Crossover Adjustment of New Zealand Marine Gravity Data, and Comparisons with Satellite Altimetry and Global Geopotential Models

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Abstract. This paper summarises the crossover adjustment of approximately 90,000-line-km of ship-track gravity observations around New Zealand. The adjustment reduced the standard deviation of the ~10^6 crossovers from ~2.0 mgal to ~0.3 mgal. These data were then used to assess four different grids of satellite-altimeter-derived gravity anomalies. The KMS02 altimeter grid was selected for use around New Zealand as it gave a better fit to the coastal ship-track data. Least-squares collocation was then used to 'drape' the altimetry onto the crossover-adjusted ship-tracks to counter the well-known problems with satellite altimeter data near the coast. The precision of this merged ship-altimeter gravity dataset is estimated to be 3.5 mgal.

Keywords. Gravity, marine gravimetry, satellite altimetry, crossover adjustment, geopotential model

1 Introduction

Marine gravity observations in the vicinity of New Zealand (NZ) have been collected over the past 45 years by various agencies at different times for different purposes (Fig. 1). Until recently, these observations were stored in different formats, in terms of different (horizontal and gravity) datums, and no attempt had been made to ensure consistency among individual cruises, let alone the datasets. The problems with offsets and tilts in marine gravimetry are well known (e.g., Wessel and Watts 1988). Therefore, a crossover adjustment of all the observations surrounding NZ has now been carried out by Intrepid Geophysics under contract to Land Information New Zealand (LINZ) to bring them into a single, coherent, internally consistent dataset.

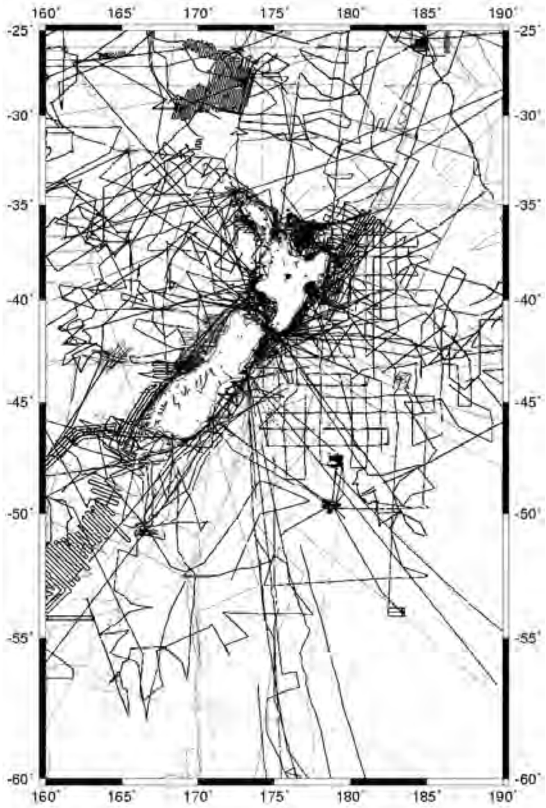

Fig 1. Coverage of ship-track gravity observations around New Zealand (Mercator projection)

This paper briefly describes the crossover adjustment of the ship-track gravity data (summarised from Brett 2004). The unadjusted and adjusted ship-track gravity anomalies are then compared with various satellite-altimeter-derived gravity anomaly grids (Table 1), and the EGM96 (Lemoine et al. 1998) and GGM01S (Tapley et al. 2004) global geopotential models (cf. Featherstone 2003; Denker and Roland 2004). The crossover-adjusted ship-track gravity anomalies are then used to select the most appropriate altimeter-derived gravity anomalies for the computation of a new NZ gravimetric geoid model. Finally, we describe the merging of the altimeter-derived and crossover-adjusted ship-track anomalies using least-squares collocation (LSC) (cf. Strykowski and Forsberg 1998).

Data	*Resolution*	*Reference*
KMS02	2'	Andersen et al (2004)
SSv11.2	2'	Sandwell and Smith (1997)
GMGA02	2'	Hwang et al (2002)
GSFC00	2'	Wang (2001)
Data	*URL*	
KMS02	ftp://ftp.kms.dk/pub/GRAVITY	
SSv11.2	http://topex.ucsd.edu/marine_grav/mar_grav.html	
GMGA02	ftp://gps.cv.nctu.edu.tw/pub/data/marine_gravity/	
GSFC00	http://magus.stx.com/mssh/mssh.html	

Table 1. Summary of some recent public domain satellite-altimeter-derived marine gravity anomalies

2 The Crossover Adjustment

The crossover adjustment of the ship-track gravity observations surrounding NZ (Fig. 1) was carried out by Intrepid Geophysics under contract to LINZ (Brett 2004). This section summarises the main points; copies of Brett (2004) are available from the first-named author.

