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Only use ship-track gravity data with caution: a case-study around Australia

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Much of the ship-track marine gravity data in the Australian national gravity database must not be relied upon because several large (>900 mGal) biases exist in them. These biases were detected and cross-validated through comparisons with marine gravity anomalies derived from re-tracked multi-mission satellite altimetry and a recent satellite-only global geopotential model derived from the *Gravity Recovery And Climate Experiment* (GRACE). This shows the need to carefully screen ship-track gravity data to ensure that they have been crossover adjusted before they are relied upon in any Earth-science study.

KEY WORDS: Marine gravimetry, satellite altimetry, satellite gravimetry, GRACE, global geopotential models, geodesy, gravity, Australia.

INTRODUCTION AND MOTIVATION

The principal problem with marine gravity measurements made onboard ships (ship-track gravimetry) is that they are subject to biases because of drift in relative gravimeters, incorrect positioning and incorrect Eötvös corrections (e.g., Dehlinger, 1978; Wessel and Watts, 1988; Torge, 1989). This bias problem can be reduced by observing ship-track gravimetry in a hashed pattern, which allows for a subsequent crossover adjustment to enforce consistency at the cross points. Without this, ship-track gravimetry should not be relied upon. Ship-track gravity data used to be included in the Australian national gravity database from Geoscience Australia (GA), the acquisition of most of which is described in Symonds and Willcox (1976), Mather *et al.* (1976) and Murray (1997). It will be shown here that these data were unadjusted and have now been withdrawn from the GA database. People who still hold earlier downloads of the GA national gravity database should not rely on the ship-track data.

Using unadjusted, and thus potentially biased, ship-track gravity data will invalidate any geological, geophysical or geodetic interpretation or application of them. For instance, a biased ship-track could indicate spurious features that may lead to incorrect follow-up surveys, needlessly taking additional resources. Another example is the [then-incorrect] assumption of crossover-adjusted GA ship-track data in the computation of AUSGeoid98 (Featherstone *et al.*, 2001) that has corrupted this model in some coastal regions (e.g., Claessens *et al*., 2001; Kirby, 2003). The unadjusted state of Australian ship-track data also raises questions as to the validity of other studies that have utilised them (e.g., Mather *et al.*, 1976; Zhang, 1998; Kirby, 1997).

Petkovic *et al*. (2001) describe a GA-contracted (to *Intrepid Geophysics*) 're-levelling' of the GA ship-track gravity data. GA ship-track data were adjusted to fit onto Sandwell's v7.2 grid of the then-available multi-mission satellite altimeter-derived marine gravity anomalies (Sandwell and Smith, 1997). This has introduced errors in the coastal zone, as demonstrated indirectly by Featherstone (2003) and confirmed by Petkovic (2002, pers. comm.) for the Bass Straight. The problem with adjusting ship-track data in this way is the implicit assumption that the satellite altimetry is correct, which is especially not the case in the coastal zone (e.g., Deng *et al*., 2002; Deng and Featherstone, 2006; Hwang *et al*., 2006) or in continental shelf and shallow-sea areas where tides and tropospheric corrections to the altimeter ranges are poorly modelled (Andersen and Knudsen, 2000). Accordingly, the GA ship-track data may have been degraded in the coastal region by this 're-levelling' process.

However, only the unadjusted ship-track data were supplied with the July 2007 and earlier on-line releases of the GA gravity database, and no mention is made of the 're-levelled' data in the metadata. Though the unadjusted ship-track data have now been withdrawn from the GA database (which appeared to occur during the review cycle of this article), the 're-levelled' data are not included. Presumably this is due to the problems identified above, but this is not possible to ascertain at present. Even when the GA ship-track gravity anomalies are charted offshore, several cruise-dependent biases are apparent, but when compared with independent external data (shown later), they become even more pronounced. As such, it will be recommended here that the GA ship-track data are not relied upon, or if they are, extreme caution must be exercised. Incidentally, we did attempt to crossover-adjust the GA data in the classical way, but the scarcity of the ship-tracks in most regions rendered the least-squares adjustment ill-conditioned and thus unreliable, which may explain the need for the approach taken by Petkovic *et al*. (2001).

