

1 Only use ship-track gravity data with 2 caution: a case-study around Australia

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

18

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

21

22 **INTRODUCTION AND MOTIVATION**

23 The principal problem with marine gravity measurements made onboard ships (ship-
24 track gravimetry) is that they are subject to biases because of drift in relative
25 gravimeters, incorrect positioning and incorrect Eötvös corrections (e.g., Dehlinger,

26 1978; Wessel and Watts, 1988; Torge, 1989). This bias problem can be reduced by
27 observing ship-track gravimetry in a hashed pattern, which allows for a subsequent
28 crossover adjustment to enforce consistency at the cross points. Without this, ship-track
29 gravimetry should not be relied upon. Ship-track gravity data used to be included in the
30 Australian national gravity database from Geoscience Australia (GA), the acquisition of
31 most of which is described in Symonds and Willcox (1976), Mather *et al.* (1976) and
32 Murray (1997). It will be shown here that these data were unadjusted and have now
33 been withdrawn from the GA database. People who still hold earlier downloads of the
34 GA national gravity database should not rely on the ship-track data.

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

44 Petkovic *et al.* (2001) describe a GA-contracted (to *Intrepid Geophysics*) ‘re-
45 levelling’ of the GA ship-track gravity data. GA ship-track data were adjusted to fit
46 onto Sandwell’s v7.2 grid of the then-available multi-mission satellite altimeter-derived
47 marine gravity anomalies (Sandwell and Smith, 1997). This has introduced errors in the
48 coastal zone, as demonstrated indirectly by Featherstone (2003) and confirmed by
49 Petkovic (2002, pers. comm.) for the Bass Strait. The problem with adjusting ship-

50 track data in this way is the implicit assumption that the satellite altimetry is correct,
51 which is especially not the case in the coastal zone (e.g., Deng *et al.*, 2002; Deng and
52 Featherstone, 2006; Hwang *et al.*, 2006) or in continental shelf and shallow-sea areas
53 where tides and tropospheric corrections to the altimeter ranges are poorly modelled
54 (Andersen and Knudsen, 2000). Accordingly, the GA ship-track data may have been
55 degraded in the coastal region by this ‘re-levelling’ process.

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

70 Using this Australian case as an exemplar, it is essential that any study that
71 utilises ship-track data from any source is first screened to ascertain that they have been
72 crossover adjusted. This can be from a careful inspection of the metadata, provided that
73 it is sufficiently detailed, or from comparisons with independent gravity data from

74 satellite altimetry and/or a global geopotential model. The latter two approaches will be
75 used here because the metadata accompanying the GA gravity data were not sufficiently
76 detailed to ascertain this problem beforehand.

77

78 **2. METHODS & RESULTS**

79 Firstly, all gravity anomalies used here refer to the GRS80 reference ellipsoid (Moritz
80 1980): GRS80 was used to recompute the GA ship-track gravity anomalies (Hackney
81 and Featherstone, 2003); GRS80 is used in the altimeter-derived gravity anomalies
82 (Sandwell and Smith, 2005), and GRS80 was set as the reference ellipsoid when
83 computing gravity anomalies from the global geopotential model.

84

85 **2.1 Comparisons with satellite altimetry**

86 Marine gravity anomalies can be deduced from satellite radar altimetry, where the
87 measured and time-averaged sea surface height can be converted to gravity using a
88 variety of inverse methods (Haxby *et al.*, 1983, Olgiati *et al.*, 1995; Hwang 1998,
89 Hwang *et al.*, 1988, 2002; Sandwell and Smith, 1997, 2005; Andersen and Knudsen,
90 1998; Wang, 2001). The benefit of altimeter-derived marine gravity anomalies is that
91 they are derived from a homogeneous data coverage and several different satellite
92 missions can be merged. They are also not subject to drift- or navigation-based errors.
93 Importantly, these altimeter-derived gravity anomalies are totally independent of the
94 ship-track data.

95 The altimeter-derived marine gravity anomalies used here around Australia
96 come from the version 16.1 grid of multi-mission satellite altimetry produced by
97 Sandwell and Smith (2005; http://topex.ucsd.edu/WWW_html/mar_grav.html). The

98 key improvements over the original treatise (Sandwell and Smith, 1997) are the use of
99 more and recent altimeter data, a different gridding algorithm (Sandwell, 1987), and the
100 use of re-tracked altimeter waveforms (Sandwell and Smith, 2005; cf. Maus *et al.*, 1998,
101 Deng and Featherstone, 2006) that can improve the gravity anomalies in the coastal
102 zone (cf. Hwang *et al.*, 2006).

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

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

117

118 Figure 1 near here

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121

122 2.2 Comparisons with global geopotential models

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

126 A GGM is a spectral representation of the Earth's external gravitational field in
127 terms of solid spherical harmonic basis functions. Satellite-only GGMs are computed
128 from the analysis of the orbits of artificial Earth satellites (e.g., Lambeck and Coleman,
129 1983; Reigber, 1989; Nerem *et al.*, 1995). Earlier satellite-only GGMs were of limited
130 precision due to a combination of (Featherstone, 2002): the power-decay of the Earth's
131 gravitational field with altitude; the inability to track complete satellite orbits from
132 ground-based stations; imprecise modelling of atmospheric drag, non-gravitational and
133 third-body gravitational perturbations; and incomplete sampling of the global gravity
134 field due to the limited number of satellite orbital inclinations then available.