A total of 3,119,289 ship-track gravity observations were collated from recent surveys conducted for NZ's UNCLOS (United Nations Convention on the Law of the Sea) continental shelf claim, the NZ Institute of Geological and Nuclear Sciences (GNS), the US National Oceanographic and Atmospheric Administration (NOAA) and Geoscience Australia (GA). The area was restricted to 160°E≤λ≤190°E and 25°S≤φ≤60°S (2,401,932 points) since this is the region over NZ which the gravimetric geoid model is required.

Where necessary, the gravity datum was transformed from the 1959 NZ (Potsdam) datum to IGSN71 by subtracting 15.21 mgal. All horizontal positions were assumed to be on a geocentric horizontal geodetic datum because the survey methods had not been stored in the respective databases (except the UNCLOS data, which is on WGS84). Also where necessary, the free-air gravity anomalies were converted to GRS80 (Moritz 1980); otherwise they were recomputed on GRS80 using a second-order free-air correction and Somigliana normal gravity.

The ship-track data were then checked for spikes using a fourth-difference examination of each profile. In addition, statistical reporting (min, max, mean, and standard deviation) was also performed on all data. Any outlier values were then examined more closely with an interactive data viewer and editor, and a judgement was made as to whether the spike or feature should be removed or retained.

When initially imported, the data for each ship cruise were stored as a single, long 'line' of data. A necessary step prior to crossover adjustment was to split the cruise data into shorter, approximately straight-line segments. The advantage of this is that two straight lines either do not cross, or if they do cross, then there is a single crossover. Given this precondition, it is possible to design a highly efficient algorithm to locate all crossovers. This process discarded no data. The only outcome was that all points were grouped into line segments for the purpose of identifying crossovers. The estimated crossover correction was applied to the cruise as a whole, taking no account of the breakdown into 'lines'.

The computer software used by Intrepid Geophysics also allows for the horizontal positions of the gravity observations to be adjusted. However, experiments indicated that this made little difference to the results (i.e., crossover statistics), so the horizontal positions were left unchanged.

The datasets were ranked according to their perceived reliability. This ranking determined the preferred processing order. Starting with the UNCLOS datasets, internal and external crossovers were computed. On the basis of this and the area of coverage the 'res00-11' cruise was ranked highest. Systematic offsets (i.e., biases) were applied to each of the other UNCLOS datasets to reduce the misclosure statistics for the UNCLOS cruises as a whole. The next ranked dataset was the GNS data, followed by the NOAA data, and then the GA data. This order was determined on the basis of internal crossover statistics, data coverage and visual inspection of the raw data.

After applying the offsets to the individual UNCLOS datasets they were concatenated into a single dataset. This was then adjusted using "loop closure levelling". This procedure is a single process that consists of several steps. Firstly, the crossovers of a dataset are identified (as described above). Each crossover was then quantified (bias only), where two crossovers were within ~1 km only one bias was evaluated. The misclosure errors around closed loops were then distributed using least-squares procedures for network adjustment to produce a correction function. The final levelling adjustment, at every observation point, was then interpolated from the correction function using an Akima spline.

The loop closure levelling was then applied to the GNS dataset. The levelled GNS data was gridded and the Intrepid GridMerge process used to determine an offset of 4.35 mgal to align it with the UNCLOS data. The GNS data was then appended to the UNCLOS data at the loop closure levelling repeated. The same process was followed to progressively include the NOAA (5.94 mgal offset) and GA (8.16 mgal offset) datasets.

Comparing the misclosures at the crossover points in Tables 2 and 3 shows a 714% improvement in the standard deviation (STD) of the crossovers, as well as a significant reduction in the mean differences. Table 4 gives the statistics of the ship-track gravity anomalies before and after the crossover adjustment.

