Is Australian data really validating EGM2008, or is EGM2008 just in/validating Australian data?

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Abstract. The tide-free release of the EGM2008 combined global geopotential model and its tide-free pre-release PGM2007A are compared with Australian land, marine and airborne gravity observations, co-located GPS-levelling on the [admittedly problematic] Australian Height Datum, astrogeodetic deflections of the vertical, and the AUSGeoid98 regional gravimetric quasigeoid model.

In all comparisons, EGM2008 performs better than any previous global gravity model. The standard deviation of the differences between free-air gravity anomalies from EGM2008 and free-air gravity anomalies from Australian land gravity observations is ±5.5 mGal, compared to, e.g., ±11.7 mGal for EGM96. Furthermore, the standard deviation of the differences between height anomalies from EGM2008 and a nation-wide set of 254 GPS-levelling points is ±17.3 cm, compared to, e.g., ±33.4 cm

for EGM96. In the comparisons with GPS-levelling, EGM2008 also outperforms AUSGeoid98 (standard deviation of ±19.1 cm in the differences with the nation-wide set of 254 GPS-levelling points), and the same holds for the comparison to astrogeodetic deflections of the vertical.

However, due to the poor quality of some of the Australian data, we cannot legitimately claim to truly validate EGM2008. Instead, EGM2008 confirms the already-known problems with the Australian data, as well as revealing some previously unknown problems. If one wants to claim validation, then EGM2008 is validated implicitly because it can confirm the errors in our regional data. Simply, EGM2008 is a good model over Australia.

1. Introduction

Australia, as a significant landmass in the Southern Hemisphere with reasonable geodetic data coverage, has been used over the years for 'ground truthing' global geopotential models (GGMs). Several studies have addressed this, mainly with a view to the later production of regional gravimetric geoid/quasigeoid models (e.g., Kearsley and Holloway 1989, Zhang and Featherstone 1995, Kirby et al. 1998, Amos and Featherstone 2003). Here, this effort is continued by comparing the tide-free version of the EGM2008 GGM (Pavlis et al. 2008) and its tide-free pre-release PGM2007A (Pavlis et al. 2007), with Australian gravity-field-related data. This is part of the International Association of Geodesy's (IAG's) Inter-Commission Working Group 2 *Evaluation of Global Earth Gravity Models* (http://users.auth.gr/~kotsaki/IAG_JWG/IAG_JWG.html). In an attempt to provide a more complete and useful 'validation', we use some newer data not used before.

We have maintained quite a close working relationship with the EGM2008 development team, providing them with access to a recent release Australian gravity database, the latest Australian digital elevation model (DEM), a nationwide set of 254 GPS-levelling data, and a nationwide set of 1080 historical astrogeodetic vertical deflections. Despite this, we have found quite a few discrepancies in this comparison that indicate problems with the Australian data, some of which were known, but some that were not.

Indeed, our attempted 'validation' has proven to be a two-way process, where EGM2008 has confirmed problems that were already known (e.g., with the Australian quasigeoid model in the coastal zone), but it has identified some problems (e.g., with the Australian gravity data) that we were previously unaware of. This alone is testament to the quality of EGM2008, i.e., an implicit validation. In this report, we first describe the Australian data and their perceived deficiencies, followed by EGM2008's confirmation of these, showing our primary conclusion that EGM2008 is implicitly validated over Australia. Results of computations from EGM2008's pre-release PGM2007A are also shown for comparison.

2. Description of the Australian Data

2.1 Australian gravity data

The Australian national gravity database (Fraser et al. 1976, Murray 1997) is now freely available via a web-based delivery system (http://www.ga.gov.au/gadds), subject to licence conditions. For this study, the July 2007 and June 2008 releases of the gravity data base are used, Compared to the 1996 data release used for AUSGeoid98, there is now much more metadata and information on the individual records in the database. However, not all individual records are accurate (e.g., marine gravity measurements are specified on the Australian Height Datum (AHD), which is impossible because the AHD is simply not defined offshore). Therefore, some caution is needed. The July 2007 release of the database contains 1,245,026 land and marine gravity observations (Fig. 1) while the June 2008 release contains 1,304,904 land observations and no marine observations (Fig. 2). The marine gravity observations were removed by Geoscience Australia during the review cycle of Featherstone (in press), which demonstrated them to be in gross error (up to 900 mGal!) because no cross-over adjustment had been applied.

The gravity datum for the June 2007 release is ISOGal84 (Wellman et al. 1985), which is tied to the IGSN71 (Morelli et al. 1971). The gravity datum for the July 2008 release is the Australian Absolute Gravity Datum 2007 (AAGD07; Tracey et al. 2007), which is not specifically tied to the IGSN71. Instead, it is based on a nation-wide set of 60 absolute gravity measurements made with a portable A10 gravimeter. AAGD07 is 0.078 mGal less than ISOGal84.

The broad-scale coverage of land gravity observations was collected on an ~11 km grid (~7 km in South Australia), mostly after the 1950s so as to promote the development of resources in Australia (Fraser et al. 1976, Murray 1988). Since most of these data were collected before the establishment of the AHD (Roelse et al. 1971, 1975), most of the heights of the gravity observations were determined by barometers

(Bellamy and Lodwick 1968), though some surveys were conducted along spirit-levelling lines available at the time (datum usually at a nearby tide-gauge). Barlow (1977) estimates the barometric elevation error of these earlier surveys to be between 3 m and 10 m; the quality of the pre-AHD levelling remains unknown.

Since these Australia-wide reconnaissance gravity surveys, additional in-fill gravity data have been added to the database by State/Territory geological and geophysical mapping agencies, the private sector, academic institutions and others. Interrogation of the 2007 release database indicates that around 30,000 of these are on AHD benchmarks giving far more precise heights (but see the later discussion on distortions in the AHD). However, the 2008 release database no longer indicates which observations are on AHD benchmarks. Though this information must be held by Geoscience Australia, it is not provided via the web-based delivery system.

Over the last decade, most of the newer gravity data in Australia has been co-ordinated using carrier-phase relative GPS techniques. However, this needs a quasi-geoid model to convert them to normal heights. [The AHD uses a truncated variant of the normal orthometric height system (Featherstone and Kuhn 2006; Roelse et al. 1971, 1975)]. Unfortunately, however, the quasi/geoid models used for this GPS height transformation are not stored in the Geoscience Australia database, nor are the original ellipsoidal heights, but the GPS-coordinated gravity surveys were identified in the 2007 database. From Featherstone's [unnamed] contacts with the major GPS-gravimetry contractors in Australia, these GPS surveys have used a variety of models, ranging from OSU91A (Rapp et al. 1991) and EGM96 (Lemoine et al. 1998) to AUSGeoid91 (Kearsley and Govind 1991), AUSGeoid93 (Steed and Holtznagel 1994) and AUSGeoid98 (Featherstone et al. 2001).

As such, the later 'validation' is broken down according to the perceived quality of the land gravity data (all data, GPS-coordinated gravity, and ship-track gravity). Hopefully, the relative accuracy of these datasets will give a more informed evaluation, rather than the 'wholesale' approach taken previously of using all data with equal weight (cf. Kearsley and Holloway 1989, Zhang and Featherstone 1995, Kirby et al. 1998, Amos and Featherstone 2003).

Second-order, atmospherically corrected, free-air gravity anomalies were re-computed from the primary observations (gravity values and 3D coordinates) in the Australian gravity databases. The formulas used are summarised in Featherstone and Dentith (1997) and Hackney and Featherstone (2003). The database claims to provide

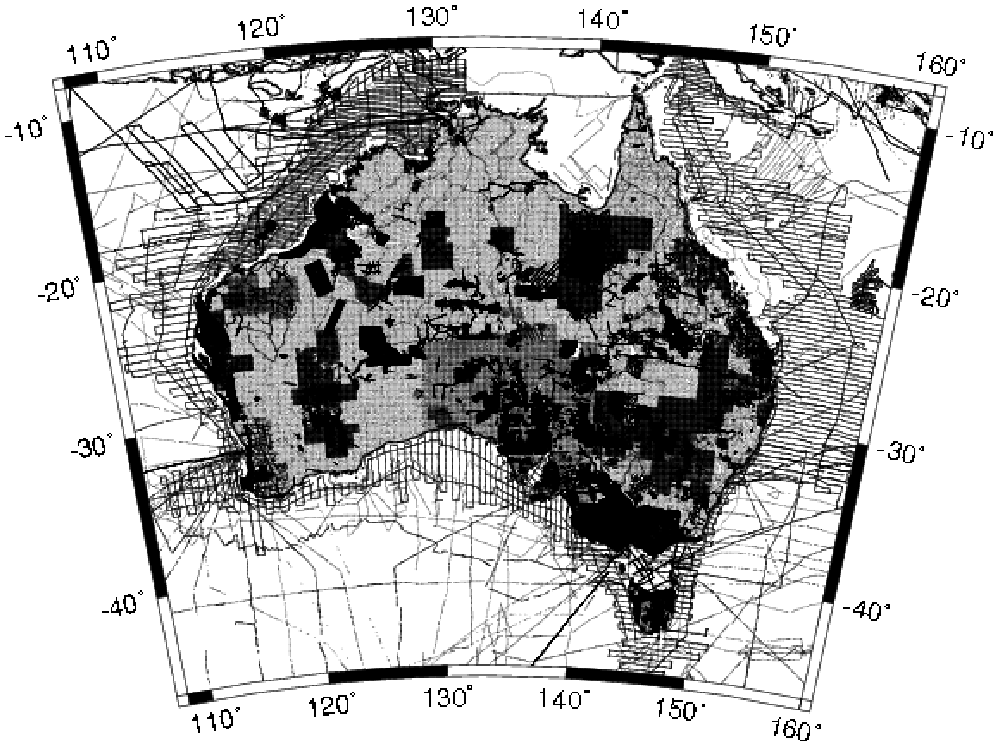

Fig 1. Coverage of the 1,245,026 Australian land and marine gravity observations in the July 2007 data release from Geoscience Australia (Lambert projection)

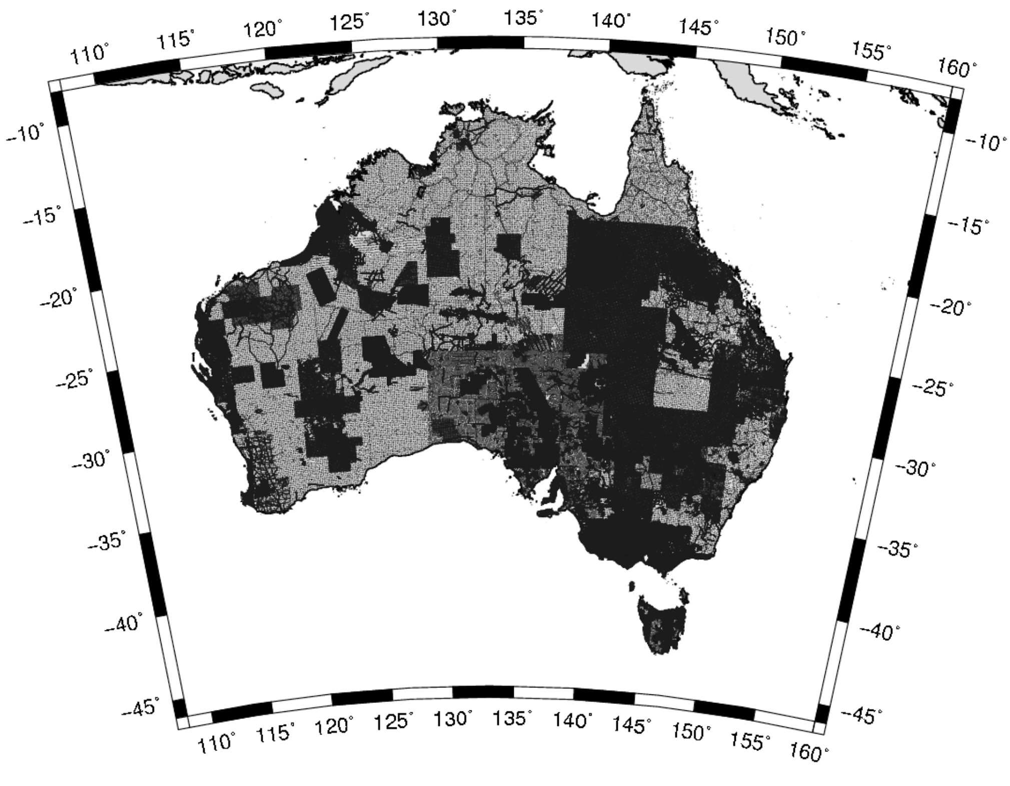

Fig 2. Coverage of the 1,304,904 Australian land gravity observations in the June 2008 data release from Geoscience Australia (Lambert projection)

horizontal coordinates on the Geocentric Datum of Australia 1994 (GDA94), but no information is given about the transformation method used (if at all). For instance, pre-1966 gravity observations were collected before the nation-wide adoption of the Australian Geodetic Datum, so transformation to GDA94 will technically be impossible. Featherstone (1995) shows that the use of a non-geocentric datum to compute gravity anomalies causes small (0.1 mGal), yet systematic, errors in the computed gravity anomalies.