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

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

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

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

164

165 **3. CONCLUSION**

166 Significant biases in much of the ship-track marine gravity data in GA's July 2007
167 national gravity database (and its predecessors) have been detected and cross-validated
168 through comparisons with gravity anomalies derived from retracked multi-mission

169 satellite altimetry and from a recent satellite-only GGM derived from the GRACE
170 satellite gravimetry mission. Large (>60 mGal in magnitude) biases exist in several
171 ship-track gravity anomalies, showing that they should be neglected from, or used with
172 extreme caution, for geological, geophysical and geodetic studies. Our [unpublished]
173 attempt to crossover-adjust the GA ship-track data showed that the observations are too
174 sparse to form a well-conditioned least-squares adjustment. Therefore, the retracked
175 satellite altimeter data are recommended as a superior alternative source of marine
176 gravity anomalies around Australia, and which might also be the case elsewhere. At the
177 very least, users of ship-track gravity data should carefully check the associated
178 metadata and cross-check them with independent data sources such as satellite altimetry
179 and GGMs as done here.

180

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186

187 **REFERENCES**

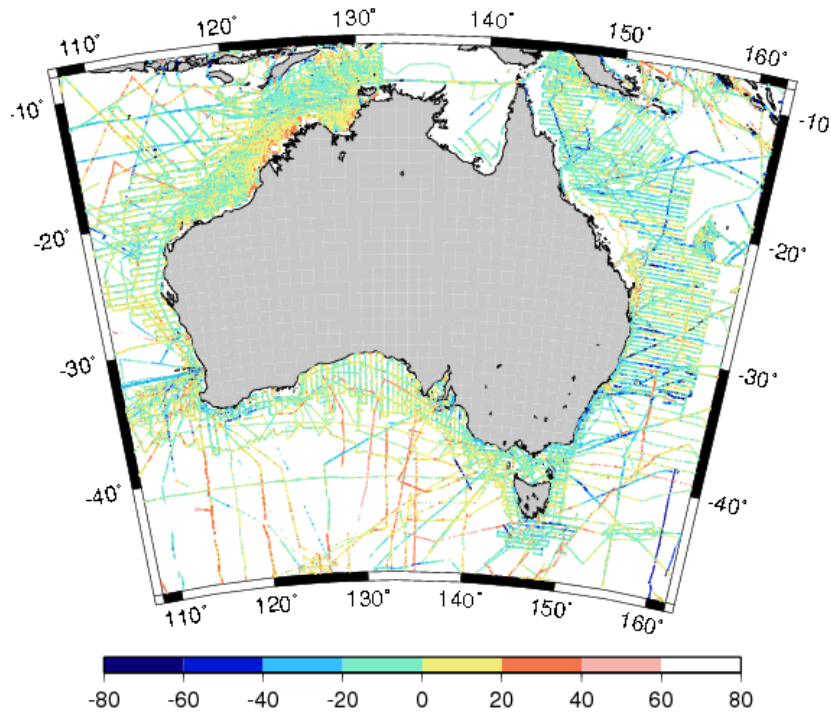
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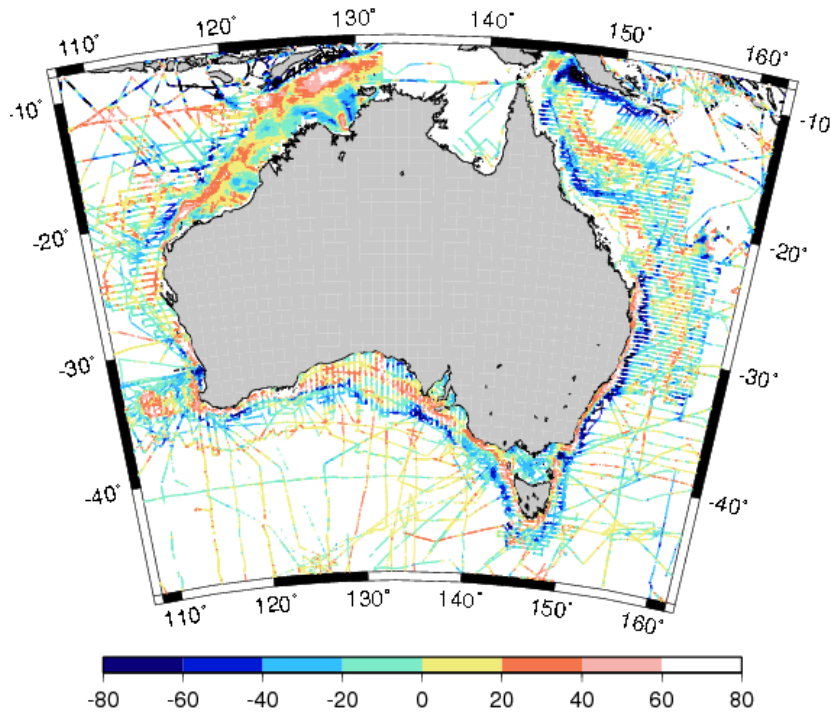
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311 **Figure 1.** a; top: Differences between ship-track gravity anomalies around Australia from the
312 July 2007 data release from GA and marine gravity anomalies from version 16.1 of the
313 Sandwell-Smith one arc-minute grid; b; bottom: Differences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