Data	*X-overs*	*Max*	*Min*	*Mean*	*STD*
UNCLOS	345	79.7	0.0	7.6	12.9
GNS	57512	271.3	0.0	2.5	7.6
NOAA	971988	236.1	0.0	0.7	0.7
GA	36271	52.6	0.0	1.6	2.7
All data	1069289	271.3	0.0	0.8	2.0

Table 2. Misclosure statistics for the original ship-track observations (mgal)

Data	*X-overs*	*Max*	*Min*	*Mean*	*STD*
UNCLOS	345	12.1	0.0	0.45	1.39
GNS	57512	68.9	0.0	0.19	1.50
NOAA	971988	1.9	0.0	0.09	0.08
GA	36271	14.9	0.0	0.04	0.11
All data	1069244	93.4	0.0	0.05	0.28

Table 3. Misclosure statistics for the adjusted ship-track observations (mgal)

Adjustment	*Max*	*Min*	*Mean*	*STD*
Original	477.0	-813.6	4.1	43.2
Adjusted	455.6	-807.7	6.9	42.6

Table 4. Statistics of the original and adjusted ship-track observations (mgal; 2,401,932 points)

3 Comparisons with Altimeter- and GGM-derived Gravity Anomalies

Firstly, it is well known that satellite-altimeter-derived gravity anomalies are less accurate close to the coast. This is due to factors such as poorly tracked altimetry close to the coast (Deng et al., 2002), poor shallow-water tidal models, and poor wet delay corrections (e.g., Andersen and Knudsen 2000). In addition, there are significant differences close to the Australian coast among altimeter-derived anomalies derived by different groups (Featherstone 2003). This is also the case in NZ, albeit to a lesser extent than near Australia (Fig. 2 and Table 5). Note that the range in Fig. 2 has been truncated for display purposes (cf. Table 5).

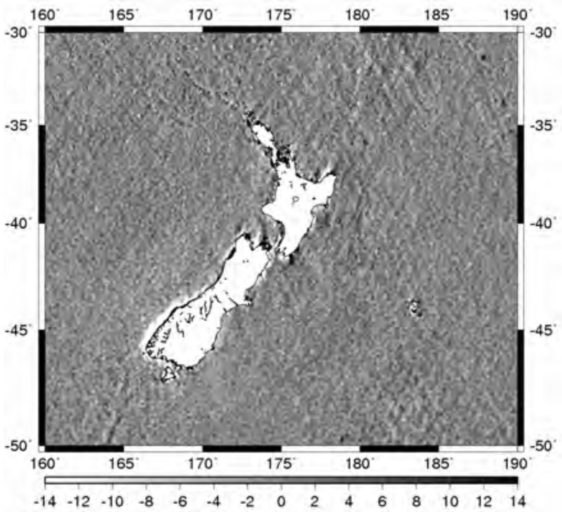

Fig 2. Difference between KMS02 and SSv11.2 gravity anomalies around NZ (mgal; Mercator projection)

Data	*Max*	*Min*	*Mean*	*STD*
KMS02-SSv11.2	139.4	-79.4	-0.1	3.0
KMS02-GMGA02	371.8	-337.3	-0.0	4.2
KMS02-GSFC00	117.2	-103.2	0.1	2.9
SSv11.2-GMGA02	380.8	-334.7	0.0	4.0
SSv11.2-GSFC00	123.9	-129.3	0.2	3.2
GMGA02-GSFC00	334.7	-366.2	0.1	4.2

Table 5. Statistics of the differences between altimeter-derived gravity anomalies around NZ (920,918 pts mgal)

The largest differences among the altimeter grids occur along the western coast of NZ's South Island (centred at: ~45°S, ~167°E); see the example in Fig. 2. This is due to a combination of the problems with coastal satellite altimetry, coupled with the very steep gravity gradients at the boundary of the Australian and Pacific plates. The latter will give a large Gibbs's phenomenon when transforming the sea surface heights/gradients to gravity anomalies because there is no gravity data on land. From Table 5, the comparisons that involve the GMGA02 grid give the largest maximum and minimum differences. These differences are concentrated as several 'spikes' located close to the NZ and Chatham

Island (183°E, 44°S) coasts. This shows that it is the least consistent with the other grids, which are reasonably self-consistent (Table 5).

Next, the various altimeter-derived anomalies (Table 1) were compared with the crossover-adjusted anomalies in order to select the best grid for future NZ geoid computations. The altimeter-derived gravity anomalies (assumed to also be on a geocentric horizontal datum) were bi-cubically interpolated to the locations of the ship-track data. The statistics in Table 6 only use the dense ship-track data in a 50-400-km band around NZ and the Chatham Islands (Fig. 3). This is because the altimeter data are less reliable within ~50 km from the NZ coast (Fig. 2). The altimeter data are probably more reliable than the ship-track data in the open oceans, especially in areas with sparse data coverage where the crossover adjustment is poorly constrained (e.g., south of 55°S; see Fig. 1).