Using this Australian case as an exemplar, it is essential that any study that utilises ship-track data from any source is first screened to ascertain that they have been crossover adjusted. This can be from a careful inspection of the metadata, provided that it is sufficiently detailed, or from comparisons with independent gravity data from satellite altimetry and/or a global geopotential model. The latter two approaches will be used here because the metadata accompanying the GA gravity data were not sufficiently detailed to ascertain this problem beforehand.

2. METHODS & RESULTS

Firstly, all gravity anomalies used here refer to the GRS80 reference ellipsoid (Moritz 1980): GRS80 was used to recompute the GA ship-track gravity anomalies (Hackney and Featherstone, 2003); GRS80 is used in the altimeter-derived gravity anomalies (Sandwell and Smith, 2005), and GRS80 was set as the reference ellipsoid when computing gravity anomalies from the global geopotential model.

2.1 Comparisons with satellite altimetry

Marine gravity anomalies can be deduced from satellite radar altimetry, where the measured and time-averaged sea surface height can be converted to gravity using a variety of inverse methods (Haxby *et al*., 1983, Olgiati *et al*., 1995; Hwang 1998, Hwang *et al*., 1988, 2002; Sandwell and Smith, 1997, 2005; Andersen and Knudsen, 1998; Wang, 2001). The benefit of altimeter-derived marine gravity anomalies is that they are derived from a homogeneous data coverage and several different satellite missions can be merged. They are also not subject to drift- or navigation-based errors. Importantly, these altimeter-derived gravity anomalies are totally independent of the ship-track data.

The altimeter-derived marine gravity anomalies used here around Australia come from the version 16.1 grid of multi-mission satellite altimetry produced by Sandwell and Smith (2005; http://topex.ucsd.edu/WWW_html/mar_grav.html). The key improvements over the original treatise (Sandwell and Smith, 1997) are the use of more and recent altimeter data, a different gridding algorithm (Sandwell, 1987), and the use of re-tracked altimeter waveforms (Sandwell and Smith, 2005; cf. Maus *et al*., 1998, Deng and Featherstone, 2006) that can improve the gravity anomalies in the coastal zone (cf. Hwang *et al*., 2006).

Figure 1a (top) shows the differences between the July 2007 release of the GA ship-track gravity anomalies and altimeter-derived marine gravity anomalies from the Sandwell-Smith vers 16.1 grid. All differences in Figure 1 were charted using GMT software (Wessel and Smith, 1995; http://gmt.soest.hawaii.edu/). Figure 1a shows the deficiencies in the GA ship-track gravity data, where biases of over 60 mGal in magnitude are evident among crossing tracks, showing that no crossover adjustment has been applied. Computing the descriptive statistics of the differences for all 149,961 observations gives: max = 972.201 mGal, min = -181.905 mGal, mean = -1.383 mGal and STD = 13.492 mGal. This very large range necessitated the use of a truncated z-scale in Figure 1a.

In some areas in Figure 1a, however (e.g., over parts of the North West Shelf), the ship-track data do appear to be more homogeneous, suggesting that some crossover adjustment may have been applied to these data, but this cannot be confirmed at present because of the lack of detailed metadata.

Figure 1 near here

2.2 Comparisons with global geopotential models

In order to cross-validate the above observation, marine gravity anomalies from a satellite-only global geopotential model (GGM), which are also completely independent from the ship-track gravity data, were used.

