Compilation and Evaluation of a Consistent Marine Gravity Data Set Surrounding Europe

Heiner Denker, Markus Roland
Institut für Erdmessung, Universität Hannover
Schneiderberg 50, D-30167 Hannover, Germany
Email: denker@ife.uni-hannover.de, Fax: +49 511 762 4006

Abstract. Various institutions have collected shipborne gravimetric measurements during the last decades. Due to different standards used for the processing of the observations and the necessary corrections, significant inconsistencies exist between different cruises. This contribution aims at producing a consistent marine gravity data set surrounding Europe, which can then be used for high precision geoid modelling, dynamic sea surface topography estimation, and other applications.

Besides our own marine gravity data holdings, data were collected from the Bureau Gravimétrique International (BGI), the National Imagery and Mapping Agency (NIMA, formerly DMA), and the National Geophysical Data Center (NGDC). The area of investigation is spanning the latitudes from 10 °N to 90 °N and the longitudes from 60 °W to 60 °E. The quality of the data varies between the individual cruises, as they originate from many projects at different epochs. Hence, systematic errors are likely to exist. Such errors can be significantly reduced by a crossover adjustment of the individual ship tracks. Because the track information was not available for all cruises, it had to be regenerated by different procedures. Furthermore, duplicate sources were removed before the crossover adjustment. The crossover adjustment is based on a bias per track error model. The adjustment of about 1.5 million observations in nearly 17,000 tracks led to a consistent high quality marine gravity data set. The RMS of the about 80,000 crossover differences is 15.5 mgal for the original data set, 8.4 mgal for an edited data set, and 4.7 mgal for the final crossover adjusted data set.

The second part of this contribution describes the evaluation of the marine gravity data set by altimeter derived gravity anomalies from different sources. These comparisons also prove the effectiveness of the crossover adjustment.

Keywords. crossover adjustment, shipborne gravity observations, altimetric gravity anomalies

1 Introduction

Shipborne gravimetric measurements, using sea gravity meters mounted on gyro stabilized platforms, have been performed around the world for several decades, see Torge (1989). Due to instrumental errors, navigational errors, and other error sources, significant inconsistencies exist between different cruises, cf. Wessel and Watts (1988). In the older marine gravity data sets, the major accuracy limiting factor was the ship's navigation, affecting the computation of the Eötvös effect. This problem could only be overcome with the GPS and other highly accurate positioning systems, but still exists in large parts of the marine gravity data.

The problem of inconsistencies in marine gravity data sets was treated successfully in the past by the analysis of intersecting ship tracks, e.g., Wessel and Watts (1988) analysed a global data set, while Strang van Hees (1983) and Wenzel (1992) studied regional data sets. From the crossover differences, error parameters per ship cruise or per track were estimated by a least-squares adjustment, yielding a significant reduction of the crossover differences. In this contribution, the marine gravity data, available for the European seas, are analysed using the crossover technique. In Section 2, the applied crossover analysis technique is outlined. Section 3 describes the data sources used in this study and the necessary preprocessing steps, e.g., the reconstruction of the ship tracks, and the removal of duplicate sources. The crossover adjustment results, based on a bias per track error model, are given in Section 4. Finally, an evaluation of the crossover adjusted data by altimetrically derived gravity anomalies is presented in Section 5.

2 Crossover Analysis Technique

Marine gravity observations are affected by instrumental errors (e.g., drift, cross-coupling, off-levelling, etc.), navigational errors, yielding incorrect Eötvös corrections and positions, and other error sources, such as incorrect ties to harbour base stations and the inconsistent use of reference systems. In the older sea gravity observations, the major limitations are coming from inaccurate Eötvös corrections, resulting partly in errors of tens of mgals. This limitation could be overcome with the GPS and other highly accurate positioning systems, enabling now gravity accuracies below 1 mgal. Moreover, for some cruises, aiming mainly at local gravity investigations, the tie to harbour base stations was incomplete or not performed at all, and such cruises may be off by a few hundred mgal with respect to an absolute system.

For the majority of the cruises, it can be assumed that a correct tie to harbour base stations was done at the beginning and end of the cruise. Furthermore, from the harbour ties, drift corrections were usually derived and applied to the observations. In addition, in the newer observations, the drift problem has been further reduced by instrumental improvements. Therefore, a bias and eventually a tilt parameter per ship track is a reasonable error model, especially in view of possible errors in the Eötvös corrections, being constant for a ship track with constant heading and velocity-over-ground. In this connection, a ship track is considered as a part of the entire cruise, where the heading is almost constant. A tilt per track parameter, which could model, e.g., drift effects, is only appropriate for long tracks. From previous investigations it was found that a tilt parameter per track does not significantly improve the crossover differences at intersecting ship tracks. Therefore, in this study, a bias per track error model was used.

