Comparison of Different Satellite Altimeter-Derived Gravity Anomaly Grids with Ship-Borne Gravity Data Around Australia

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Abstract. The GMGA97, KMS01 and Sandwell's v.9.2 grids of marine gravity anomalies, derived from multi-mission satellite altimetry, are compared with one another and with ship-track gravity anomalies computed from the Australian marine gravity database. The results show some significant differences among these data sources, especially close to the coasts and in regions of steep horizontal gravity gradients, such as along the continental shelf. These are attributed to loss of altimeter lock as it passes over the coast and poorly modelled shallow-sea tides, and data interpolation errors, respectively. The comparisons also show that there are some serious biases among ship-tracks in the Australian marine gravity database, which illustrates that these data have not been crossover corrected properly. Therefore, users of any of these data should treat them with caution.

Keywords. Satellite altimetry, marine gravimetry, coastal zone, Australia.

1 Introduction

Marine gravity measurements from ship-borne platforms are notoriously problematic (eg Wessel and Watts 1988). Conversely, the near-homogeneous, near-global coverage of marine gravity anomalies derived from multi-mission satellite radar altimetry arguably offers a superior source of gravity data (eg Haxby et al. 1983). Several different altimeter-derived gravity anomaly grids are now available in the public domain, which have been computed by various groups using slightly different data combinations and computational philosophies. Therefore, the question arises as to which, if any, is superior. One approach to answering this question is to compare the altimeter-derived gravity anomalies with those calculated from ship-borne gravimetry (eg Rapp and Basic 1992; Olgiati et al. 1995; Rapp 1998; Zhang 1998). However, this assumes that the ship-track gravity anomalies are accurate.

This paper compares three recent, public-domain altimeter-derived gravity anomaly grids around Australia, namely GMGA97 (Hwang et al. 1998), KMS01 (Andersen et al. 2001) and Sandwell's version 9.2 (Sandwell and Smith 1997). These will be compared with one another, and with ship-track gravity anomalies computed from Geoscience Australia's gravity database (Murray 1997). It will be shown that significant differences exist among these data sources, but it is not possible to ascertain which is the more precise source of marine gravity data around Australia. However, it will be shown that the Australian ship-track gravity data have not all been crossover corrected properly.

2 Gravity Anomalies From Altimetry

The commonly used techniques to compute marine gravity anomalies from satellite altimetry include:

1. Conversion of marine geoid heights (ie sea surface heights corrected for sea surface topography) using the inverse Stokes formula (eg Olgiati et al. 1995).
2. Conversion of vertical deflections (along-track first derivatives of sea surface heights) using the inverse Vening-Meinesz formula (eg Hwang 1998).
3. Conversion of vertical deflections via integration of Laplace's equation (eg Haxby 1983; Sandwell and Smith 1997; Olgiati et al. 1995).

All three approaches use the so-called remove-compute-restore technique, where a global geopotential model is used during the FFT-based conversion of geoid heights or vertical deflections to gravity anomalies/disturbances. An associated problem is the edge effect that occurs at the coasts because there are no altimeter data on land.

However, probably the most significant problem in altimetry-gravimetry is gridding the data for use in the FFT. There is a high along-track spatial resolution of altimeter data, whereas the cross-track resolution is generally poorer (depending on the missions used). Gridding errors are compounded in areas of large horizontal gravity gradients (eg where orbital errors cause incorrect co-registration) and in areas with a high sea surface variability, notably in areas close to the coasts.

Different groups tend to use different gridding algorithms, but the two most popular options appear to be splines (Olgiati et al. 1995; Sandwell and Smith 1997) and least squares collocation (Rapp and Basic 1992; Andersen and Knudsen 1998; Hwang et al. 1998). Accordingly, differences can be expected among altimeter-derived gravity anomaly grids computed from the same satellite missions due solely to the gridding technique used.

Finally, several authors have investigated the estimation of marine gravity anomalies by combining satellite altimetry with ship-track gravimetry, with numerous techniques being used (eg Knudsen 1993; Kirby and Forsberg 1998; Li and Sideris 1997; Tziavos e*t al*. 1998a). However, the problem common to all is accurate determination of the relative data weights. As will be seen from the results presented later, combination of the Australian ship-track gravity data with altimetry is not yet a sensible option because of large errors currently in the Australian marine gravity data.