A GGM is a spectral representation of the Earth's external gravitational field in terms of solid spherical harmonic basis functions. Satellite-only GGMs are computed from the analysis of the orbits of artificial Earth satellites (e.g., Lambeck and Coleman, 1983; Reigber, 1989; Nerem *et al.*, 1995). Earlier satellite-only GGMs were of limited precision due to a combination of (Featherstone, 2002): the power-decay of the Earth's gravitational field with altitude; the inability to track complete satellite orbits from ground-based stations; imprecise modelling of atmospheric drag, non-gravitational and third-body gravitational perturbations; and incomplete sampling of the global gravity field due to the limited number of satellite orbital inclinations then available.

The GRACE (Gravity Recovery And Climate Experiment) twin-satellite gravimetry mission (Tapley *et al*., 2004) is now delivering satellite-only GGMs that are a significant improvement upon earlier results (e.g., Tapley *et al*., 2005; Mayer-Gürr *et al*., 2005; Förste *et al*., 2007). The homogeneous and high accuracy of the gravity field from GRACE data alone now provides an independent and reliable data source with which to better identify errors in ship-track gravity anomalies. However, one limitation with some GRACE-derived GGM solutions is the north-south striping problem in the high-degrees (cf. Han *et al*., 2005; Swenson and Wahr, 2006; Kusche, 2007). As such, GRACE satellite-only GGMs are often truncated to spherical harmonic degree 60. Koch (2005) also shows that the GRACE-derived GGMs are unreliable beyond degree

60. Therefore, a recent satellite-only GGM was truncated to degree 60 for this comparison.

Marine free-air gravity anomalies were computed from the EIGEN-GL04S1 GRACE-only GGM using our in-house `harmonics.f` software, which is a modification of Rapp's (1982) code that includes the accelerated routines of Holmes and Featherstone (2002). The GGM-derived gravity anomalies were computed by spherical harmonic synthesis directly at the locations of the GA-ship-track gravity anomalies, then subtracted and charted in Figure 1b.

Comparing Figures 1a and 1b (noting the same scales), cross-validates the biases in the GA ship-track gravity anomalies. The biases in Figure 1b are not as clear as in Figure 1b because a degree 60 GGM can only resolve gravity anomaly features with a spatial resolution (half-wavelength) of ~333 km, whereas the altimeter-derived anomalies can resolve 20-40 km (cf. Sandwell and Smith, 2005). Nevertheless, this does give an independent cross-validation that the GA ship-track gravity data do contain biases because they have not all been crossover adjusted. The descriptive statistics of the differences are: max = 931.029 mGal, min = -229.847 mGal, mean = -2.659 mGal and STD = 38.297 mGal. The extremes are consistent with the differences for the altimetry data, but the larger mean and standard deviation reflect the lower spatial resolution of the satellite-only GGM (cf. Figure 1).

3. CONCLUSION

Significant biases in much of the ship-track marine gravity data in GA's July 2007 national gravity database (and its predecessors) have been detected and cross-validated through comparisons with gravity anomalies derived from retracked multi-mission satellite altimetry and from a recent satellite-only GGM derived from the GRACE satellite gravimetry mission. Large (>60 mGal in magnitude) biases exist in several ship-track gravity anomalies, showing that they should be neglected from, or used with extreme caution, for geological, geophysical and geodetic studies. Our [unpublished] attempt to crossover-adjust the GA ship-track data showed that the observations are too sparse to form a well-conditioned least-squares adjustment. Therefore, the retracked satellite altimeter data are recommended as a superior alternative source of marine gravity anomalies around Australia, and which might also be the case elsewhere. At the very least, users of ship-track gravity data should carefully check the associated metadata and cross-check them with independent data sources such as satellite altimetry and GGMs as done here.