The ship-track gravity data around Australia (Symonds and Willcox 1976, Mather et al. 1976) are far more problematic. In AUSGeoid98, these data were [incorrectly] assumed to have previously been crossover adjusted (Featherstone et al. 2001). However, they were not, as shown through comparison with multi-mission satellite altimetry data (Featherstone, in press) or via point-mass modelling (Claessens et al. 2001). Indeed, the later 'validation' of EGM2008 using AUSGeoid98 clearly shows that the erroneous ship-track data have distorted AUSGeoid98 in offshore regions. Therefore, rather than 'validating' EGM2008 using AUSGeoid98, EGM2008 is 'invalidating' AUSGeoid98 in some coastal areas, but this problem has been known for some time now.

Petkovic et al. (2001) readjusted these ship-track data [note that AUSGeoid98 used the 1996 data release], but the ship-tracks were constrained to Sandwell and Smith's satellite-altimeter-derived gravity anomalies (version unknown). Since satellite-altimeter data are notoriously problematic in the coastal zone (e.g., Andersen and Knudsen 2000, Deng and Featherstone 2006), it is highly likely that the so-adjusted Australian ship-track gravity data have become distorted in this region. For instance, Petkovic (2004, pers comm) commented that they had significant problems in the Bass Straight between the Australian mainland and Tasmania. Therefore, the evaluations using Australian ship-track data should be treated very sceptically. We did attempt to crossover-adjust the Australian ship-track observations ourselves, but the adjustment failed because it is very poorly conditioned in many places because of the large distances involved and the scarcity of ship tracks (cf. Fig. 1).

Later, it will be shown that the ship-track gravity observations in the 2007 Australian gravity database are not the readjusted values from Petkovic et al. (2001). This works on the assumption that the Australian ship-track data have *not* been used in the development of EGM2008, where some tracks show large consistent offsets. Moreover, these are consistent with the differences shown in Featherstone (in press).

As such, the Australian ship-track data simply should not be used to try to 'validate' EGM2008. Instead, EGM2008 invalidates these data. As stated, the ship-track gravity observations have all been removed in the 2008 release of the gravity database, during the review cycle of Featherstone (in press).

Many of the land gravity observations in the July 2008 release of the Australian gravity database have not been used in the computation of EGM2008. Therefore, these observations can provide a more independent validation of EGM2008. The EGM2008 development team (Factor 2008, pers. comm.) provided us with the horizontal locations of all 905,483 land gravity observations that were used in the computation of EGM2008. Matching of these locations (after application of a datum shift to the GDA94) with locations of observations in the 2008 gravity database revealed that 548,787 points in the Australian gravity database do not match any observation used in EGM2008 to within 100m. These form an independent set of observations (Fig. 3).

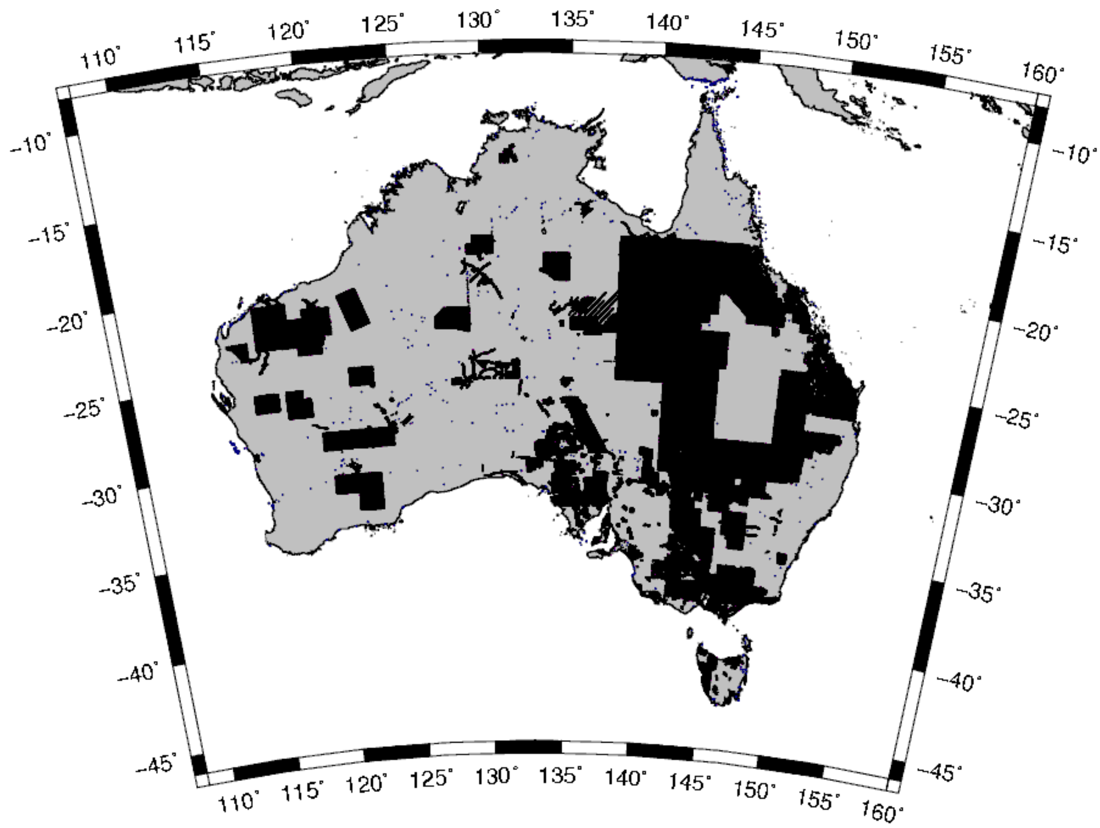

Fig 3. Coverage of the 548,787 Australian land and marine gravity observations in the June 2008 data release from Geoscience Australia that were not used in the computation of EGM2008 (Lambert projection)

It was also found that 156,269 observations used in the computation of EGM2008 do not match any of the points in the Australian gravity database to within 100 m. The reason for this is probably that NGA holds gravity observations not stored in the Australian gravity data base.

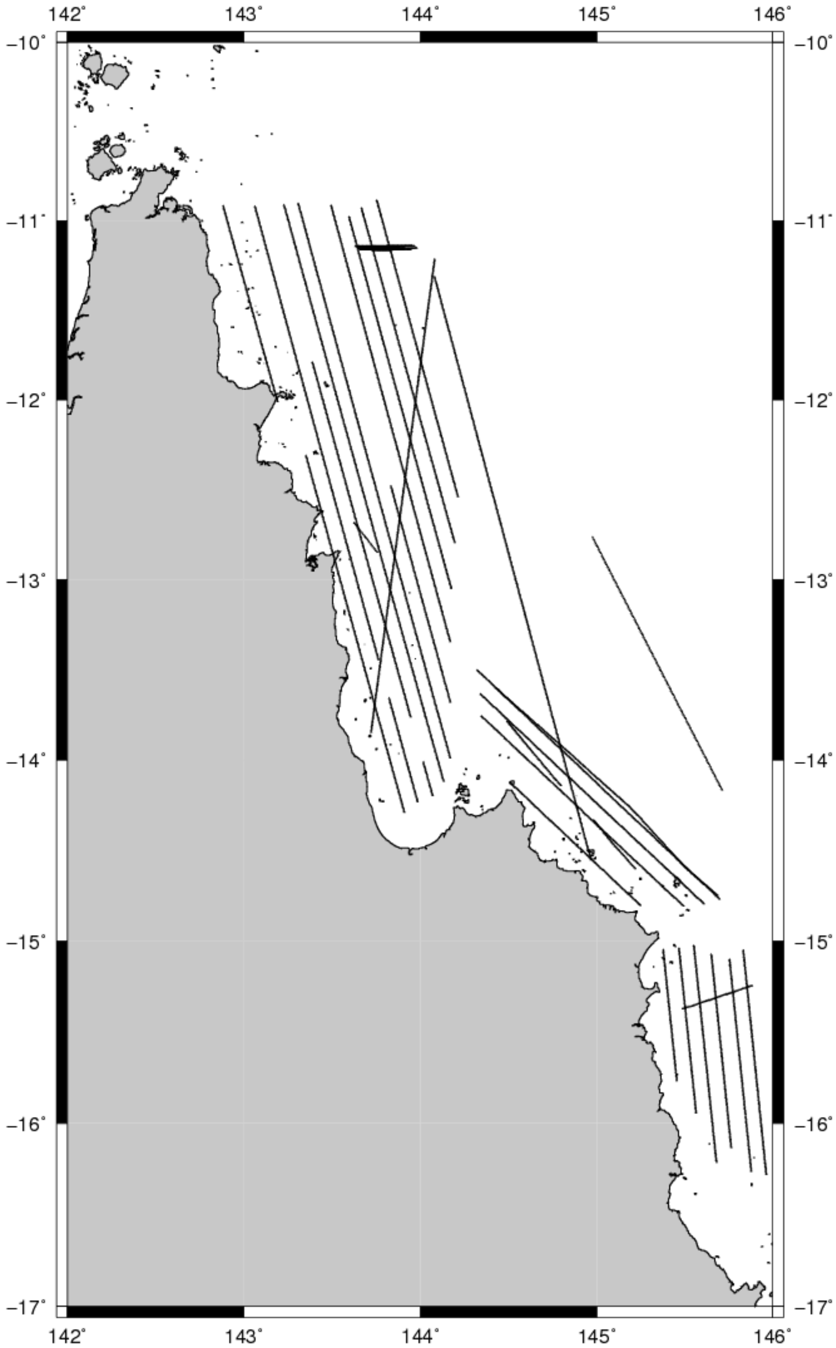

Fig 4. Coverage of the 6,725 observations from the Barrier Reef Airborne Gravity Survey 1999 (BRAGS'99) (Mercator projection)

An additional dataset of gravity observations used in this study consists of airborne gravimetry from the Barrier Reef Airborne Gravity Survey (BRAGS'99) (Sproule et al. 2001), provided by Forsberg (2004, pers. comm.). This survey covers an area over the shallow waters of the Great Barrier Reef to the north-east of Australia (Fig. 4). The airborne gravity data were taken at a flight altitude of ~500 m and low-pass filtering was applied with filter parameters set such that the survey has a spatial resolution of 8 km. Sproule et al. (2001) estimate the noise level of the data is 2.8 mGal, based on a crossover analysis. Molodensky-type free-air gravity anomalies were computed from the raw gravity observations at flight altitude to allow for a comparison with EGM2008 at flight altitude.

