

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

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4 **W.E. FEATHERSTONE**

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6 *Western Australian Centre for Geodesy and The Institute for Geoscience Research,*

7 *Curtin University of Technology, GPO Box U1987, Perth WA 6845, Australia*

8 *Tel.: +61-8-9266-2734; Fax: +61-8-9266-2703; Email: [W.Featherstone@curtin.edu.au](mailto:W.Featherstone@curtin.edu.au)*

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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33 been withdrawn from the GA database.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](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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120

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  $\sim 333$  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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## 187 **REFERENCES**

- 188 ANDERSEN, O.B., & KNUDSEN, P. 1998. Global marine gravity field from the ERS-1 and GEOSAT  
189 geodetic mission altimetry, *Journal of Geophysical Research – Oceans*, **103**(C4): 8129-8137.
- 190 ANDERSEN, O.B., & KNUDSEN, P. 2000. The role of satellite altimetry in gravity field modelling in  
191 coastal areas, *Physics and Chemistry of the Earth*, **25**(1), 17-24.
- 192 CLAESSENS, S.J., FEATHERSTONE, W.E. & BARTHELMES, F. 2001. Experiences with point-mass  
193 gravity field modelling in the Perth region, Western Australia, *Geomatics Research Australasia*, **75**,  
194 53-86.

- 195 DEHLINGER, P. 1978. Marine Gravity, Elsevier, Amsterdam, 322 pp.
- 196 DENG, X.L. & FEATHERSTONE, W.E. 2006. A coastal retracking system for satellite radar altimeter  
197 waveforms: application to ERS-2 around Australia, *Journal of Geophysical Research – Oceans*, **111**,  
198 C06012, doi: 10.1029/2005JC003039.
- 199 DENG, X.L., FEATHERSTONE, W.E., HWANG C. & BERRY, P.A.M. 2002. Estimation of  
200 contamination of ERS-2 and POSEIDON satellite radar altimetry close to the coasts of Australia,  
201 *Marine Geodesy* 25(4): 249-271, doi: 10.1080/01490410290051572.
- 202 FEATHERSTONE, W.E. 2002. Expected contributions of dedicated satellite gravity field missions to  
203 regional geoid determination with some examples from Australia, *Journal of Geospatial*  
204 *Engineering*, **4**(1), 2-19
- 205 FEATHERSTONE, W.E. 2003. Comparison of different satellite altimeter-derived gravity anomaly grids  
206 with ship-borne gravity data around Australia, in: TZIAVOS, I.N. (ed) *Gravity and Geoid 2002*, Ziti  
207 Editions, Thessaloniki, pp 326-331
- 208 FEATHERSTONE, W.E., KIRBY, J.F., KEARSLEY, A.H.W., GILLILAND, J.R., JOHNSTON, G.M.,  
209 STEED J., FORSBERG, R. & SIDERIS, M.G. 2001. The AUSGeoid98 geoid model of Australia:  
210 data treatment, computations and comparisons with GPS-levelling data, *Journal of Geodesy*, **75**(5-6),  
211 313-330, doi: 10.1007/s001900100177
- 212 FÖRSTE, C., SCHMIDT, R., STUBENVOLL, R., FLECHTNER, F., MEYER, U., KÖNIG, R.,  
213 NEUMAYER, H., BIANCALE, R., LEMOINE, J-M., BRUINSMA, S., LOYER, S.,  
214 BARTHELMES, F. & ESSELBORN, S. 2007. The GeoForschungsZentrum Potsdam/Groupe de  
215 Recherche de Géodésie Spatiale satellite-only and combined gravity field models: EIGEN-GL04S1  
216 and EIGEN-GL04C, *Journal of Geodesy* (online first), doi: 10.1007/s00190-007-0183-8
- 217 HACKNEY, R.I. & FEATHERSTONE, W.E. 2003. Geodetic versus geophysical perspectives of the  
218 ‘gravity anomaly’, *Geophysical Journal International* **154**(1): 35-43, doi: 10.1046/j.1365-  
219 246X.2003.01941.x [Errata in **154**(2): 596, doi: 10.1046/j.1365-246X.2003.02058.x and **167**(2): 585-  
220 585, doi: 10.1111/j.1365-246X.2006.03035.x].
- 221 HAN, S-C., SHUM, C.K., JEKELI, C., KUO, C-Y., WILSON, C. & SEO, K-W. 2005. Non-isotropic  
222 filtering of GRACE temporal gravity for geophysical signal enhancement, *Geophysical Journal*  
223 *International*, **163**(1), 18–25, doi:10.1111/j.1365-246X.2005.02756.x