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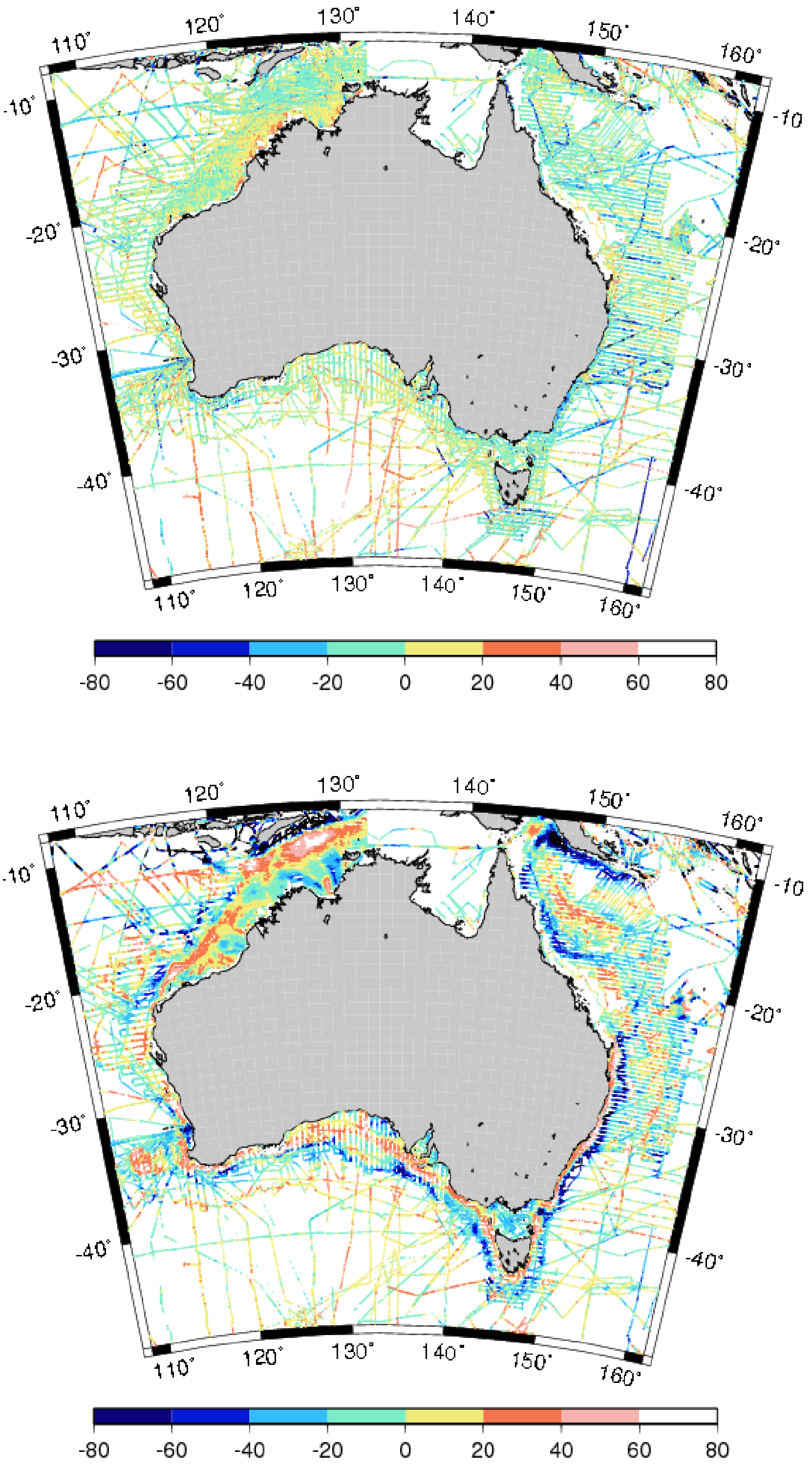

Figure 1. a; top: Differences between ship-track gravity anomalies around Australia from the July 2007 data release from GA and marine gravity anomalies from version 16.1 of the Sandwell-Smith one arc-minute grid; b: bottom: Differences between GA ship-track gravity anomalies and marine gravity anomalies from a degree-60 spherical harmonic synthesis of the EIGEN-GL04S1 GRACE-only GGM [units in mGal; Lambert projection]