The basic principle of the crossover analysis technique is that the gravity value at intersecting ship tracks should by identical in both tracks involved. Thus for two tracks i and j and a bias per track error model, the gravity value at the crossover point, g_x, is

$$l_i + v_i + b_i = g_x, \tag{1}$$

$$l_j + v_j + b_j = g_x, \tag{2}$$

where l_i, l_j are the gravity observations of tracks i and j at the crossover point, v_i, v_j are the corresponding observation residuals for tracks i and j, and b_i, b_j are the bias parameters for tracks i and j. By combining the above equations, the crossover difference is obtained in the form of an observation equation for the adjustment:

$$(l_i - l_j) + (v_i - v_j) = d_{ij} + v_{ij} = b_j - b_i, \tag{3}$$

where $d_{ij} = l_i - l_j$ is the crossover difference, and v_{ij} is the corresponding residual.

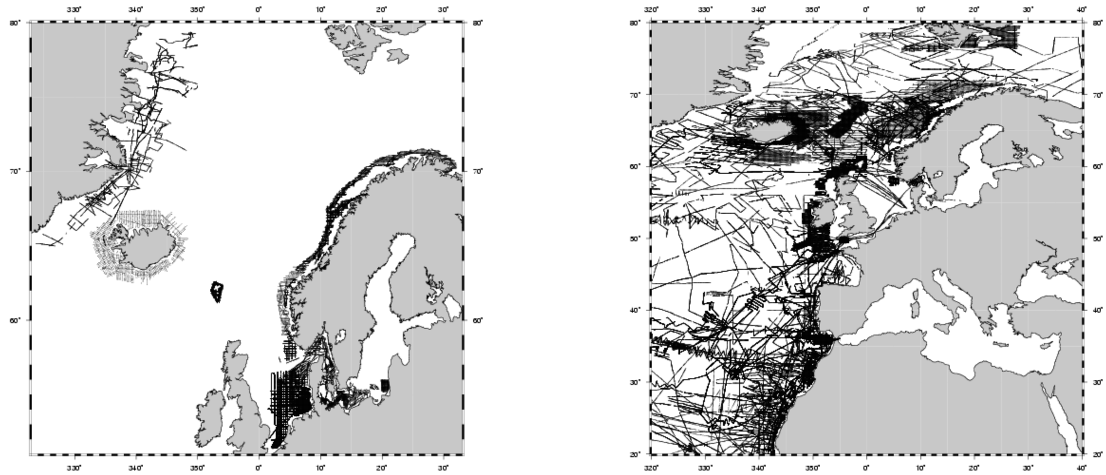
The above observation equations can now be used to estimate the unknown track biases by a standard least-squares adjustment procedure. The resulting normal equations can be solved under the assumption that all tracks have crossovers and that all tracks form a connected network, while the gravity datum has to be supplied either by constraining the track bias for one track to a given value or by a so-called free network adjustment, where the sum of all track biases is forced to zero. As there are often unconnected tracks, weak a priori informations are introduced for all track biases, allowing the solution of the normal equations in any case. This procedure is implemented in the program SEAGRA, being used in this study. The program was originally developed by Wenzel (1992), but the present version of the program includes several modifications regarding the crossover computation algorithm, the handling of unconnected tracks, and the output of statistical informations on a per track and per cruise basis. The program uses sparse matrix techniques and now can handle up to 50,000 tracks. The crossover points are detected automatically by a sophisticated iterative algorithm, which also works for curved tracks. The gravity values at the crossover points are computed by linear interpolation within the track, which was found to be sufficient, see also Wessel and Watts (1988). The adjustment can be done for one cruise only, giving the internal crossovers (within a cruise), or for many cruises, providing the internal and external crossovers (between different cruises).

3 Data Preprocessing

In this investigation, marine gravity data were selected for the area shown in Fig. 2. The data originate from the following four institutions (cf. Fig. 1):