- 224 HAXBY, W.F., G.D. KARNER, J.L. LABRECQUE & J.K. WEISSEL 1983. Digital images of combined  
225 oceanic and continental data sets and their use in tectonic studies, *EOS - Transactions of the*  
226 *American Geophysical Union*, **64**(52), 995-1004.
- 227 HOLMES, S.A. & FEATHERSTONE, W.E. 2002. A generalised approach to the Clenshaw summation  
228 and the recursive computation of very-high degree and order normalised associated Legendre  
229 functions. *Journal of Geodesy*, **76**(5), 279-299, doi: 10.1007/s00190-002-0216-2.
- 230 HWANG, C. 1998. Inverse Vening Meinesz formula and deflection-geoid formula: applications to the  
231 predictions of gravity and geoid over the South China Sea, *Journal of Geodesy*, **72**(5): 304-312, doi:  
232 10.1007/s001900050169
- 233 HWANG, C., KAO, E-C. & PARSONS, B.E. 1998. Global derivation of marine gravity anomalies from  
234 SEASAT, GEOSAT, ERS-1 and TOPEX/Poseidon altimeter data, *Geophysical Journal*  
235 *International*, **134**: 449-459.
- 236 HWANG, C., HSU, H-Y. & JANG, R-J. 2002. Global mean sea surface and marine gravity anomalies  
237 from multi-satellite altimetry: applications of deflection-geoid and inverse Vening Meinesz formulae,  
238 *Journal of Geodesy*, **76**(8), 407-418, doi: 10.1007/s00190-002-0265-6.
- 239 HWANG, C., GUO, J., DENG, X., HSU, H-Y. & LIU, Y. 2006. Coastal gravity anomaly from retracked  
240 Geosat/GM altimetry: improvement, limitation and the role of airborne gravity data, *Journal of*  
241 *Geodesy*, 80(4), 204-216, doi: 10.1007/s00190-062-0052-x.
- 242 KIRBY, J.F. 1997. Fast combination of satellite and marine gravity data, *Exploration Geophysics*, **28**(1-  
243 2): 94-96, doi: 10.1071/EG997094
- 244 KIRBY, J.F. 2003. On the combination of gravity anomalies and gravity disturbances for geoid  
245 determination in Western Australia, *Journal of Geodesy*, **77**(7-8): 433-439, doi: 10.1007/s00190-003-  
246 0334-5
- 247 KOCH, K-R. 2005. Determining the maximum degree of harmonic coefficients in geopotential models by  
248 Monte Carlo methods, *Studia Geophysica et Geodaetica*, **49**(3), 259-275, doi: 10.1007/s11200-005-  
249 0009-1.
- 250 KUSCHE, J. 2007. Approximate decorrelation and non-isotropic smoothing of time-variable GRACE-  
251 type gravity field models, *Journal of Geodesy*, **81**(11), 733-749, doi: 10.1007/s00190-007-0143-3