2.2 Australian GPS-levelling data

Although Featherstone et al. (2001) and Featherstone and Guo (2001) used a set of 1013 GPS-levelling data across Australia (Fig. 5) to 'validate' AUSGeoid98, it has since been discovered that an unknown number of these ellipsoidal heights were observed *indirectly*. The term indirectly means that a GPS survey was tied to a base

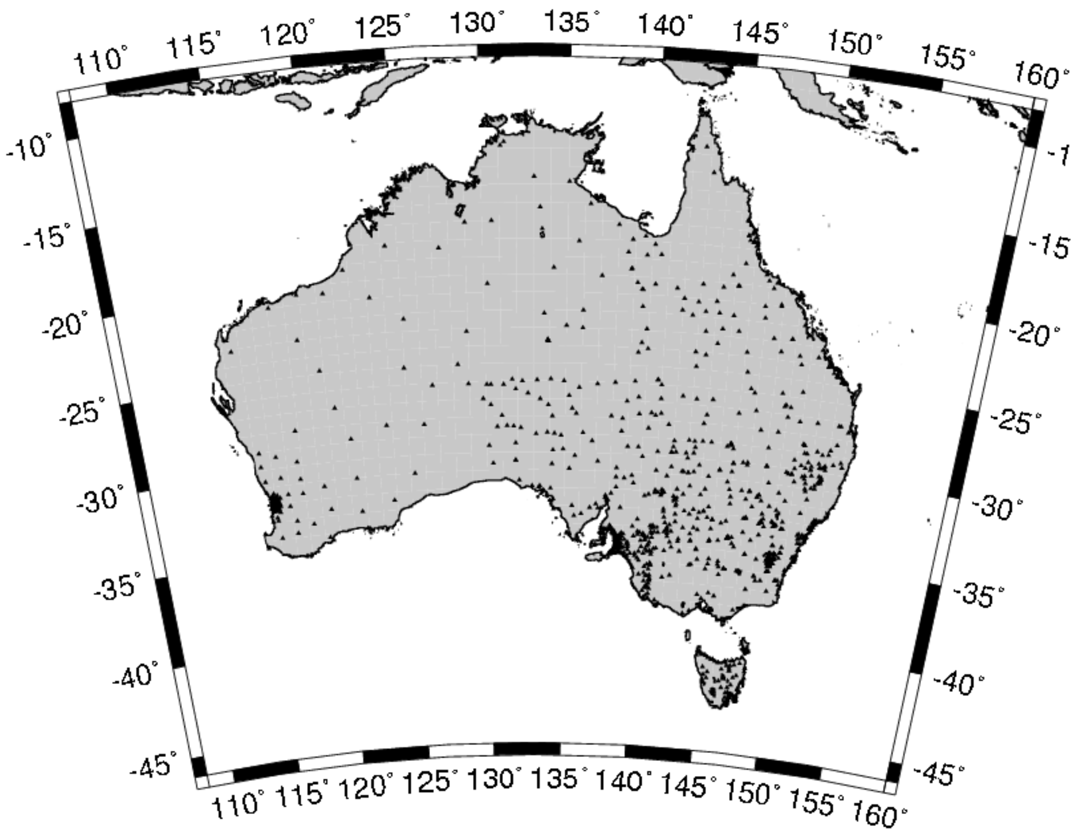

Fig 5. Coverage of the older 1013 GPS-levelling points (Lambert projection)

station whose ellipsoidal height had been calculated from the AHD height and a quasi/geoid model. Although the ellipsoidal height at the other end of the baseline was used to populate this database of 1013 points, they are considered 'impure' because the starting ellipsoidal height will have been contaminated by AHD and quasi/geoid model errors, thus propagating into some of the 1013 heights used.

Since then, a newer 'pure' GPS ellipsoidal height dataset has been observed at 254 junction points of the AHD (cf. Soltanpour et al. 2006, Featherstone and Sproule 2006). These ellipsoidal heights (Fig.6) used typically five or more days of observations and most were post-processed with the AUSPOS on-line GPS processing service (http://www.ga.gov.au/bin/gps.pl). However, there are still some problems with these ellipsoidal heights because they are not all on the same realisation of the International Terrestrial Reference Frame (ITRF). Current metadata prevents this being rectified immediately by transformation (e.g., just ITRF is specified for some States/Territories instead of the exact ITRF realisation and the epoch used for the GPS data processing). The differences are estimated to be a few centimetres.

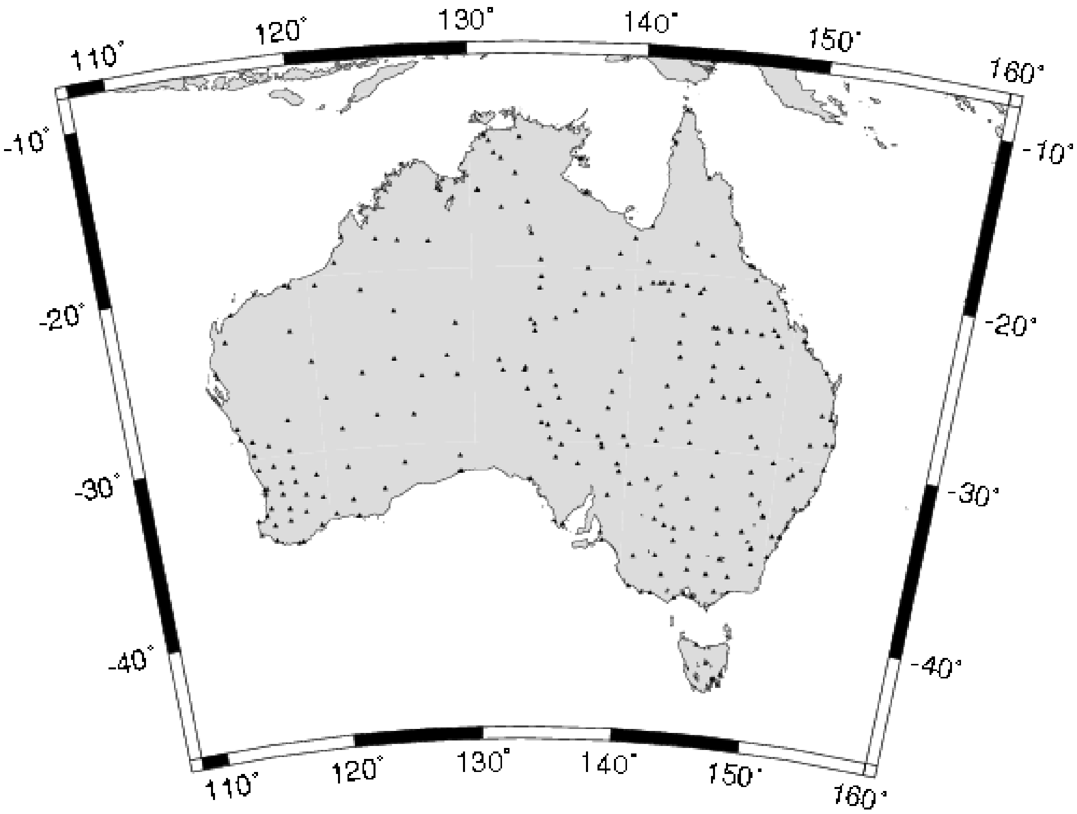

Fig 6. Coverage of the newer 254 GPS-levelling points (Lambert projection).

These and other GPS observations will be reprocessed by Geoscience Australia [the custodian of these data] to bring them to ITRF 2005 (Altamimi et al. 2007), thus homogenising this 254-point dataset, as well as including newer GPS surveys (Johnston 2007, pers comm). However, this reprocessed dataset is not yet available, so we have had to work with the same data used by Soltanpour et al. (2006) and Featherstone and Sproule (2006).

Two more reliable GPS-levelling datasets available in Australia are over the regional areas of the southwest seismic zone (SWSZ) in Western Australia (cf. Featherstone 2004, Featherstone et al. 2004) and the South Australian Seismic Zone (SASZ) near Adelaide. While they do not cover huge areas (Fig. 7), the dual-frequency GPS data were collected for at least seven days per station (some for a month) and processed with Bernese v5.0 and IGS (International GNSS Service) precise 'final orbits' (e.g., Featherstone et al. 2004). The levelled heights were later collected by the relevant State geodetic agencies by two-way closed levelling to the nearest AHD benchmarks.

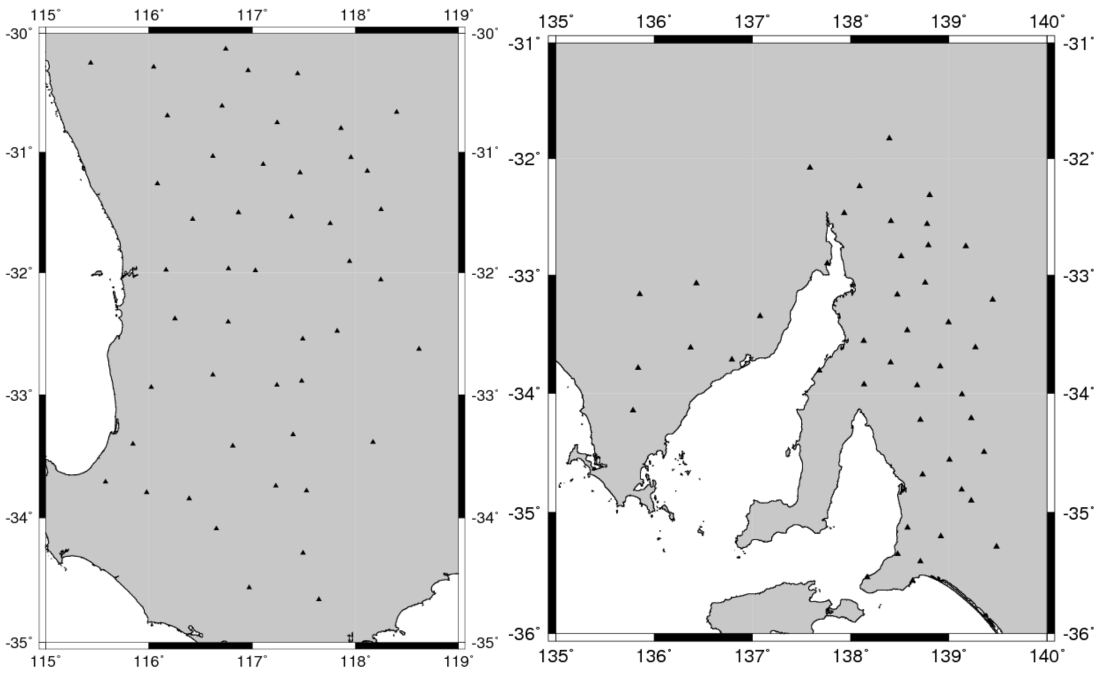

Fig 7. Coverage of the **(a: left)** 48 GPS-levelling points in the SWSZ, and **(b: right)** 45 GPS-levelling points in the SASZ (Mercator projections).

The final GPS-levelling dataset used in this study is a set of 243 points in Western Australia (Fig. 8). The GPS observations for this dataset were taken between 1995 and 2007 over a period of at least six hours using dual-frequency receivers. The data were processed with Bernese v5.0 and IGS precise 'final' orbits in the ITRF2005 reference frame, and corrected for ocean tide loading effects. The mean of the estimated formal standard deviations of the ellipsoidal heights is 2.0 mm, though this is probably overoptimistic by a factor of 5 to 10. .

