histogram of the differences is shown in Fig. 8. The mean difference amounts to 4 mGal. This value represents the accuracy of the measurements after applying the mentioned low-pass filter guaranteeing a spatial resolution of 5 km half-wavelength. The value could be reduced by further or stronger low-pass filtering at the expense of reduced spatial resolution.

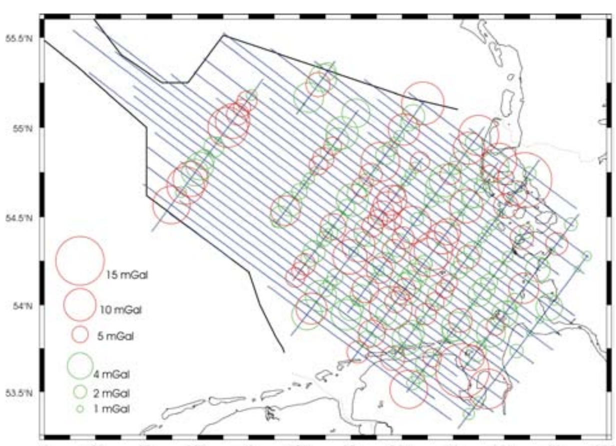

Fig. 7 Map of the value differences at profile crossovers.

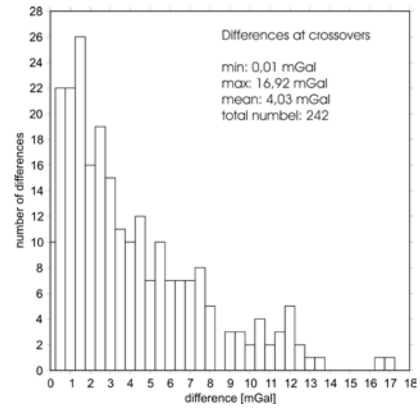

Fig. 8 Histogram of the value differences at the 242 profile crossovers.

Map of the free-air gravity anomalies

Fig. 9 shows the map of the free-air gravity anomalies based on the 43 profiles with a total length of 9000 km. The anomalies range from -45 mGal in the North Sea Basin around Helgoland to +40 mGal northwest of Sylt.

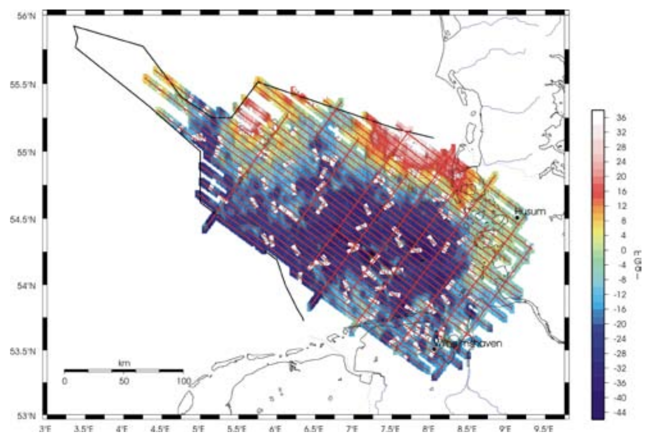

Fig. 9 Map of the free-air gravity anomalies in the survey area based on a 0.5 x 0.5 minutes grid. The map is drawn up to a distance of 3 (arc-) minutes from the lines.

In June/July 2007 marine gravity measurements were carried out with the same gravity meter during cruise BGR07 with R/V FRANKLIN (Neben et al., 2007). The aim of the cruise was a detailed survey in the north westernmost area of the German EEZ (exclusive economic zone), the so-called 'Entenschnabel'. The marine gravity data were gathered both to compare the airborne measurements with ground truth data and to complete the data in the NW. The location of the marine profiles (blue) is shown together with the aero profiles (red) in Fig. 10. Along four lines there is in parts good agreement of the position of marine and aero profiles. Fig. 11 shows the comparison of the free-air gravity data along two profiles. The consistence between the data is rather good, especially, if the aero profile data are additionally low-pass filtered. The marine data are not upward continued due to the low flight altitude.