- 252 LAMBECK, K. & COLEMAN, R. 1983. The Earth's shape and gravity field: a report of progress from  
253 1958 to 1982, *Geophysical Journal of the Royal Astronomical Society*, **74**(1), 25-54.
- 254 MATHER, R.S., RIZOS, C., HIRSCH, B. & BARLOW, B.C. 1976. An Australian gravity data bank for  
255 sea surface topography determinations (AUSGAD76), *Unisurv G25*, School of Surveying, University  
256 of New South Wales, Sydney, pp. 54-84.
- 257 MAUS, S., GREEN, C.M. & FAIRHEAD, J.D. 1998. Improved ocean-geoid resolution from retracked  
258 ERS-1 satellite altimeter waveforms, *Geophysical Journal International*, **134**(1), 243–253.
- 259 MAYER-GÜRR, T., ILK, K-H., EICKER, A. & FEUCHTINGER, M. 2005. ITG-CHAMP01: a CHAMP  
260 gravity field model from short kinematic arcs over a one-year observation period, *Journal of*  
261 *Geodesy*, **78**(7-8): 462-480, doi: 10.1007/s00190-004-0413-2.
- 262 MORITZ, H. 1980. Geodetic reference system 1980, *Bulletin Géodesique*, **54**(4), 395-405.
- 263 MURRAY, A.S. 1997. The Australian national gravity database, *AGSO Journal of Australian Geology &*  
264 *Geophysics*, **17**(1), 145-155.
- 265 NEREM, R.S., JEKELI, C. & KAULA, W.M. 1995. Gravity field determination and characteristics:  
266 retrospective and prospective, *Journal of Geophysical Research – Solid Earth*, **100**(B8), 15053-  
267 15074.
- 268 OLGIATI, A., BALMINO, G., SARRAILH, M. & GREEN, C.M. 1995. Gravity anomalies from satellite  
269 altimetry: comparison between computation via geoid heights and via deflections of the vertical,  
270 *Bulletin Géodésique*, **69**(3), 252-260.
- 271 PETKOVIC, P., FITZGERALD, D., BRETT, J., MORSE, M., & BUCHANAN, C. 2001. Potential field  
272 and bathymetry grids of Australia's margins, *Proceedings of the ASEG 15<sup>th</sup> Geophysical Conference*  
273 *and Exhibition*, Brisbane, August [CD-ROM].
- 274 RAPP, R.H. 1982. A FORTRAN program for the computation of gravimetric quantities from high-degree  
275 spherical harmonic expansions, *Report 334*, Department of Geodetic Science and Surveying, Ohio  
276 State University, Columbus.
- 277 REIGBER, C. 1989. Gravity field recovery from satellite tracking data, in: in: SANSÒ, F. & RUMMEL,  
278 R. (eds) *Lecture Notes in Earth Sciences*, **25**, Springer, Berlin Heidelberg New York, pp 197-234.
- 279 SANDWELL, D.T. 1987. Biharmonic spline interpolation of GEOS-3 and SEASAT altimeter data,  
280 *Geophysical Research Letters*, **14**(4), 139-142.

281 SANDWELL, D.T. & SMITH, W.H.F. 1997. Marine gravity anomaly from GEOSAT and ERS 1 satellite  
282 altimetry, *Journal of Geophysical Research – Solid Earth*, **102**(B5), 10039-10054.

283 SANDWELL, D.T. & SMITH, W.H.F. 2005. Retracking ERS-1 altimeter waveforms for optimal gravity  
284 field recovery, *Geophysical Journal International*, **163**(1), 79–89, doi: 10.1111/j.1365-  
285 246X.2005.02724.x

286 SWENSON, S. & WAHR, J. 2006. Post-processing removal of correlated errors in GRACE data,  
287 *Geophysical Research Letters*, **33**, L08402, doi: 10.1029/2005GL025285.

288 SYMONDS, P.A. & WILLCOX, J.B. 1976. The gravity field offshore Australia, *BMR Journal of*  
289 *Australian Geology & Geophysics*, **1**, 303-314.

290 TAPLEY, B. D., S. BETTADPUR, M. WATKINS, & C. REIGBER 2004. The gravity recovery and  
291 climate experiment: mission overview and early results, *Geophysical Research Letters*, **31**, L09607,  
292 doi: 10.1029/2004GL019920

293 TAPLEY, B., RIES, J., BETTADPUR, S., CHAMBERS, D., CHENG, M., CONDI, F., GUNTER, B.,  
294 KANG, Z., NAGEL, P., PASTOR, R., PEKKER, T., POOLE, S. & WANG, F. 2005. GGM02 - An  
295 improved Earth gravity field model from GRACE, *Journal of Geodesy*, **79**(8), 467-478, doi:  
296 10.1007/s00190-005-0480-z.

297 TORGE, W. 1989. *Gravimetry*, Walter de Gruyter, Berlin New York, 465 pp.

298 WANG, Y-M. 2001. GSFC00 mean sea surface, gravity anomaly, and vertical gravity gradient from  
299 satellite altimeter data, *Journal of Geophysical Research – Oceans*, **106**(C12): 31167-31174, doi:  
300 10.1029/2000JC000470.