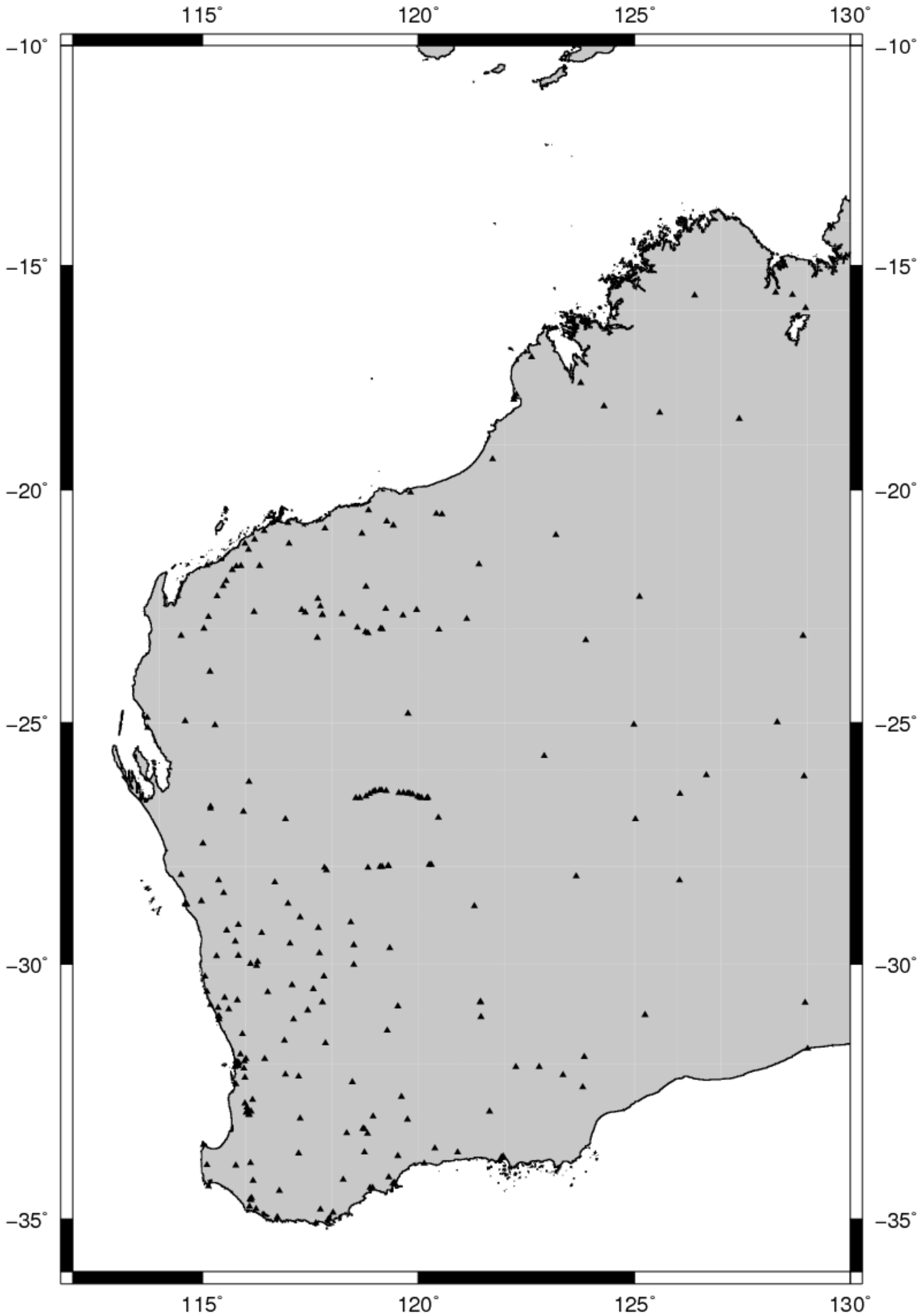

Fig 8. Coverage of the 243 GPS-levelling points in Western Australia (Mercator projection)

Due to the differences in processing strategies and perceived quality of the different GPS-levelling datasets, as with the gravity data, the evaluation of EGM2008 is conducted for the separate datasets.

Of more concern in any GPS-levelling evaluation in Australia is the quality of the levelling data. The AHD is principally a third-order vertical datum (Roelse et al. 1971, 1975; Morgan 1992), where third-order spirit-levelling measurements in Australia allow for a 12 root km millimetre misclose (ICSM 2007), which is considerably worse than in most parts of Europe (Adam et al. 1999) and North America (Zilkoski et al. 1992) for example. Moreover, the AHD was realised by a fixed-network adjustment constrained to mean sea level (MSL) observed over a three-year period at 30 tide gauges around the Australian mainland and two tide gauges in Tasmania (e.g., Featherstone 2001). Finally, the AHD uses a truncated version of the normal orthometric height system (Roelse et al. 1971, 1975; Featherstone and Kuhn 2006).

The largest problem in the spirit-levelled and MSL-fixed-adjusted AHD heights is a predominantly north-south-oriented distortion of around 1-2m (Featherstone 2001, 2004, 2006, 2007), which presents the major limitation to using GPS-levelling in Australia to 'validate' any quasigeoid model. We believe that most of this distortion has been caused by the constraints to MSL, in which mainly north-south-oriented sea-surface topography around Australia causes the adjustment to be north-south-tilted with respect to an equipotential surface. As such, the GPS-levelling 'validation' presented later should be given less weight, but some interpretation of the north-south, AHD-induced, tilt in the differences will be included in an attempt to rate their relative credibility.

To overcome the distortions in the AHD, we readjusted the levelling observations, provided by Geoscience Australia (Johnston 2007, pers. comm.), fixing the height of one tide-gauge only, so that the network is minimally constrained. The normal orthometric heights of the national and Western Australian GPS-levelling datasets were fixed to the tide gauge at Albany on Western Australia's south coast, while the normal orthometric heights of the South Australian Seismic Zone dataset were fixed to the tide gauge at Port Lincoln on the Eyre Peninsula. These minimally constrained readjusted heights do not show the north-south oriented distortion that the AHD contains and are therefore more useful for validation of EGM2008.

2.3 Australian astrogeodetic vertical deflections

During correspondence with the EGM2008 development team, we provided them with 1080 Australian astrogeodetically observed vertical deflections/deviations (Fig. 9). Vertical deflection data, being higher order derivatives of the Earth's disturbing potential, provide a better validation of high-degree GGMs (cf. Jekeli 1999; Müller et al. 2007a; Hirt et al. 2007; Featherstone and Morgan 2008). The provenance and estimated quality of these data are described in Featherstone (2006, 2007), Featherstone and Morgan (2007) and Featherstone and Lichti (2008). The accuracy is crudely estimated to be around one arc-second in each deflection component, but this is difficult to ascertain as the original records no longer seem to exist. [At least, neither we nor Geoscience Australia could locate them.]

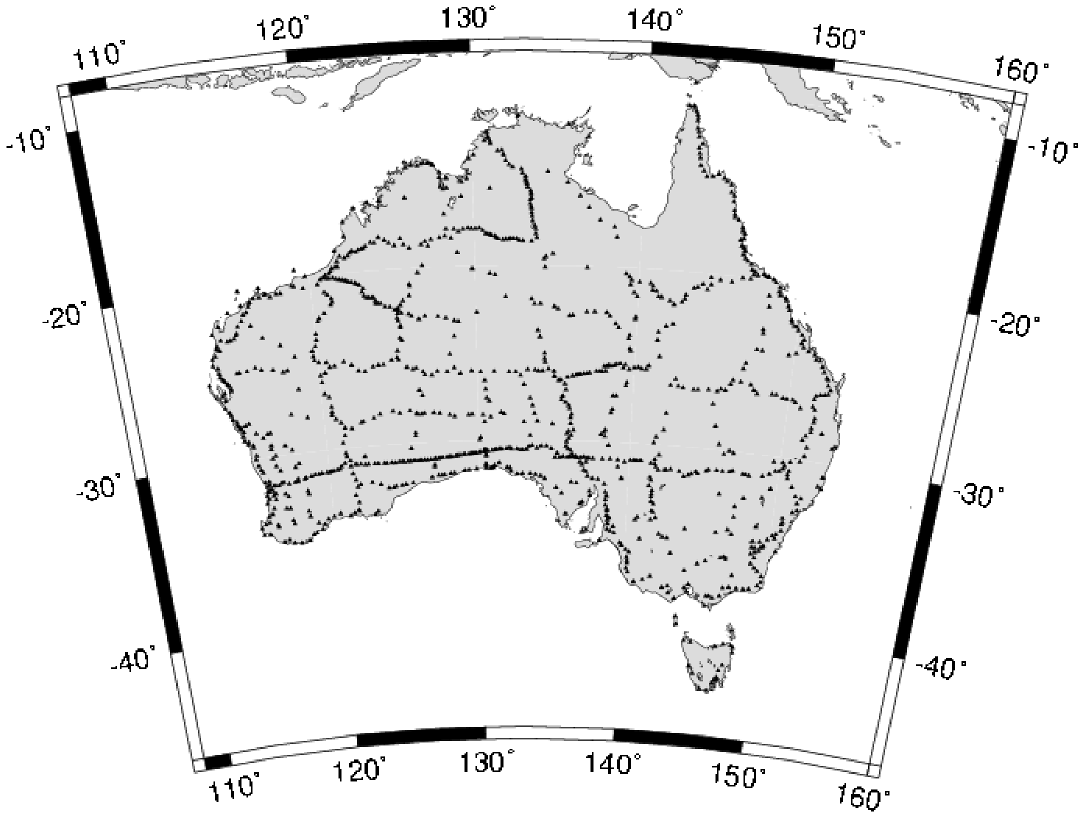

Fig 9. Coverage of the 1080 astrogeodetically observed vertical deflections [Lambert projection]

As such, the main problem with the reliability of the Australian vertical deflection is the vintage of the data (cf. Kearsley 1976). Most, if not all [no dates are available], observations were made before or during the establishment of the AGD66 (i.e., pre-1966; Bomford 1967), so are subject to timing, instrumental and star-almanac errors over 40 years ago (cf. Featherstone and Lichti 2008). While new digital zenith cameras, coupled with GPS, are now producing high precision vertical deflection data (Hirt and Bürki 2002; Hirt and Seeber 2007; Müller et al. 2007b), no such data are available in Australia, yet. As such, the Australian 'validation' of EGM2008 using vertical deflections must account for the poorer quality of the data.

2.4 AUSGeoid98

The AUSGeoid98 regional gravimetric quasigeoid model (Featherstone et al., 2001) remains the nationally recognised standard in Australia for the transformation of GPS-derived ellipsoidal heights to the AHD, despite being computed nearly a decade ago. It refers to the GRS80 ellipsoid. A new model is currently being computed based on EGM2008 (e.g., Featherstone et al. 2007). However, it is informative to compare EGM2008 with AUSGeoid98 to see if there are any spatial differences that warrant further investigation. Indeed, this 'validation' highlights known problems with AUSGeoid98 in marine areas, as well as identifying some previously unknown ones. As such, EGM2008 'invalidates' AUSGeoid98 in some regions.

AUSGeoid98 (Fig. 10) was computed from EGM96 (Lemoine et al. 1998) to degree and order 360, the 1996 release of Geoscience Australia's land and marine gravity data (note the earlier comments on the quality of the Australian ship-track gravity data), marine gravity anomalies from Sandwell and Smith (1997; version 9.2) warped to fit the [incorrect] ship-track data using least-squares collocation (Kirby and Forsberg 1998), and terrain corrections from the version 1 Australian digital elevation model (DEM). The latter had to be generalised to 27 arc-seconds because of errors in the DEM (Kirby and Featherstone 1999, 2001).

The computation method chosen for AUSGeoid98 was a hybrid of the remove-compute-restore and deterministically modified kernel approach with the degree-20 Featherstone et al. (1998) kernel for a 1.5 degree spherical cap. The zero-degree term of ~1m (including any vertical datum offset for the AHD) was estimated by computing a mean difference between the 1013 GPS-levelling data described earlier and AUSGeoid98, but no tilts were estimated nor applied. AUSGeoid98 is shown in Fig. 10.

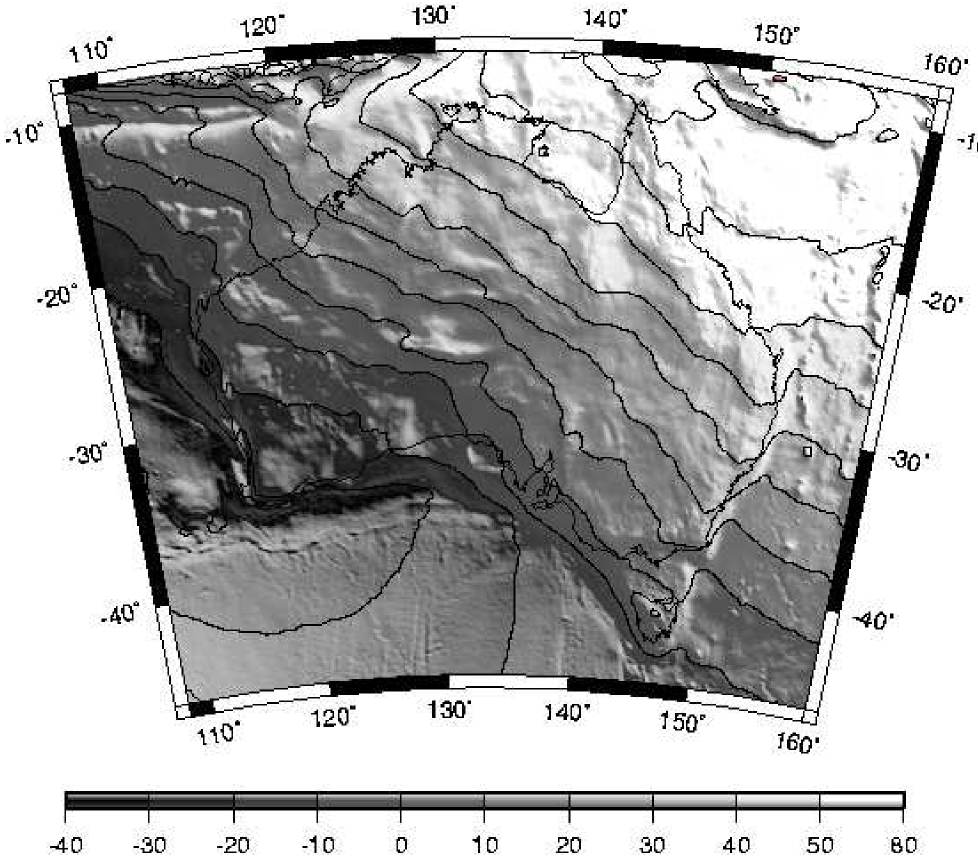

Fig 10. AUSGeoid98 with respect to GRS80 [Lambert projection; units in metres]

3 Results

All gravity-field-related quantities computed from PGM2007A and EGM2008 in this Australian 'validation' used the `HARMONIC_SYNTH.f` FORTRAN software provided by the EGM2008 development team. This software was adapted slightly so as to run on the Western Australian Centre for Geodesy's Sun UNIX workstations. It was tested using the sample datasets, also provided by the EGM2008 development team, and compared with our in-house code, showing that the insignificant differences were only due to computer-dependent algebra.