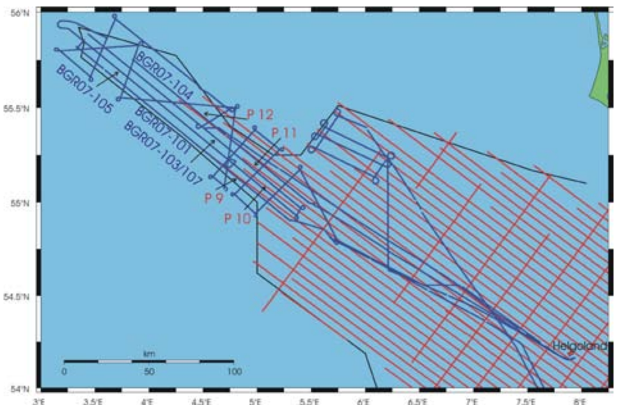

Fig. 10 Map of the marine (blue) and aero (red) profiles in the north western survey area. The nearly identically running profiles are marked.

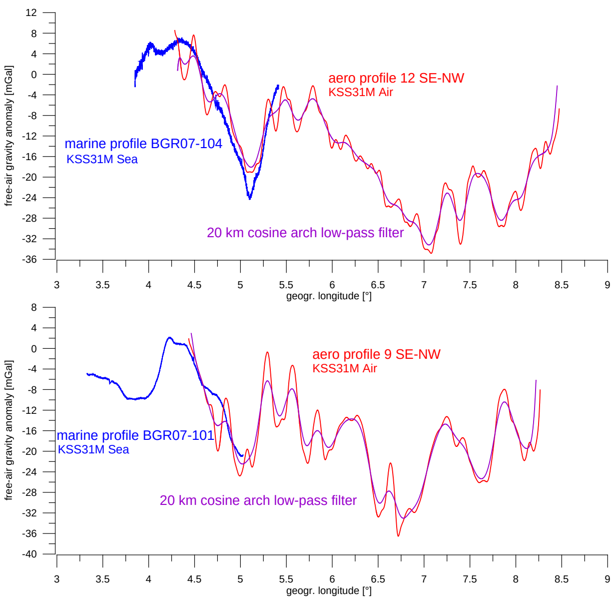

Fig. 11 Comparison of free-air gravity anomalies measured along nearly identical marine and aero profiles.

Considering the error of the marine data as insignificant the accuracy of the aero data amounts again to about 4 mGal.

The aero gravity data were combined with the BGR07 marine data and land gravity data of Northern Germany. The land gravity data from the Leibniz Institute for Applied Geosciences (LIAG) in Hannover have for the most parts a spacing of 5 to 10 km. Fig. 12 shows the free-air gravity anomaly map combining the 3 datasets. The aero gravity data were filtered again with a 10 km 2D low-pass median filter (Wessel and Smith, 1998). The broad gravity minimum in the middle corresponds to the southern North Sea basin. Further elongated minima reflect the runs of the Central Graben and the Horn Graben. The gravity maximum in between corresponds to a carboniferous/ devonian basement high. This constitutes an extension of the Rynkøbing-Fyn high further east characterized by gravity maxima also.

Summary and further work

The survey in the German Bight showed that the KSS31M can be used for aerogravity surveys. A new gravity data set for a large part of the German EEZ in the North Sea was acquired. With the KSS31M and the NovAtel GPS/INS equipment BGR has now a tested aerogravity system ready for operation. The accuracy of the free-air gravity data amounts to about 4 mGal with a spatial resolution of 5 km.

The behaviour of the sensor and particularly the platform have to be examined and optimized further to improve the accuracy of the data. Therefore it is indispensable to involve BGGS GmbH. With the aid of our experiences BGGS should revise the platform control, which is based on discrete analogue technology developed in the early 1980s. Additionally BGGS is working at the control circuit of the gravity sensor with the aim to reduce its response time. The pre-adjustment of the gravity sensor after profile changes should be applied routinely to reduce the actual settling time of 400 s.

However, the final accuracy is limited also by the accuracy of the DGPS/INS navigation data. The error of this data could be reduced by data of more satellites, which will be available if the GALILEO system should become available.

References

Harlan, R. B., 1968, Eotvos Corrections for Airborne Gravimetry. *Journal of Geophysical Research*, 73, 14, 4675-4679.

Heyde, I. und Kewitsch, P., 2006, Neue Flugergebnisse mit dem BGR-Aerogravimetriesystem. – Vortrag: Tagungsband 66. Jahrestagung der Deutschen Geo-physikalischen Gesellschaft, S. 325-326, März 2006, Bremen.

Kennedy, S., Cosandier, D., and Hamilton, J., 2007,GPS/INS Integration in Real-Time and Post-processing with NovAtel's SPAN System. International Global Navigation Satellite Systems Society Symposium 2007, Sydney.

Moritz, H., 1984, Geodetic Reference System 1980. In: C. C. Tschernig (ed.), The Geodesist's Handbook 1984 – Bull. Geod. 58, 388-398.