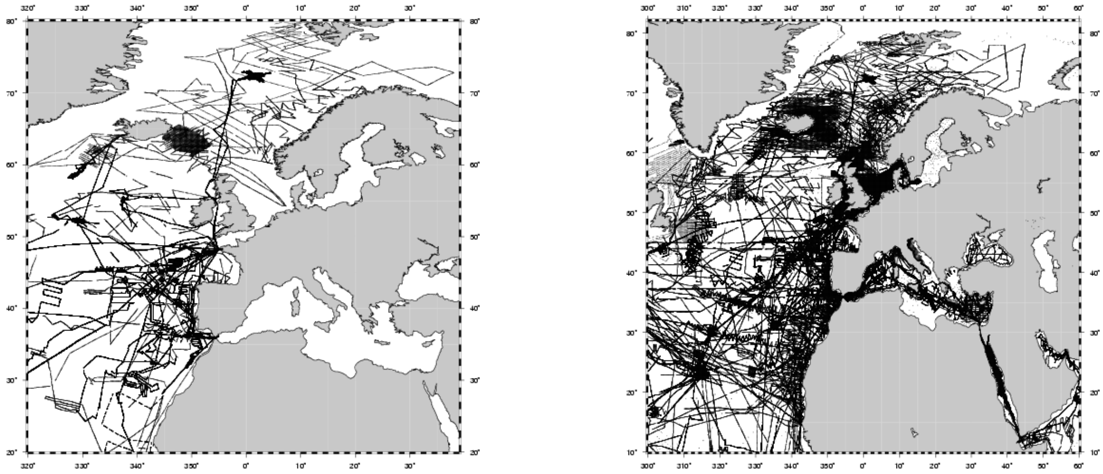
- Institut für Erdmessung (IfE),
- National Imagery and Mapping Agency (NIMA, formerly DMA),
- National Geophysical Data Center (NGDC),
- Bureau Gravimétrique International (BGI).

For most of the individual ship cruises, unfortunately, the original track structure was not preserved. However, as this is the basic prerequisite for the application of the crossover analysis technique, this information had to be reconstructed. Basically three different procedures were used, depending on the original data formats and storage sequence, see also Behrend (1999). All procedures rely on the basic assumption that observations within one track have approximately the same azimuth and point separation. The first track reconstruction technique presupposes that the data are stored time-ordered in the original observation sequence. The segmen-



(a) Institut für Erdmessung, IfE

(b) National Imagery and Mapping Agency, NIMA



(c) National Geophysical Data Center, NGDC

(d) Bureau Gravimétrique International, BGI

Fig. 1. Marine gravity data collected from the four institutions IfE, NIMA, NGDC, and BGI.

tation of the entire cruise into tracks can then be accomplished quite easily by azimuth and distance criteria. The second segmentation procedure is used for cruises, which have given track numbers, but are not stored in the original observation sequence. This is, e.g., the case, if data were extracted from a data base ordered in geographical bins. In this case, data sorting within a track with respect to latitude, longitude, or distance yields the original track structure. The third case deals with data stored in arbitrary sequence and without any track numbers available. This most general and also most complicated case is handled iteratively using azimuth and distance criteria and often requires manual interactions, cf. Behrend (1999). For all three procedures, a low navigation accuracy, pretending a zigzag course, is a problem. However, in this investigation, the ship positions were not filtered and changed.

In a further preprocessing step, duplicate cruises were identified by computing the percentage of identical position and gravity values between all cruises. Thereby, duplicate cruises were found between the four different institutions (see above), but also within a single institution, where data sets were archived more than once. The duplicate sources were excluded from the following crossover analysis.

4 Crossover Adjustment Results

Altogether, 626 cruises with 2,491,697 observations without an error flag were collected from the four agencies IfE (24 cruises, 103,782 observations), NIMA (206 cruises, 458,626 observations), NGDC (56 cruises, 351,896 observations), and BGI (340 cruises, 1,577,393 observations). Within the pre-

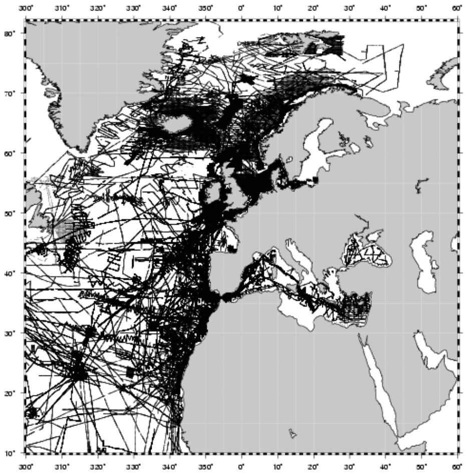


Fig. 2. Final edited gravity data set for the European seas.

processing step, 200 duplicate cruises with 697,644 observations were eliminated. Furthermore, additional cruises were excluded from the crossover adjustment because the reconstruction of the track informations was unsuccessful (36 sources, 49,796 observations), and because of extremely large (internal and external) crossover differences and discrepancies with altimetric data (5 sources, 24,829 observations).