In order to enforce compatibility with the GRS80 ellipsoid used for all the Australian data, GRS80 parameters were set in the 'parameter input' files for the `HARMONIC_SYNTH.f` so that the zero-degree term and scaling of the even-degree coefficients were computed according to the algorithm in Lemoine et al. (1998). [Note that the previous Australian treatment of the zero degree term, neglecting differences in potential (Kirby and Featherstone 1997) is incorrect.]

3.1 Comparisons with Australian gravity data

First, the computer time required to evaluate a GGM up to degree and order 2160 at a large number of scattered points is very long, even though the accelerated routines of Holmes and Featherstone (2002) are used in `HARMONIC_SYNTH.f`. Due to the large number of gravity observations (~1.3 million), and because gravity observations are generally irregularly spaced, spherical harmonic recursions along parallels cannot be utilised to accelerate the computations. Some of the results presented below for the Australian land gravity anomalies have therefore used pre-evaluation of PGM2007A and EGM2008 on a 2 arc-minute grid, followed by bicubic interpolation to the gravity observations' locations.

The `HARMONIC_SYNTH.f` software needs to 'know' the 3D location of the gravity observation with respect to the geometrical surface of the reference ellipsoid used (GRS80 in the case of this Australian 'validation'). This will not yield gravity disturbances because `HARMONIC_SYNTH.f` is configured to deliver gravity anomalies at the point of observation (i.e., Molodensky-type free-air gravity anomalies). However, since only AHD heights of gravity observations are available in the Australian national gravity database, height anomalies (quasigeoid heights) were first computed at the gravity observation locations from PGM2007A/EGM2008, and these were added to the AHD heights to obtain an ellipsoidal height for each gravity observations. These ellipsoidal heights were used to compute (linearly approximated) free-air gravity anomalies at the gravity observation points via the fundamental equation of physical geodesy (boundary condition). Tables 1 and 2 show results from comparisons of various GGMs with the 2007 and 2008 releases of the Australian gravity database, respectively.

The majority of the free-air gravity anomalies computed from PGM2007A and EGM2008 over land show a good correspondence with the land free-air gravity anomalies (Fig. 11), even in areas where there are large gravity anomaly gradients such as in central Australia. Figure 11 shows that the largest differences are in the mountainous regions (cf. Fig. 12), notably in Tasmania and along the Great Dividing Range along the eastern coastline. This could be caused by erroneous Australian data, but internal validation (Sproule et al. 2006) does not show such a problem.

model	*# points*	*degree*	*max*	*min*	*mean*	*std*
raw data (all data)	1,245,026	n/a	+931.029	–229.847	+4.292	±26.565
PGM2007A (land data)	1,095,065	2160	+68.741	–79.860	–0.296	±4.954
EGM2008 (land data) Fig. 11	1,095,065	2160	+68.728	–78.169	–0.296	±4.924
EGM96 (land data)	1,095,065	360	+111.393	–95.202	–0.307	±11.756
PGM2007A (marine data)	149,961	2160	+972.004	–171.687	–0.810	±12.104
EGM2008 (marine data) Fig. 15	149,961	2160	+970.963	–171.681	–0.748	±12.034
EGM96 (marine data)	149,961	360	+988.674	–124.895	–1.278	±17.641
PGM2007A (all data)	1,245,026	2160	+972.004	–171.687	–0.358	±6.266
EGM2008 (all data)	1,245,026	2160	+970.963	–171.681	–0.350	±6.226
EGM96 (all data)	1,245,026	360	+988.674	–124.895	–0.424	±12.611

Table 1 Fit of the geopotential models to Australian free-air gravity anomalies in the 2007 release database [units in mGal]

model	*# points*	*degree*	*max*	*min*	*mean*	*std*
PGM2007A (all data)	1,304,904	2160	+192.523	–88.485	+0.486	±5.557
EGM2008 (all data)	1,304,904	2160	+192.294	–88.756	+0.498	±5.541
EGM96 (all data)	1,304,904	2160	+189.775	–110.010	+0.296	±11.678
EGM2008 (independent data)	548,787	2160	+191.677	–67.641	+0.566	±6.373

Table 2 Fit of the geopotential models to Australian free-air gravity anomalies in the 2008 release database [units in mGal]

It can be seen from Fig. 13 that differences between EGM2008 and gravity observations at high altitude (> 1000 m) are more dispersed than those at lower altitudes. Figure 13 also shows that the differences have a small negative correlation with terrain height. Curiously, some surveys in mountainous regions that are part of the Australian gravity database appear to show a much larger correlation with terrain height than the total database. This requires further investigation.

The larger differences in mountainous areas are more likely to be a combination of problems modelling the variable gravity field in these mountainous regions (topographical and downward continuation corrections) and the omission error in EGM2008, where gravity field variations with a wavelength shorter than 5 arc-minutes will not be modelled. The omission error can be seen in Fig. 11, where a 'cantaloupe' pattern can be discerned throughout the image. Figure 14 shows a zoom-in on the southern Australian Alps for the GPS-coordinated gravity data from the

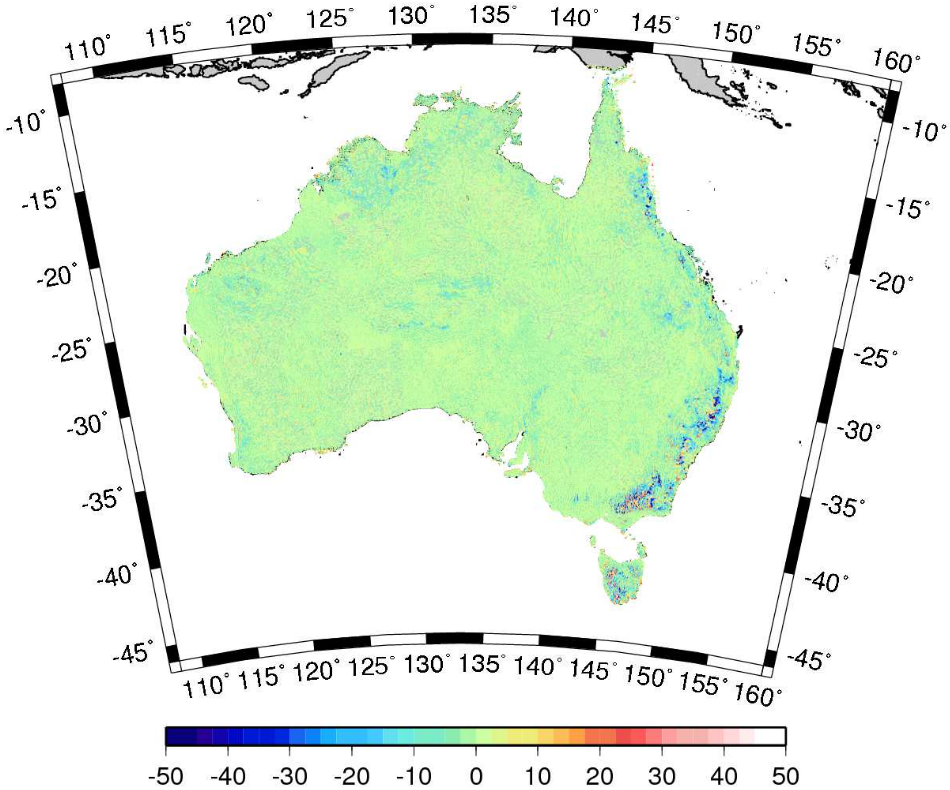

Fig 11. Differences between free-air gravity anomalies from EGM2008 and Australian free-air gravity anomalies on land [Lambert projection; units in mGal].

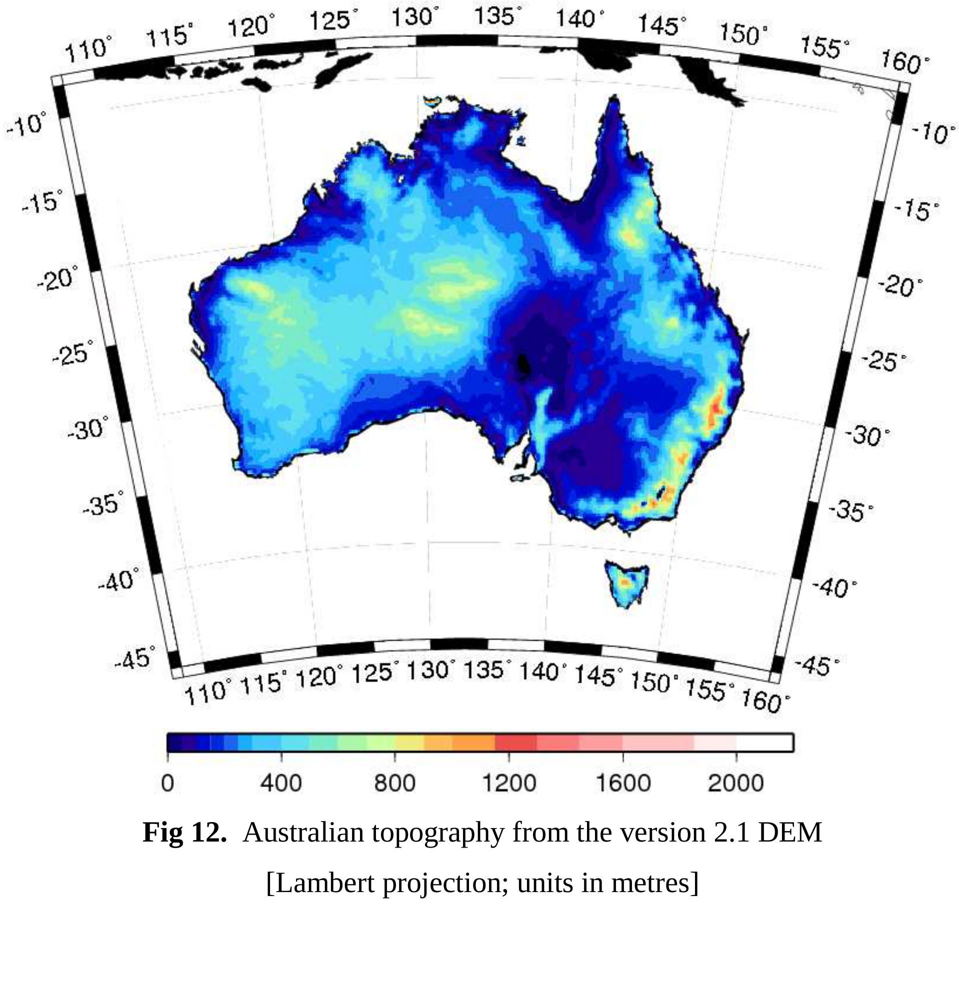

Fig 12. Australian topography from the version 2.1 DEM [Lambert projection; units in metres]