Neben, S., Reinhardt, L. and cruise participants, 2007., BGR Cruise BGR07 FRANKLIN Leg 1: Geophysics, Project: Nordsee. Cruise Report.

Wessel, P., and W. H. F. Smith, 1998,New, improved version of Generic Mapping Tools released, *EOS Trans. Amer.Geophys. U.*, vol. 79 (47), pp. 579.

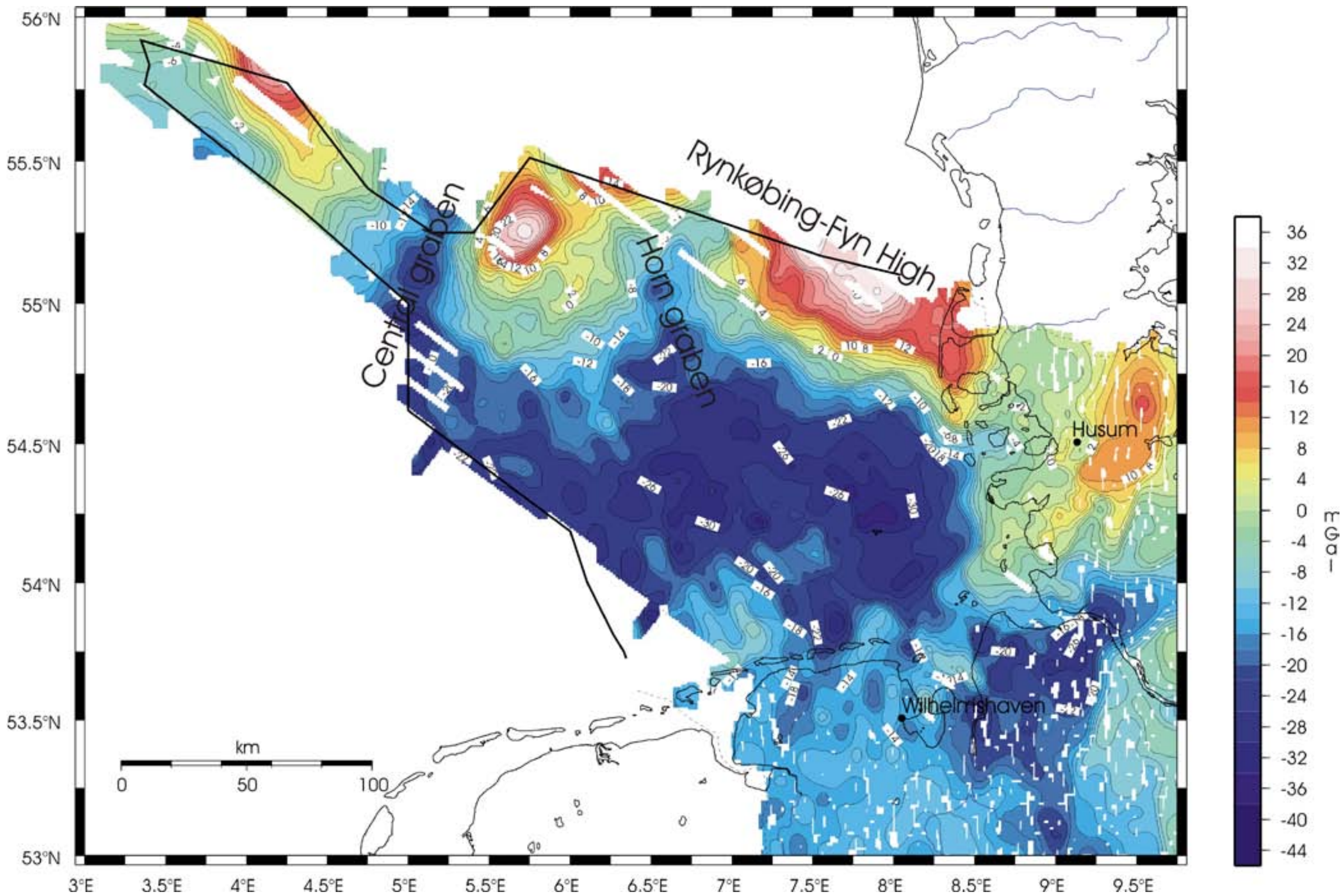

Fig. 12 Free-air gravity anomaly map combining the aero, BGR07 marine and land station gravity data. The map is drawn up to 3 (arc-) minutes from surveyed data.