3 The Data

3.1 The Altimeter Gravity Grids

The KMS01 2 arc-minute by 2 arc-minute gravity anomaly grid (Andersen et al. 2001) results from refinements to the techniques described by Andersen and Knudsen (1998), and is available in the public domain via ftp from ftp.kms.dk/GRAVITY. KMS01 has been computed using a combination of ERS-1 and GEOSAT satellite altimetry via the geoid (method 1 above). The sea surface topography was not modelled explicitly, but reduced by fitting the altimeter-sensed sea surface heights to EGM96 (Lemoine et al. 1998). The AG95 tidal model (Shum *et al*. 1997) was used to reduce sea surface variability. The residual (to EGM96) marine geoid heights were interpolated onto a regular grid using least-squares collocation. The residual gravity anomalies were then computed using an FFT implementation of the inverse Stokes formula, including a Wiener-type filter. The gravity anomalies implied by EGM96 were then restored.

The GMGA97 gravity anomaly grid (Hwang et al. 1998) is supplied at a 2 arc-minute spatial resolution. This and an extraction program are available via anonymous ftp from http://gps.cv.nctu.edu.tw. GMGA97 uses a combination of SEASAT, GEOSAT, ERS-1 and TOPEX/POSEIDON data. The mean sea surface heights were converted to geoid heights using the Levitus (1982) sea surface topography model, then along-track geoid gradients taken to yield vertical deflections. The CSR v.3.0 ocean tide model (Eanes and Bettadpur 1995) was used to reduce sea surface variability. The vertical deflections were gridded using least squares collocation. These were converted to gravity anomalies using the inverse Vening-Meinesz formula (Hwang 1998) via the one-dimensional FFT (method 2 above), and using a Wiener-type filter. EGM96 was used in the remove-compute-restore procedure.

Sandwell's v.9.2 grid of marine gravity anomalies is the most recent in his series (cf. Sandwell and Smith 1997), with the refinements reported via README files provided with the data. The version 9.2 grid is available at 1 or 2 arc-minute resolutions from http://topex.ucsd.edu/marine_grav/mar_grav.html. Only the 2 arc-minute grid is used in this study to be compatible with KMS01 and GMGA97. The Sandwell v.9.2 grid uses GEOSAT, ERS-1 and TOPEX data, and refinements in filtering during gridding and FFT conversion. The along-track gradients were computed and gridded iteratively using splines that include Wiener-type filters. The CSR v.3.0 ocean-tide model, but no sea surface topography model, was used. The gravity anomalies were computed from this grid using the FFT implementation of the Laplace-based inversion of the vertical deflections (method 3 above), also using Wiener-type filters. EGM96 was used in the remove-compute-restore implementation of the FFT.

3.2 The Australian Ship-Tracks

The 111,394 ship-track gravity observations used in the comparisons are taken from an area bound by 108°E ≤ λ ≤ 162°E and 8°S ≤ ϕ ≤ 48°S from the 1992 release of AGSO's (now Geoscience Australia) gravity database (Murray 1997). Importantly, many of these ship-borne gravity observations have not been crossover adjusted, as will be shown later. Unfortunately, the data were not supplied in a format such that the individual tracks can be identified reliably, so no crossover adjustment is possible.

Therefore, in addition to the problems inherent to ship-borne gravimetry, the AGSO92 data cannot offer any definitive control on the accuracy of the satellite altimeter-derived gravity anomalies in the Australian region. As such, comparisons of the data sources are just that; they only indicate the levels of agreement (and perhaps precision), but not accuracy. Nevertheless, the comparisons will be informative to the users of these data.

4 Comparisons and Discussion

Rectangular sub-grids were extracted from the respective altimeter datasets over the study area. Since gravity anomalies implied by EGM96 have been used to infill the land areas in each grid, these data were removed using the ***grdlandmask*** option in GMT v.3 (Wessel and Smith 1995) for a 2 arc-minute grid before statistics were computed (Table 1). Table 1 also shows statistics of the AGSO92 marine free-air gravity anomalies.

grid	*#pts*	*Max*	*Min*	*Mean*	*STD*
KMS01	1302317	287.26	-229.24	-5.85	32.23
Sand v9.2	1302317	308.47	-236.30	-5.80	32.87
GMGA97	1302317	306.90	-221.50	-5.86	31.97
AGSO92	111394	292.13	-241.44	-3.43	34.52

Table 1. Descriptive statistics of the altimeter-derived, EGM96-implied and AGSO92 ship-track gravity anomalies around Australia (units in mGal)

From Table 1, the satellite altimeter-derived marine gravity anomalies appear to be in broad agreement with one another, which is to be expected since they use some common data. The AGSO92 data show a comparable range, but the standard deviation is larger, which is also to be expected because of the dense sampling along the ship-tracks. However, as will be shown later, the extrema in the AGSO92 data generally occur in different locations to the extrema in the altimeter data.