Thus, the initial crossover adjustment of the entire data set was started with 385 sources and 1,719,428 observations. In the following, this data set is denoted as the ”original data set”. The crossover differences before the adjustment show a RMS value of 15.5 mgal and maximum values up to about 260 mgal, while after the adjustment the RMS value reduces to 7.0 mgal with maximum differences up to 205 mgal (cf. Table 1). The results from the crossover adjustment were analysed for gross errors, and a manual editing was done by inspecting the suspicious tracks. Often, problems were found at the beginning and end of the tracks, which is typically resulting from ship turns. Moreover, all data sources in the Red Sea area showed a very bad performance in the crossover adjustment and altimeter comparisons, and there were also problems in the regeneration of the track informations. Therefore, it was decided to exclude all data for the Red Sea, because these data sources would have required a very high effort for a careful data preprocessing and editing, which was considered as inadequate, especially because the Red Sea is outside our primary area of interest.

After the manual editing (42,039 observations) and exclusion of the Red Sea data (20 cruises, 149,033 observations), the crossover adjustment was repeated iteratively, and further editing of entire tracks was done. 64 short tracks with less than 3 points and 34 tracks with large crossover differences (mean>25 mgal, RMS>25 mgal, max.>50 mgal) were excluded (6037 points in total). In a final step, an editing of the unconnected tracks was done based on the comparison with the KMS02 altimetric anomalies (see Section 5). This led to the exclusion of 281 unconnected tracks with 13,800 points, where the differences exceeded the threshold values (mean>10 mgal, RMS>25 mgal, max.>50 mgal).

Table 1. Statistics of crossover differences before and after adjustment for original and edited data set. Units are mgal.

data set	original		edited	
adjustment	before	after	before	after
#	89328	89328	78929	78929
mean	0.20	-0.02	0.04	-0.01
RMS	15.48	7.01	8.37	4.69
min	-258.43	-204.98	-109.91	-48.56
max	259.54	198.37	128.40	49.16

Thus, the final data set after the editing consists of 365 cruises with 1,508,519 points in 16,896 tracks, and will be denoted as the ”edited data set” in the following. The locations of these data are displayed in Fig. 2. For the edited data set, 78,929 crossovers were detected by program SEAGRA (cf. Section 2). The statistics of the crossover differences before and after the adjustment are provided in Table 1, and corresponding histograms are given in Fig. 3. Table 1 clearly shows that the careful and time-consuming data editing is very important, resulting already in a reduction of the RMS crossover difference before the adjustment by a factor of two (15.5 mgal for the original data set vs. 8.4 mgal for the edited data set). For both, the original and the edited data set, the crossover adjustment reduces the RMS crossover difference by about a factor of two, leading to a RMS difference of 4.7 mgal for the final edited data set. Compared to the original data set, this is an improve-

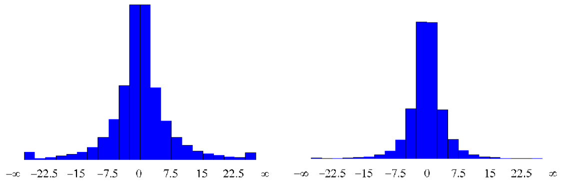


Fig. 3. Histograms of crossover differences before (left) and after (right) adjustment for the edited data set. Units are mgal.

Table 2. Statistics of crossover differences before and after adjusting the ship data separately by institution. Units are mgal.

	IfE		NIMA		NGDC		BGI	
	before	after	before	after	before	after	before	after
#	7091	7091	12481	12481	2655	2655	27035	27035
mean	0.16	-0.02	0.08	0.02	0.06	-0.07	-0.36	-0.04
RMS	4.41	2.35	5.41	3.71	8.20	3.82	10.23	5.00
min	-40.94	-22.84	-54.11	-37.47	-49.09	-28.97	-109.91	-46.72
max	51.55	25.66	60.88	45.19	45.45	28.34	128.40	49.15

ment by a factor of 3 to 4. Furthermore, Table 2 also provides the crossover statistics before and after adjusting the ship data (from the edited data set) separately by institution. The RMS differences vary between 4.4 mgal (IfE) and 10.2 mgal (BGI) before the adjustment, while the corresponding values after the adjustment range from 2.4 mgal (IfE) to 5.0 mgal (BGI). This shows that the level of accuracy differs for the four institutions, and once more the gain from the adjustment is about a factor of two for all institutions. In the end, it has to be noted that all adjustments were done with equally weighted crossover observations, as no reliable a priori error informations were available. This could eventually be improved in the future by deriving individual weights per cruise or per agency from the crossover analysis, cf. also Wessel and Watts (1988).