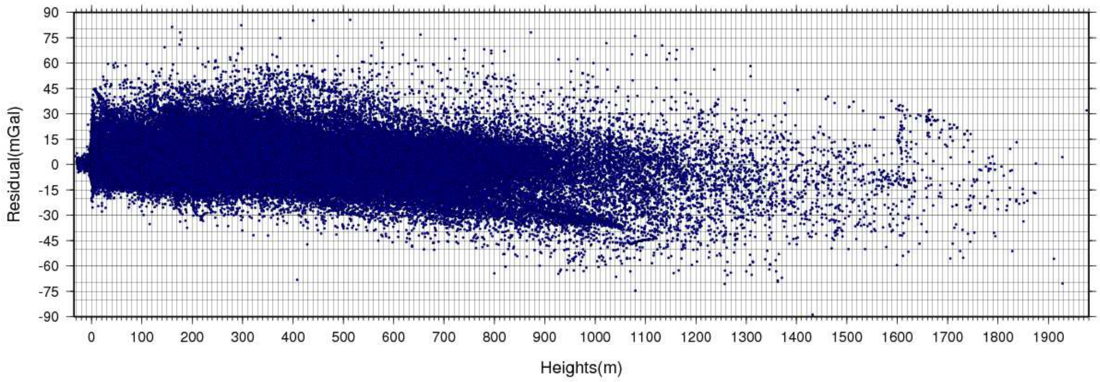

Fig 13. Differences between free-air gravity anomalies from EGM2008 and the 2008 release of the Australian gravity database as a function of terrain height

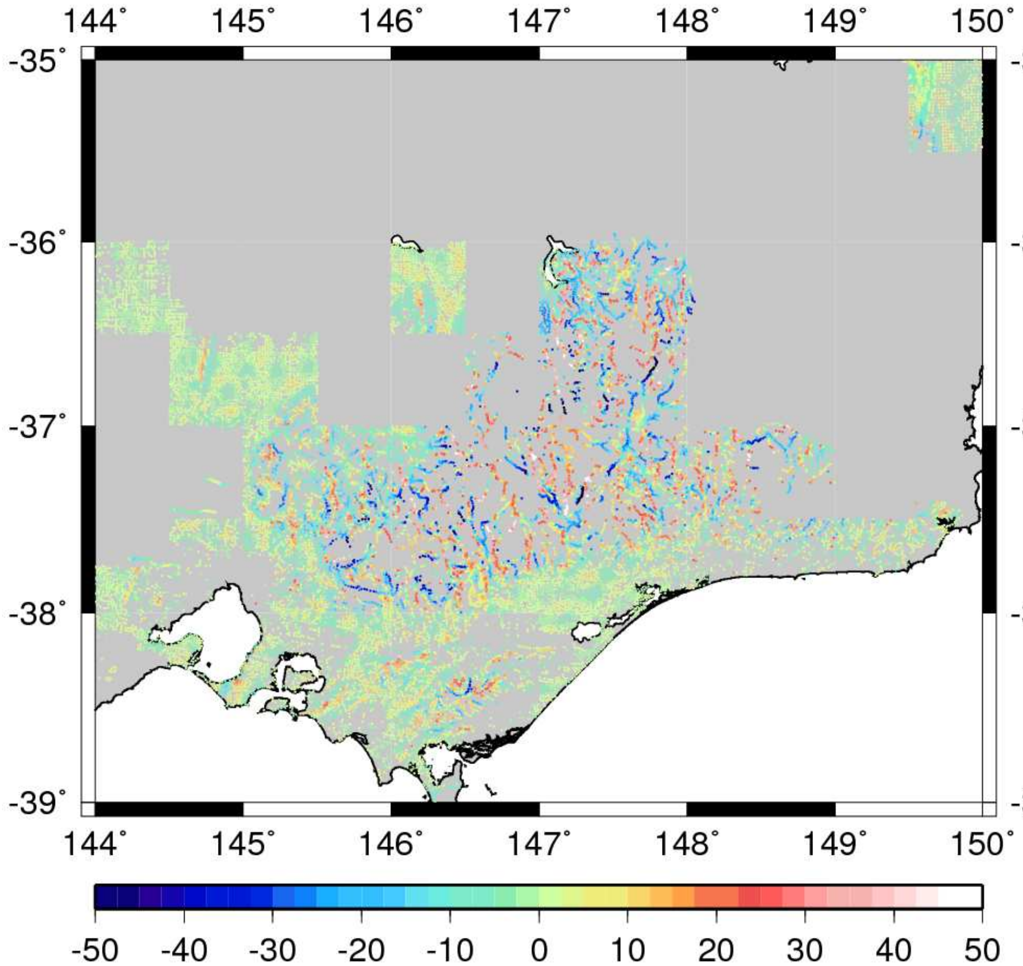

Fig 14. Differences between free-air gravity anomalies from PGM2007A and Australian free-air gravity anomalies over the Australian Alps [Mercator projection; units in mGal]

2007 data release. We suspect that these are not GPS-coordinated surveys, which are more usually conducted on a regular grid, and this is probably an error in the metadata in the 2007 data release.

There are also some larger differences in Fig. 11 close to the coastline (the land gravity database also includes a few hundred sea-bottom gravity observations and gravity observations made on sandbanks at low tide). We will revisit this later, but it is plausible that the satellite altimeter-derived gravity anomalies used in PGM2007A and EGM2008 remain in error in the problematic coastal zone (cf. Deng and Featherstone 2006).

From Fig. 15, the bulk of the free-air gravity anomalies computed from EGM2008 agree with the ship-track gravity anomalies to within ~5 mGal. However, several ship tracks show considerable biases of over 50 mGal (reaching over 900 mGal; Table 1), as was noted by Featherstone et al. (2001) who deleted most but not all of these (see later). This confirms that the Australian ship-track gravity database

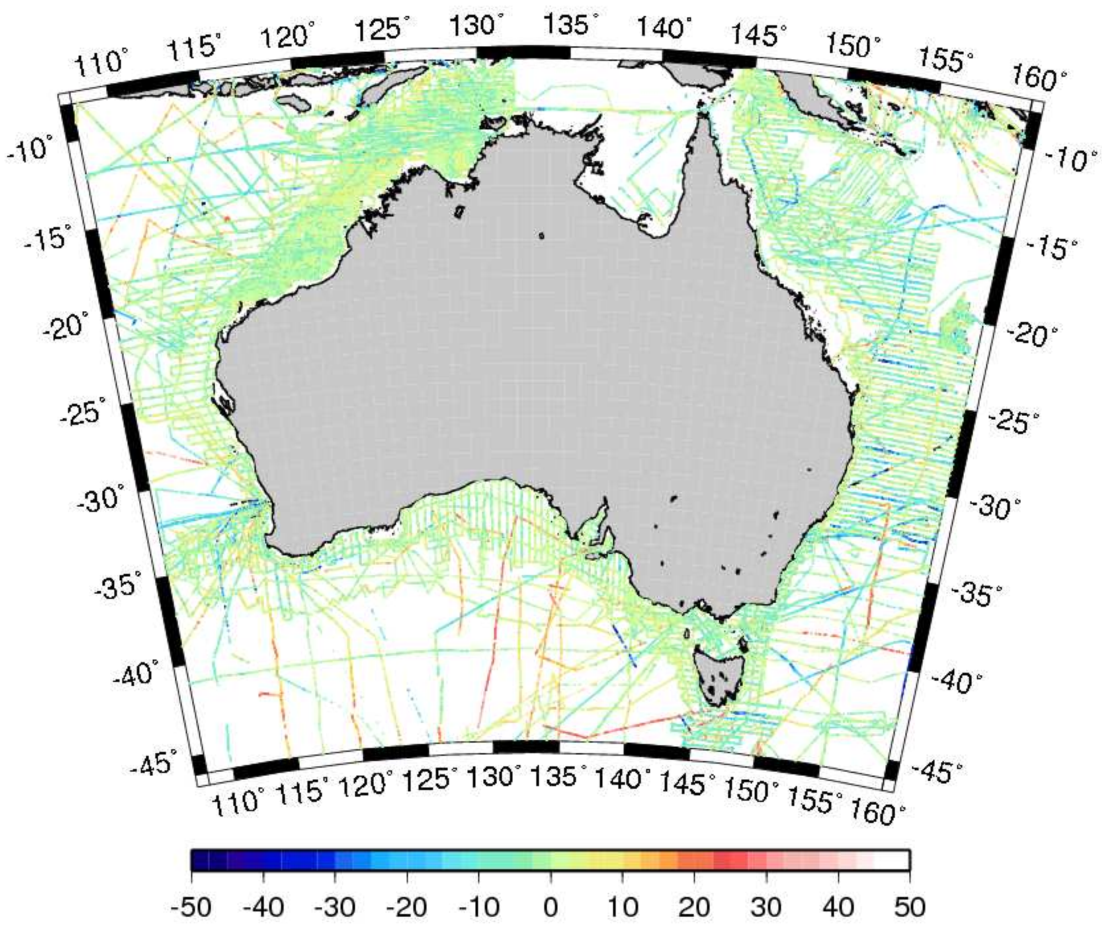

Fig 15. Differences between free-air gravity anomalies from EGM2008 and Australian ship-track gravity anomalies [Lambert projection; units in mGal].

has not been crossover adjusted. Though uncertain, we suspect that no ship-track data were used in EGM2008, so these differences essentially reflect the difference between altimeter-derived gravity anomalies in EGM2008 and the ship-tracks. Unlike the comparison in Featherstone (2003), large differences are not seen near the coast, indicating that the altimeter data have been improved in these regions.

The airborne gravity observations show a good agreement with EGM2008 (Fig. 16), with a standard deviation of the differences of 4.0 mGal (Table 3). This is only slightly larger than the expected noise level of the airborne gravity observations,

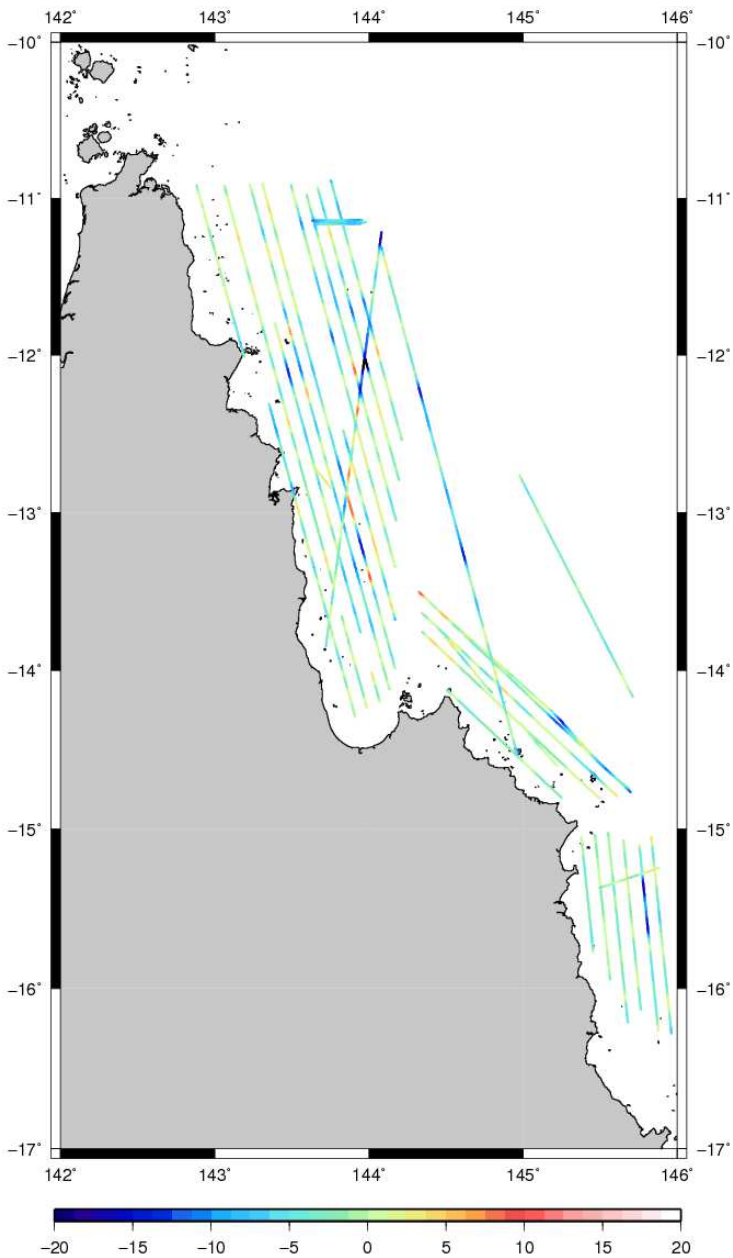

Fig 16. Differences between gravity anomalies from EGM2008 and airborne gravity anomalies at flight height [Lambert projection; units in mGal].

model	*# points*	*degree*	*max*	*min*	*mean*	*std*
raw data	6,725	n/a	212.008	–88.205	+89.038	±65.109
EGM96	6,725	360	41.356	–88.526	–13.107	±22.324
PGM2007A	6,725	2160	12.830	–19.682	–3.842	±3.962
EGM2008	6,725	2160	13.239	–22.434	–2.495	±3.954

Table 3 Descriptive statistics of the airborne gravity anomalies and of the relative differences with gravity anomalies computed from various GGMs [units in mGal]

which is estimated to be 2.8 mGal from crossover analysis (Sproule et al., 2001). Figure 16 shows that the differences are mainly of a very short wavelength nature, reflecting the low-pass filtering that is applied to airborne gravimetry. It can be seen in Table 3 that the comparisons with PGM2007A and EGM2008 give similar statistics and are a significant improvement on EGM96.