Data	*Max*	*Min*	*Mean*	*STD*
KMS02	194.5	-108.7	1.7	8.2
SSv11.2	196.0	-109.1	1.6	8.2
GMGA02	197.3	-107.7	1.7	8.2
GSFC00	193.9	-107.4	2.2	8.0

Table 6. Statistics of the differences between the altimeter-derived altimetry grids and the 890,290 crossover-adjusted NZ ship-track observations within 50–400 km of the coast (mgal)

From the results in Table 6, no single altimeter grid is significantly better than another in the 50-400-km region around NZ. However, an analysis of the comparison between the altimetry grids and all 2,401,932 adjusted ship-track data reveals that the KMS02 altimetry grid gives an overall better fit. As such, this grid was selected for use because it will reduce the amount of 'draping' required to fit it to the ship-track data (see section 4).

Finally, the 2,401,932 original and crossover-adjusted anomalies were compared with gravity anomalies implied by the EGM96 (Lemoine et al. 1998) and GGM01S (Tapley et al. 2004) (Table 7). Because of increased noise in the high-degree coefficients, GGM01S was truncated at spherical harmonic degree and order 90; EGM96 was used to degree and order 360. Acknowledging that the ship-track data has different frequency content to the long-wavelength GGMs, Table 7 indicates that the adjusted ship-track data give a better agreement with the GGMs, thus providing further verification of the success of the crossover adjustment.

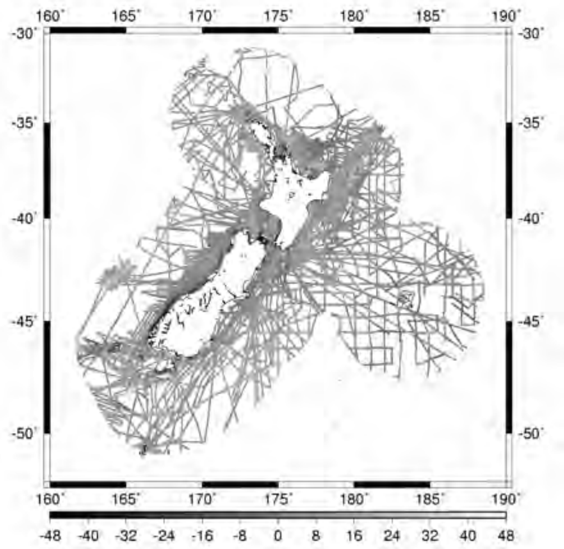

Fig 3. Difference between the adjusted NZ ship-track observations and KMS02 altimeter-derived gravity anomalies up to 400 km from coast (mgal; Mercator projection)

	Max	*Min*	*Mean*	*STD*
Original				
EGM96	500.5	-784.3	-0.4	22.7
GGM01S	494.5	-795.7	-1.8	37.4
Adjusted				
EGM96	479.1	-778.4	2.3	22.6
GGM01S	473.2	-789.8	0.9	37.1

Table 7. Statistics of the differences between the 2,401,932 original and adjusted NZ ship-track observations and gravity anomalies implied by global geopotential models (mgal)

4 Operational Merging using LSC

Now that it has been proven that the crossover adjustment has been successful and, in turn, allowed the identification of KMS02 as the 'best' grid of altimeter-derived gravity anomalies around NZ, we now aim to use the crossover-adjusted ship-tracks to correct for the poorer altimeter data near the coast (cf. Strykowski and Forsberg 1998; also see Figs. 2 and 3). This was achieved using the least-squares collocation (LSC) interpolation routines in the GRAVSOFT suite (Tscherning et al. 1992).

The LSC 'draping' procedure broadly followed the procedures of Strykowski and Forsberg (1998). Firstly, the crossover-adjusted ship-track data was supplemented with land gravity information. Next, the differences between the ship-track/land data and the KMS02 altimeter data within the study area were determined. These differences were then 'softly' gridded (predicted with LSC with a relatively large standard deviation) to a 2 arc-minute correction grid over the computation area. A second-order Markov covariance model was used with a correlation length of 20 km and 3 mgal RMS noise of the gravity data. These parameters were optimised by testing them over a range of 5 – 100 km and 1 – 5 mgal, respectively (see next paragraph). The correction grid was then added to the pre-gridded altimetry data. This yields an altimetry data set that is consistent with the ship-track data, thus correcting the well-known coastal errors in the altimetry data.