4.1 Comparison among altimeter grids

Though the KMS01, Sandwell and GMGA97 data are supplied on 2 arc-minute grids, the grid nodes are offset by 1 arc-minute. Therefore, the data were re-gridded using the ***surface*** routine in GMT v.3 with a tension factor of 0.25, which is the recommended value of this parameter for potential field data (Smith and Wessel 1990). The statistics of the differences between the grids were then calculated using the ***grdinfo*** routine in GMT v.3 (excluding the EGM96-implied gravity anomalies on land); see Figures 1 through 3 and Table 2.

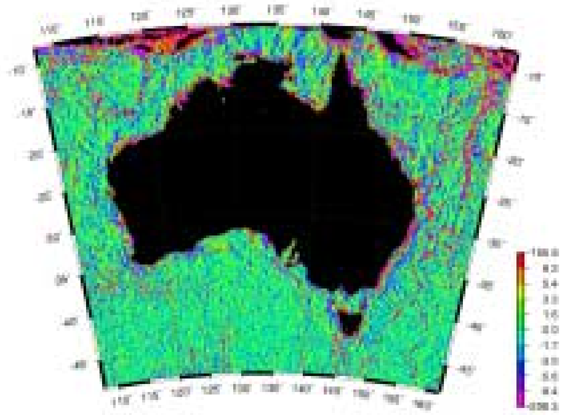

Figure 1. Differences between KMS01 and Sandwell v9.2 gravity anomalies (units in mGal; Lambert projection)

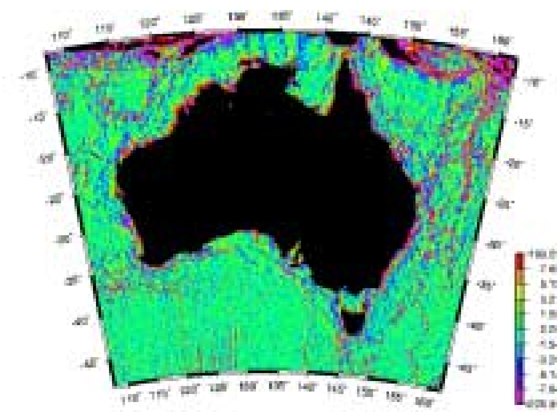

Figure 2. Differences between KMS01 and GMGA97 gravity anomalies (units in mGal; Lambert projection)

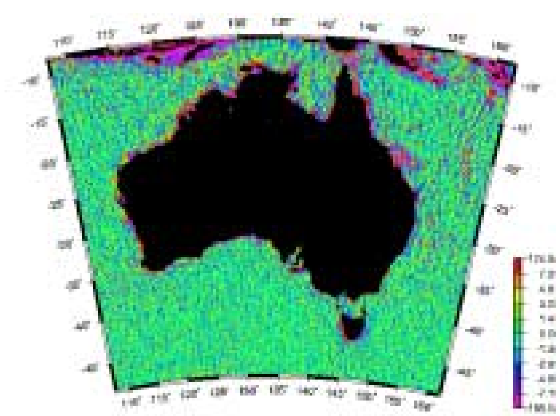

Figure 3. Differences between Sandwell v9.2 and GMGA97 gravity anomalies (units in mGal; Lambert projection)

grid	*Max*	*Min*	*Mean*	*STD*
KMS01-Sand_v9.2	155.94	-206.36	-0.06	6.58
KMS01-GMGA97	183.29	-205.40	-0.01	6.12
Sand_v9.2-GMGA97	174.54	-165.03	0.06	5.64

Table 2. Descriptive statistics of the differences between altimeter-derived gravity anomalies around Australia (1302317 points; units in mGal)

From Figures 1 through 3 and Table 2, there are some very large (~200 mGal) differences among the altimeter-derived gravity anomaly grids. These occur mostly in coastal regions and in regions of steep horizontal gravity gradients, such as over seamounts and the edges of the continental shelf. Large differences also occur over the Great Barrier Reef, which are probably due to a combination of a higher sea surface variability and failure of the tidal models in this region. The large differences in areas of large horizontal gravity gradients are probably an artefact of orbit errors causing mis-registration in the altimeter profiles, coupled with the different gridding techniques used by each group.