3.2 Comparisons with AUSGeoid98

Height anomalies (quasigeoid heights) were computed from PGM2007A and EGM2008 up to degree and order 2160 on a 2' x 2' grid and compared directly with the gravimetric-only AUSGeoid98 solution (Featherstone et al. 2001). This provides some of the most interesting (to us) results (Fig. 17 and Table 4).

	PGM2007A minus AUSGeoid98	*EGM2008 minus AUSGeoid98*
Number of points	1,781,101	1,781,101
% of area	3.842	3.842
Min	-2.472 m (120.917˚E, 10.633˚S)	-2.476 m (159.633˚E, 9.900˚S)
Max	13.062 m (125.217˚E, 8.567˚S)	12.983 m (147.367˚E, 8.400˚S)
Arithmetic mean	0.057 m	0.064 m
Area mean	0.072 m	0.081 m
Arithmetic RMS	0.458 m	0.462 m
Area RMS	0.504 m	0.509 m
Arithmetic STD	0.454 m	0.458 m
Area STD	0.499 m	0.504 m

Table 4 Descriptive statistics of the relative differences between quasigeoid heights computed from PGM2007A/EGM2008 and AUSGeoid98 on a 2’x2’ grid.

The differences are mainly of a medium-wavelength nature over the Australian mainland (Fig. 17). From a comparison with the differences between EGM96 (used in AUSGeoid98) and GGM02C (Tapley et al. 2005) (Fig. 18), these differences seem to come mostly from the GRACE data. The largest medium-wavelength difference in Fig. 17 appears in the Gulf of Carpentaria (centred on 140˚E, 12˚S), where only a very limited number of ship-track gravity observations is available (cf. Figs. 1 and 15). It could be that the altimeter-derived gravity anomalies are in error in this shallow sea. However, Tregoning et al. (2008) show that a weather-driven annual sea surface height variation of ~40 cm amplitude affects GRACE gravity field solutions. Therefore, the differences in this region are more likely due to aliasing in the GGMs, but errors in the altimeter data cannot be ruled out. Clearly, this needs further attention. The differences in Fig. 17 to the north of Australia are because no gravity data were available in this region for the computation of AUSGeoid98.

Figure 19 shows the differences between height anomalies from PGM2007A and EGM2008 over the AUSGeoid98 area. The differences over land are in the range of ±20 cm and mainly of medium wavelength nature. This is due to the use of a different GRACE-derived satellite only GGMs in PGM2007A and EGM2008. Over the oceans, a short wavelength noise is also visible. This is due to the use of different satellite altimeter gravity anomalies in PGM2007A and EGM2008. The difference over the Gulf of Carpentaria is now much less, suggesting that the aliasing was larger in EGM96. However, care still needs to be exercised in this region.

The next most noticeable features in Fig. 17 are the stripes offshore (e.g., to the east of Queensland and northern New South Wales). These stripes are due to the unadjusted ship-track data used in AUSGeoid98 (discussed earlier). We are unsure whether ship-track data were used in the computation of EGM2008, but from these analyses it appears not, or if they were, they have been crossover adjusted properly.

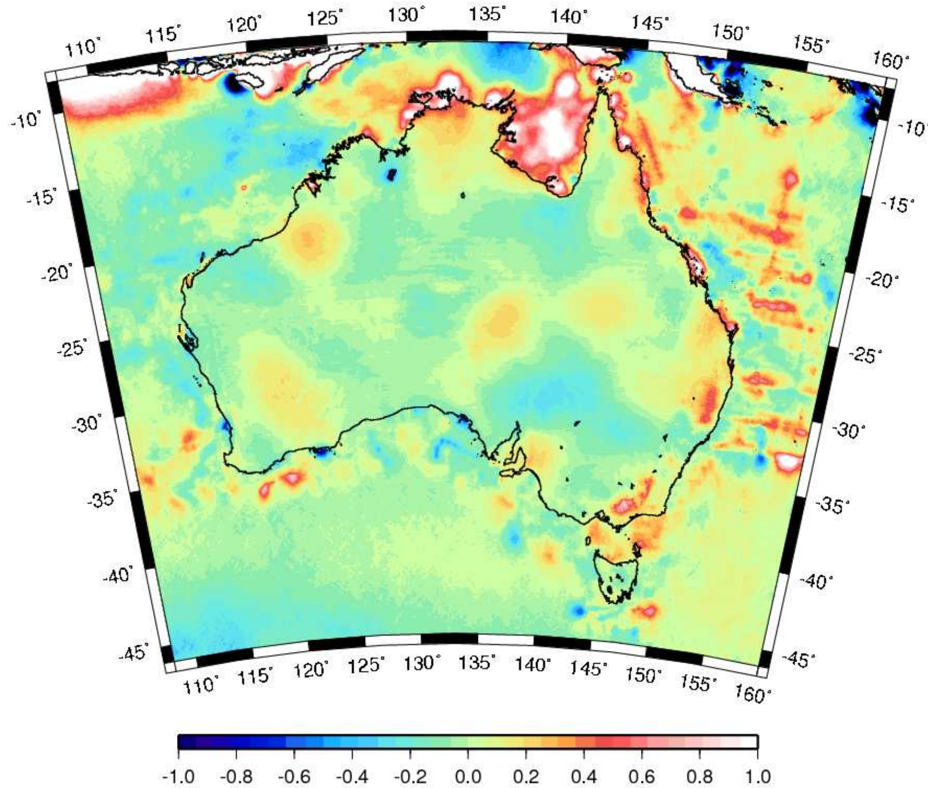

Fig 17. Differences between height anomalies computed from EGM2008 and AUSGeoid98 [Lambert projection; units in metres]

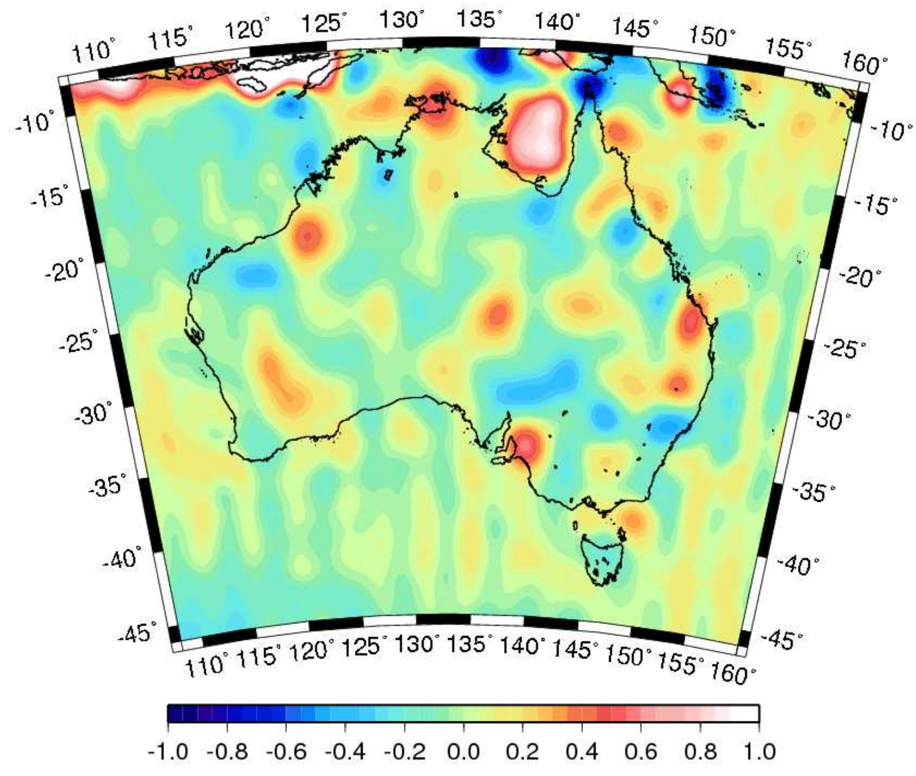

Fig 18. Differences between EGM96 and GGM02C quasigeoid heights to degree 200 (~100 km resolution) over the AUSGeoid98 area [Lambert projection; units in metres].

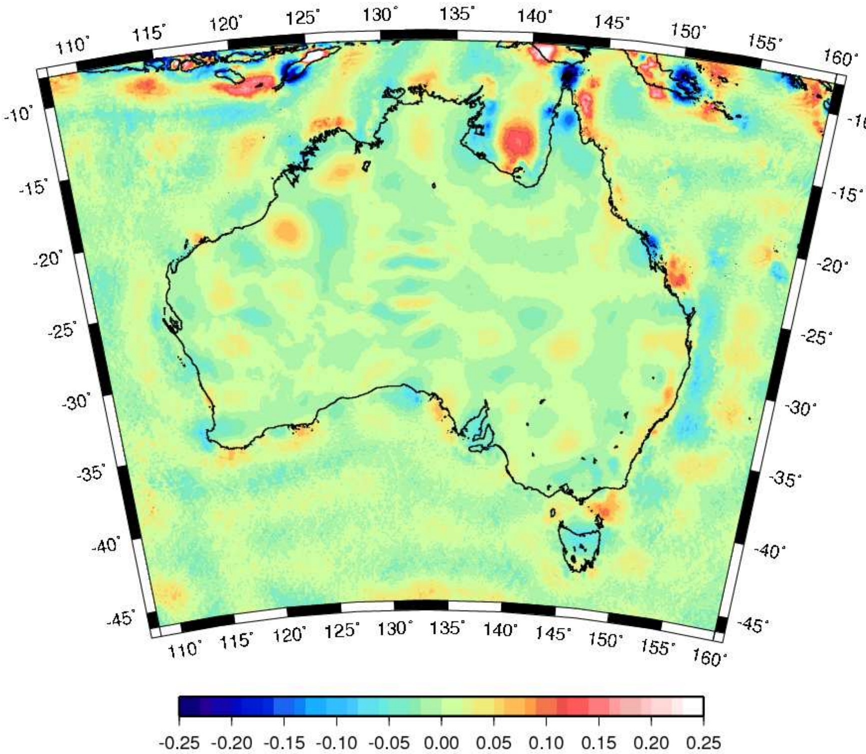

Fig 19. Differences between PGM2007A and EGM2008 quasigeoid heights to degree 2160 over the AUSGeoid98 area [Lambert projection; units in metres].

Short-wavelength differences in Fig. 17 occur in some of the mountainous regions (e.g., the Australian Alps; ~147˚E, ~37˚S). However, this only occurs for part of the Great Dividing Range, unlike the differences with the gravity data (Fig. 11). The large difference in Fig. 17 over the Australian Alps (~147˚E, ~37˚S) correlates almost exactly with the differences between gravity anomalies in Fig. 11. This indicates that the Australian data may be in error here, which will be investigated further. The same applies for the difference centred on (~151˚E, ~30˚S).

There are also large short-wavelength differences in Fig. 17 in many coastal regions (e.g., off the coast of Perth, Western Australia; ~116˚E, ~32˚S). These are in some cases due to differences in altimeter data used in EGM2008 and AUSGeoid98, and in other cases due to the use of unadjusted ship-track gravity data in AUSGeoid98, which will be elaborated upon next.

Claessens et al. (2001) and Kirby (2003) have shown that the inclusion of ship-track gravity data in the computation of AUSGeoid98 have probably caused an erroneous rise in AUSGeoid98 quasigeoid heights in marine areas offshore Perth. The negative differences between height anomalies from EGM2008 and AUSGeoid98 in these areas (Fig. 20) are therefore expected. However, the differences in Fig. 20 do not show a strong spatial correlation with the poor-quality ship-track data. This is because the least-squares collocation draping of the altimeter-derived gravity anomalies onto the land and ship-track data has smeared out the effect. It is then smeared out further when the residual gravity anomalies were Stokes-integrated.