5 Evaluation by Altimetric Data

For the evaluation of the quality and consistency of the compiled marine gravity data set, altimetric gravity anomalies were utilized as an independent source of information. The altimetric results are available in grids and were interpolated to the locations of the ship observations by splines. Then differences of shipborne minus altimetric gravity anomalies were computed, and atmospheric corrections were considered for the shipborne data. The following four public domain altimetric data sets were used for the evaluation:

- CLS99, cf. CLS (2003),
- GSFC00, cf. GSFC (2003),
- KMS02, cf. Andersen and Knudsen (1998) and Andersen et al. (2003),
- Scripps 10, cf. Sandwell and Smith (1997).

Table 3. Statistics of the differences between the crossover adjusted shipborne and altimetric gravity anomalies. Units are mgal.

	CLS99	GSFC00	Scripps	KMS02
#	1399895	1400999	1400688	1400999
mean	-1.44	-1.04	-1.09	-0.97
RMS	9.21	8.18	8.20	7.78
min	-156.73	-158.47	-155.59	-157.73
max	115.91	102.02	106.46	106.00

The above altimetric gravity anomaly grids were computed directly from the sea surface heights (CLS99, GSFC00, KMS02) or via deflections of the vertical (Scripps 10), cf. the given references. The results of all comparisons with the final crossover adjusted marine gravity data set are summarized in Table 3. Unlike Fig. 2, the evaluation area was limited to 72 °N, because some of the altimetric grids do not extend further north. The mean difference is about -1 mgal for all four data sets, the reason for this being not clear at present. However, it should also be noted that the mean difference varies by geographical area, e.g., see Table 4. The RMS difference ranges from 9.2 mgal (CLS99) to 7.8 mgal (KMS02). Thus, the latest of the considered altimetric models, KMS02, shows the best agreement with the shipborne gravity data. The large minimum and and maximum differences are located in the vicinity of islands and in fjords, where the altimeter results may not be reliable.

In order to check the gain in accuracy due to the preprocessing and crossover adjustment, Table 4 provides the comparison results with KMS02 for the original and the edited data set. It becomes clear, that already the data editing significantly improves the agreement with the altimetry data. The

Table 4. Statistics of the differences between unadjusted and crossover adjusted shipborne and altimetric gravity anomalies (KMS02) including a subset. Units are mgal.

data adj.	original before	edited before	edited after	Iceland after
#	1551572	1400999	1400999	54370
mean	-0.34	-0.51	-0.97	0.46
RMS	18.01	10.23	7.78	4.20
min	-159.87	-155.63	-157.73	-60.52
max	221.25	115.55	106.00	40.56

RMS crossover difference before the adjustment reduces from 18.0 mgal to 10.2 mgal, solely through the editing of 3.6% bad data and the exclusion of the Red Sea sources (8.7%). A further reduction of the differences is resulting from the crossover adjustment, yielding a RMS value of 7.8 mgal. Furthermore, even better results can be obtained in areas with high quality shipborne gravity data, e.g., around Iceland a RMS value of only 4.2 mgal is found, cf. Table 4. However, it has to be noted that close to islands, where the altimeter results may have problems, larger RMS differences can be found, e.g., about 10 mgal around the Canary Islands. Similar results from the comparison of shipborne and altimetric gravity data were obtained by other researches, e.g., RMS differences of 8.5 mgal were found by Featherstone (2003), 7–11 mgal by Rapp (1998), 5.8 mgal by Andersen and Knudsen (1998), and 3–7 mgal by Sandwell and Smith (1997). At last, the differences between shipborne and altimetric gravity data are not displayed here due to space restrictions, but color plates of the differences between the unadjusted and crossover adjusted ship gravity data (edited data set) and KMS02 can be found in Denker and Roland (2003).

6 Conclusions

In this contribution, a consistent marine gravity data set for the European seas was compiled. This was achieved by merging data from four institutions, regeneration of the track structure, data editing, and crossover adjustment. Solely through the data editing, the RMS crossover difference reduced from 15.5 mgal to 8.4 mgal, while the crossover adjustment led to a final value of 4.7 mgal. Similarly, the differences between shipborne and altimetric data from KMS02 improved, yielding RMS values of 18.0 mgal for the original data, 10.2 mgal for the edited data before adjustment, and 7.8 mgal for the edited and crossover adjusted data. An even better agreement can be found in areas with high quality shipborne gravity data, e.g., around Iceland the RMS difference reduces to 4.2 mgal. The KMS02 altimetric data showed the best agreement with the compiled final ship data set with a RMS difference of 7.8 mgal, while the corresponding values are 8.2 mgal for both GSFC00 and Scripps and 9.2 mgal for CLS99.

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