The differences between KMS01-Sandwell (Figure 1) and KMS01-GMGA97 (Figure 2) exhibit quite similar features in the open oceans, which are spatially correlated with ocean depth and geological structures. Since largely the same altimeter datasets are used, these differences are due to the different computational philosophies taken by these groups. Recall that KMS01 is computed via geoid heights, whereas the Sandwell and GMGA97 grids are computed via vertical deflections. There will also be a difference due to the different filters used. However, it cannot be ascertained which is the more precise grid of marine gravity anomalies from this comparison. Other common features in Figures 1 and 2 are a large linear trend close to the southeast coast and large variable differences off the northwest coast. These are probably due to incorrect tidal modelling in shallow waters.

The differences between Sandwell-GMGA97 (Figure 3) are generally smaller, but exhibit high-frequency features (a 'speckled' effect) in the open oceans. This closer agreement is also to be expected since both groups use vertical deflections. The differences in the open oceans are most probably due to the different gridding and filtering techniques used, though GMGA97 uses a sea surface topography model whereas Sandwell does not. The larger differences occur close to the coasts. These are probably due to the problematic coastal sea surface topography and the effects of sea surface variability on the gridding, since both grids use the same tidal model.

A final point worth noting is that the differences between the grids (Table 2) are slightly larger than the implied precision of these grids, as estimated from fits to selected ship-track gravimetry (Sandwell and Smith 1997; Andersen and Knudsen 1998; Hwang et al. 1998). It is also worth noting that the ship-track gravimetry selected by these authors is away from the 'problematic' coastal regions. Therefore, it is clear that all the altimeter-derived gravity anomaly grids should be treated with caution in the coastal zone, say within a distance of, say, ~100 km from the Australian coastline.

4.2 Comparison with Australian ship-tracks

The altimeter data were bi-cubically interpolated from their grids to the locations of the AGSO92 ship-track observations and the statistics of the differences calculated using ***geoid_abs_tester.f*** (Featherstone 2001). Table 3 shows the statistics of the differences between the altimeter data and the 111,394 AGSO92 ship-track free-air gravity anomalies. Figures 4 to 6 show charts of the mean differences in 5 arc-minute bins (for display purposes) for which AGSO92 data are available.

From Table 3 and Figures 4 to 6, there are some very large (~240 mGal) and spatially correlated differences between the altimeter data and the AGSO92 ship-track gravity anomalies. The results in Table 3 are considerably worse than such differences reported elsewhere in the literature (eg Rapp and Basic 1992; Rapp 1998; Sandwell and Smith 1997; Andersen and Knudsen 1998; Hwang et al. 1998). This is because the latter studies are selective, using only well navigated or highly precise marine gravity surveys that are generally located away from the coastline. The present study deliberately uses all available data so as to give a more objective comparison. Moreover, such an approach is useful for identifying the outlying ship-tracks in the AGSO92 database. This information will be of use to any past and potential users of these data.

From Figures 4 to 6, the majority of the large differences are due to the same ship-tracks, most notably those that comprise long 'oceanic' cruises to the southwest of Australia. These ship-track data cannot be crossover adjusted (because there are so few crossovers), and are more susceptible to biases and tilts due to gravimeter drift (cf. Wessel and Watts 1988). Therefore, it is recommended that these data are 'corrected' to fit the altimeter data or are rejected altogether.

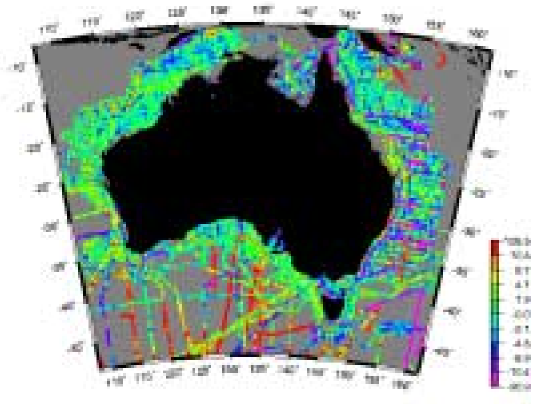

Figure 4. Differences between KMS01 and AGSO gravity anomalies (units in mGal; Lambert projection)