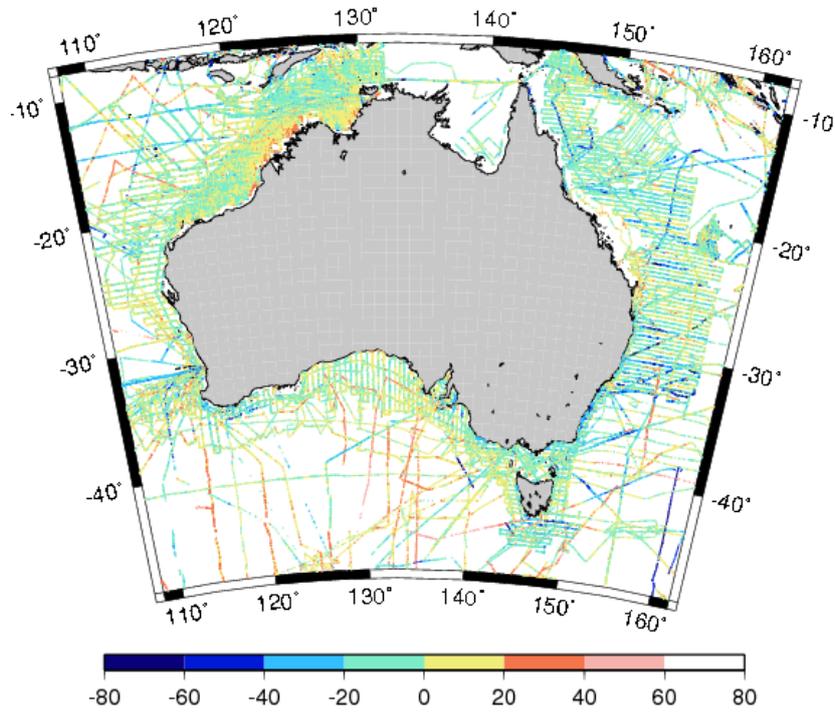
301 WESSEL, P. & SMITH, W.H.F. 1995. New version of the Generic Mapping Tools released, *EOS -*  
302 *Transactions of the American Geophysical Union*, **72**, 441,445-446.

303 WESSEL, P. & WATTS, A.B. 1988. On the accuracy of marine gravity measurements, *Journal of*  
304 *Geophysical Research – Solid Earth*, **94**(B4), 7685-7729.

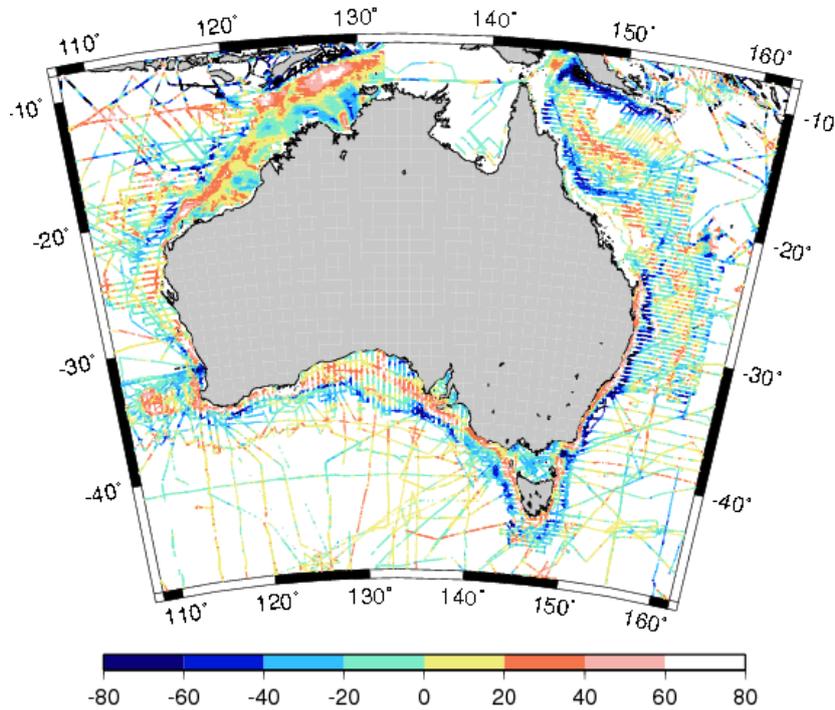
305 ZHANG, K. 1998. Altimetric gravity anomalies, their assessment and combination with local gravity  
306 field, *Finnish Geodetic Institute Report*, **98**(4), 137-144.

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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]