Importantly, this LSC combination procedure only used the dense ship-track data within 400 km of the NZ coast and Chatham Island (Fig. 3). This is because the sparse oceanic ship-track data are considered less reliable than the altimeter data because the crossover adjustment is poorly constrained beyond this distance. The LSC data combination was [partly] independently tested by extracting 2,328 observations (~0.2%) from the adjusted ship-track data within 400 km of the coast. These observations were selected by removing every 2,328th record from the ship-track data file. These data were not used in the LSC combination, but used later to test the results; it also allowed empirical optimisation of the choice of RMS noise and correlation length. Coincidently, this optimisation resulted in the same values for the noise and correlation length as adopted by Strykowski and Forsberg (1998). The comparison between the 2,328 extracted marine observations and the KMS02 altimetry anomalies before and after draping revealed a significant improvement in the fit (Table 8). An additional comparison was made between all of the ship-track anomalies (Table 9). This also demonstrates an improved fit between the datasets after the LSC draping has been performed.

From this comparison, we cautiously estimate the precision/accuracy of the LSC combined gravity anomalies to be ~3.5 mgal, which is a GLOPOV (General Law of Propagation of Variance) combination of the estimated error in the ship-tracks from the crossover adjustment (0.3 mgal; Table 3) and the STD of the differences with the independent points (3.2 mgal; Table 8). The final marine gravity grid (LSC combined using all the ship-track data) is shown in Fig. 4.

Grid	*Max*	*Min*	*Mean*	*STD*
Original	61.2	-89.7	0.7	9.9
Draped	32.0	-32.1	0.0	3.2

Table 8. Statistics of the differences between 2328 ship-track observations (within 400 km of the coast) and the KMS02 anomalies before and after draping (mgal)

Grid	*Max*	*Min*	*Mean*	*STD*
Original	486.3	-789.5	1.4	11.2
Draped	486.2	-789.5	0.9	9.1

Table 9. Statistics of the differences between 2,401,932 ship-track observations and the KMS02 anomalies before and after draping (mgal)

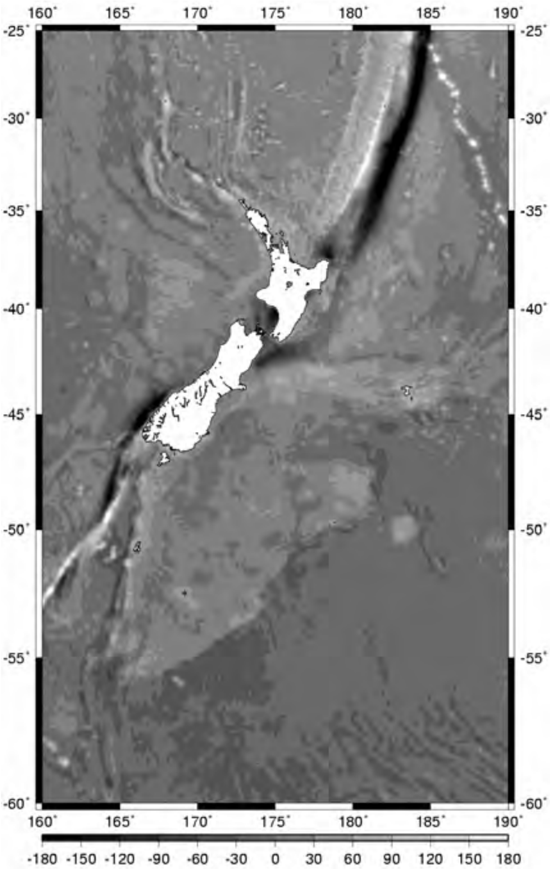

Fig 4. The final NZ 2' marine gravity anomaly grid combining adjusted ship-track observations and KMS02 altimeter-derived gravity anomalies (mgal; Mercator projection)

5 Conclusion

This paper has summarised the crossover adjustment of approximately 90,000-line-km of ship-track gravity observations around New Zealand. The standard deviation of the ~10^6 crossovers was reduced from ~2.0 mgal to ~0.3 mgal. These data were then used to assess four different grids of satellite-altimeter-derived gravity anomalies. After excluding known problematic data areas, this showed no single altimeter grid as being significantly better than another. The KMS02 grid was selected for use around New Zealand as it had a better fit than the others when the coastal and offshore areas were included in the comparison. This grid was then 'draped' onto the crossover adjusted ship-tracks using least-squares collocation to counter the well-known problems with satellite altimeter data near the coast. The precision of this merged dataset is estimated to be 3.5 mgal.

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