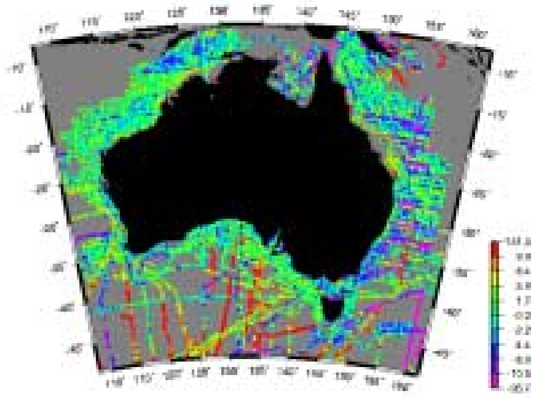

Figure 5. Differences between Sandwell v9.2 and AGSO gravity anomalies (units in mGal; Lambert projection)

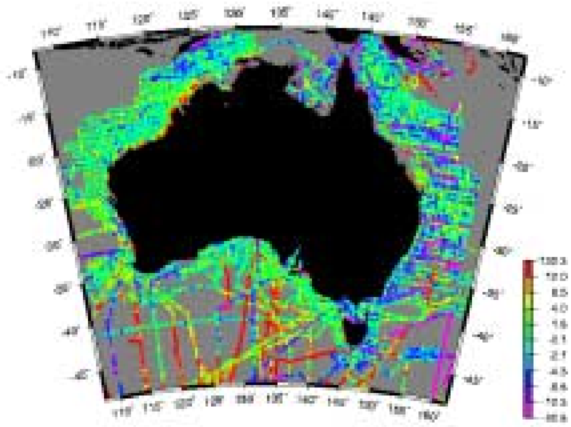

Figure 6. Differences between GMGA97 and AGSO gravity anomalies (units in mGal; Lambert projection)

grid	*Max*	*Min*	*Mean*	*STD*	*RMS*
KMS01	143.69	-239.34	-0.42	8.56	8.57
Sand v9.2	150.80	-241.68	-0.64	8.47	8.50
GMGA97	137.35	-238.63	-0.54	8.41	8.42

Table 3. Descriptive statistics of the differences between altimeter-derived grids and the 111,396 AGSO marine free-air gravity anomalies around Australia (units in mGal)

Numerous smaller differences (~5-10 mGal) tend to occur in areas where there are dense, 'hashed' ship-tracks closer to the Australian coasts (Figures 4 to 6). These data are more likely to have been subjected to some form of crossover analyses, and are thus more reliable than the long 'oceanic' cruises. Nevertheless, larger differences (> 10 mGal) that are consistent for all altimeter grids (Figures 4 to 6) do remain, which adds evidence to some of these coastal tracks being in error. However, the differences in Figures 4 to 6 are not always spatially correlated for all the altimeter grids, especially in the coastal regions where there are large differences among the altimeter grids (cf. Figures 1 to 3).

Put simply, the differences observed near the Australian coasts (Figures 4 to 6) could be due to the inability of the altimeter to accurately recover gravity field information in these regions, or to the AGSO92 ship-track data, or both. Given the earlier arguments, it is more probable that the altimeter data are in error in the near-coastal regions. Nevertheless, it remains difficult to ascertain which, if any, is the superior data source.

5 Conclusions and Recommendations

There are significant differences among marine gravity anomalies computed by different groups from multi-mission satellite radar altimetry. These tend to be larger in the coastal zone, which is due to the numerous problems associated with properly tracking and correcting altimeter data in these regions. Therefore, these data should be used with extreme caution, say 100 km from the Australian coasts. Since the altimeter grids are derived from predominantly the same data sources, the differences are due to one of all of the data treatment (notably gridding and filtering), poorly modelled sea surface topography and shallow-sea tides, and the computational philosophies taken by each group.

Other published validations of altimeter-derived gravity anomalies almost exclusively use ship-track gravimetry. This approach was replicated here in an attempt to ascertain which, if any, of the altimeter-derived grids is superior around Australia. However, the comparisons are inconclusive in this regard because of the quality of the ship-track data. Importantly, using the altimeter data only identified this. Principally, the ship-track data have not been, nor can be, crossover adjusted and thus cannot provide any definitive indication of the accuracy or precision of the altimeter-derived grids. Therefore, while comparisons among these data are useful, there is no objective means of ascertaining the more precise data source. Given this limitation, it is necessary to devise suitable editing or combination techniques. Until this is achieved, the Australian ship track data should not be used, and the altimeter-derived gravity anomaly grids should be treated with extreme caution close (say 100 km) to the Australian coasts.

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