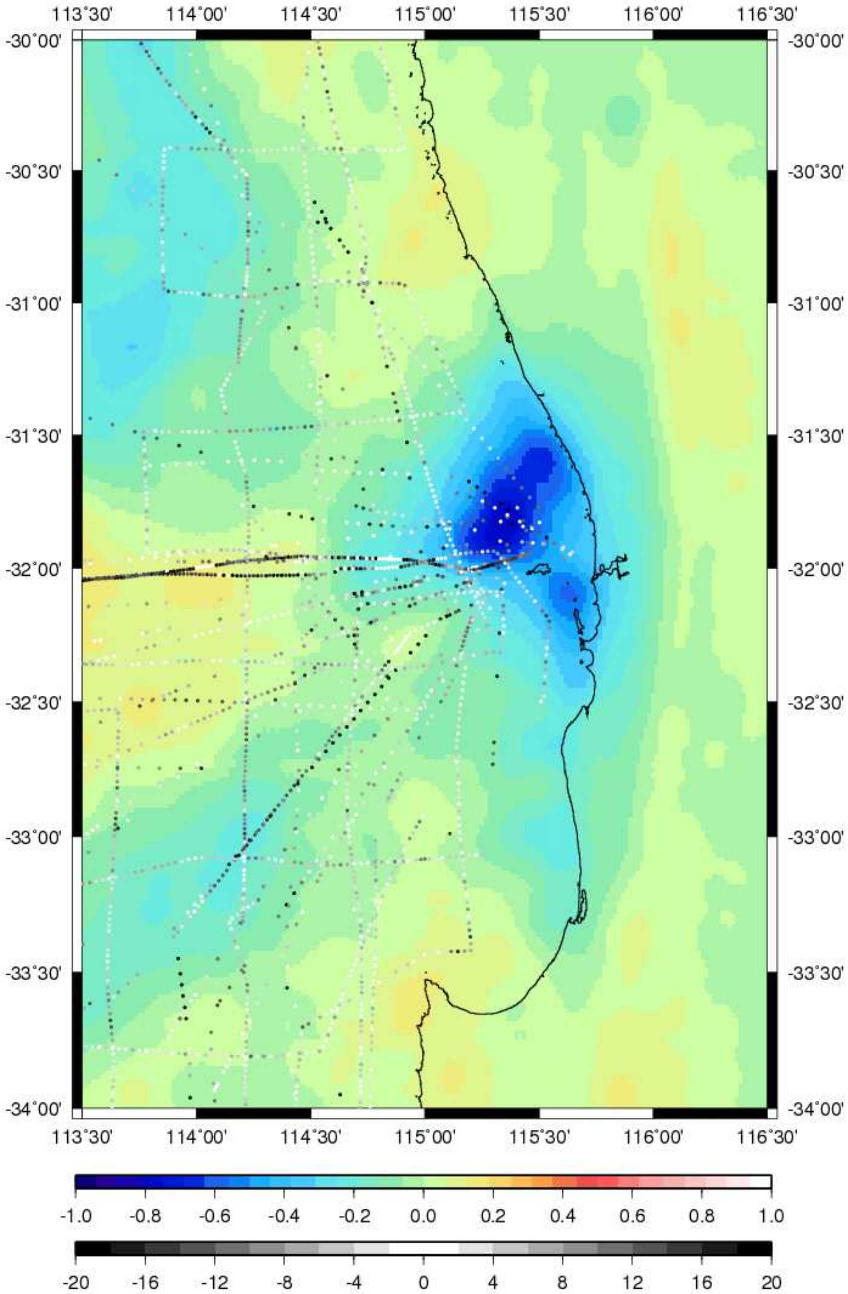

Fig 20. Differences between height anomalies computed from EGM2008 and AUSGeoid98 in the Perth region (colour scale) and differences between free-air gravity anomalies from EGM2008 and from ship-track observations (greyscale)

[Mercator projection; units in metres and mGal]

Figure 21 shows differences in height anomalies from EGM2008 and AUSGeoid98 over the eastern part of the Great Australian Bight (around and to the west of Adelaide). The central western part of Fig. 21 contains a particularly clear example of the distortion in AUSGeoid98 due to the inclusion of faulty ship-track data. The influence of faulty ship-track data can also be seen in Fig. 22, which shows differences in height anomalies from EGM2008 and AUSGeoid98 off the Queensland coast.

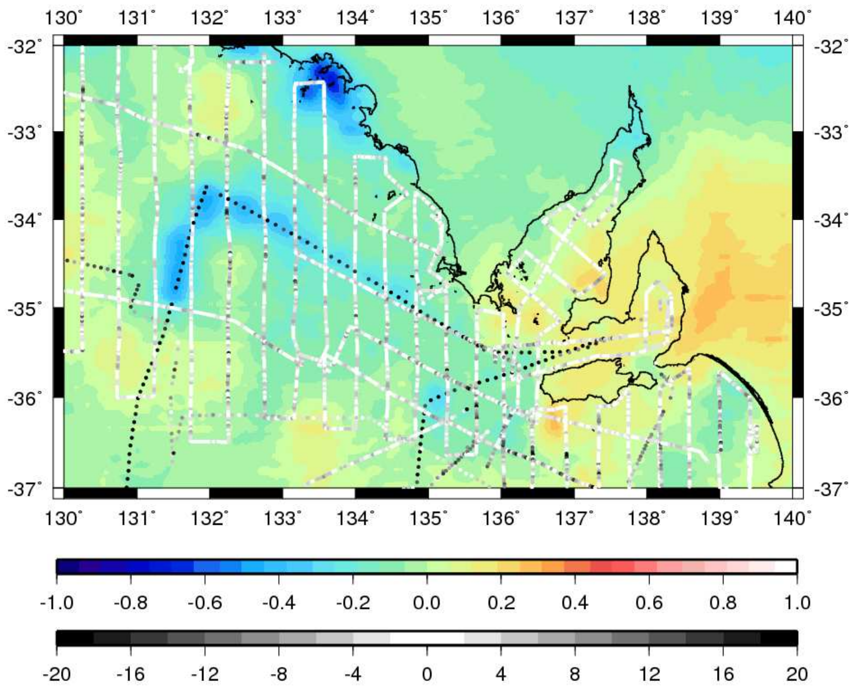

Fig 21. Differences between height anomalies computed from EGM2008 and AUSGeoid98 in the eastern part of the Great Australian Bight (colour scale) and differences between free-air gravity anomalies from EGM2008 and from ship-track observations (greyscale) [Mercator projection; units in metres and mGal]

However, larger differences closer to the coast, e.g., near Ceduna (~133.5E, ~32.5S; Fig. 21), near Mackay (~149E, ~21S; Fig. 22) and near Bundaberg (~152E, ~25S; Fig. 22), cannot be explained by inaccurate ship-track data, and are more likely explained by differences in the altimeter data used in the computation of EGM2008 and AUSGeoid98. We cannot isolate which altimetry dataset is in error in these areas. The differences offshore Queensland (Fig. 22) are exacerbated by the presence of the Great Barrier Reef, which prevents dense ship-track surveys and complicates tidal modelling in this region. The relatively large differences in height anomalies over land near Adelaide (~139E, ~35S; Fig. 21) will be discussed in the next section.

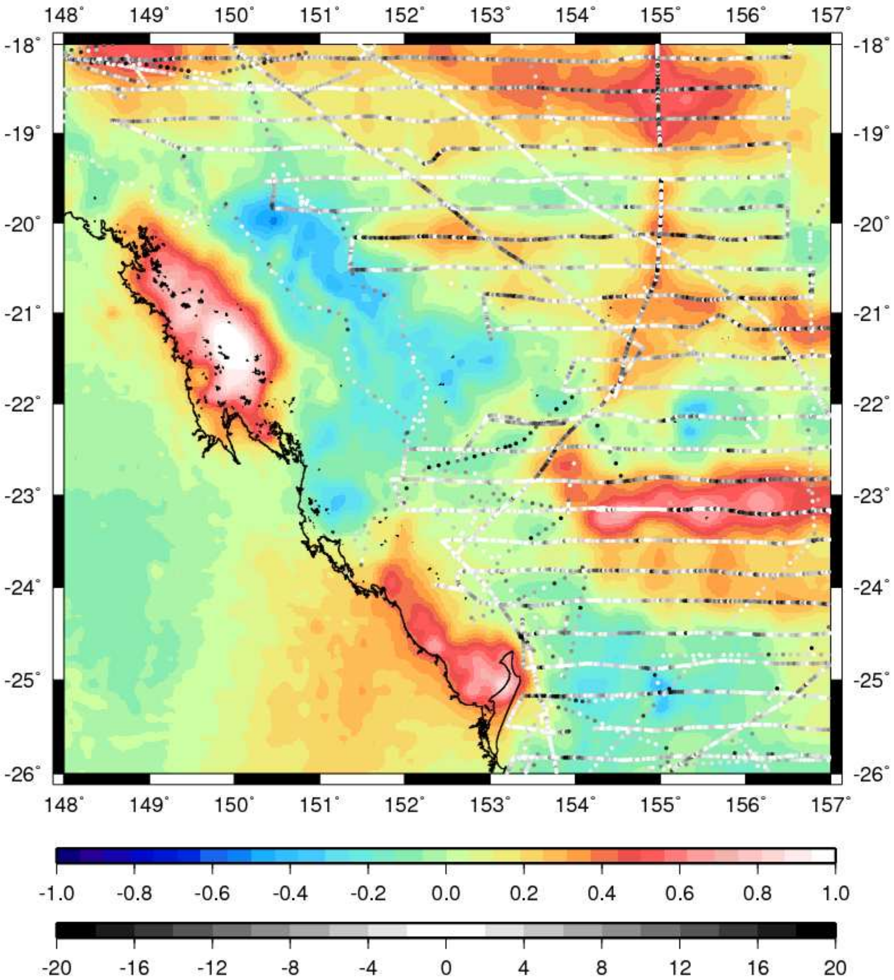

Fig 22. Differences between height anomalies computed from EGM2008 and AUSGeoid98 off Queensland (colour scale) and differences between free-air gravity anomalies from EGM2008 and from ship-track observations (greyscale) [Mercator projection; units in metres and mGal]

3.3 Comparisons with Australian GPS-levelling data

Table 5 indicates that PGM2007A and EGM2008 improve on many earlier GGMs in terms of standard deviation (STD) of the differences with respect to the 254 GPS-levelling points across Australia. It should, however, be recalled that the levelling data suffers from a north-south-oriented trend in the AHD (see earlier), which is clearly visible in Fig. 23. The STD of the differences between AUSGeoid98 and PGM2007A over the 254 GPS-levelling points is ±0.171m, and the STD of the differences between AUSGeoid98 and EGM2008 is ±0.164m (both not shown in Table 5). These numbers are considerably smaller than any of the standard deviations reported in Table 5. Comparisons with a larger set of 1013 GPS-levelling points of more dubious quality (see Section 2.2) are shown in Table 6. The GPS-levelling dataset of 243 points in Western Australia shows better agreement with all tested quasigeoid models (see Table 7).

Quasigeoid	*Degree*	*Bias/tilt removed?*	*Max*	*Min*	*Mean*	*STD*
EGM96	360	No	+0.894	–0.961	+0.009	±0.334
GGM02C	200	No	+0.950	–1.318	+0.007	±0.415
EIGEN-GL04C	360	No	+0.789	–0.653	+0.059	±0.293
AUSGeoid98	~5400	No	+0.865	–0.721	+0.077	±0.284
PGM2007A	2160	No	+0.663	–0.536	+0.068	±0.249
EGM2008	2160	No	+0.648	–0.535	+0.063	±0.242
AUSGeoid98	~5400	Yes	+0.518	–0.756	+0.000	±0.191
PGM2007A	2160	Yes	+0.551	–0.769	+0.000	±0.179
EGM2008	2160	Yes	+0.571	–0.701	+0.000	±0.173

Table 5 Descriptive statistics of the absolute differences between quasigeoid models and 254 co-located GPS-AHD points [units in metres]

Quasigeoid	*Degree*	*Bias/tilt removed?*	*Max*	*Min*	*Mean*	*STD*
AUSGeoid98	~5400	No	+3.558	–2.572	–0.003	±0.317
PGM2007A	2160	No	+3.153	–2.695	–0.021	±0.278
EGM2008	2160	No	+3.180	–2.711	–0.025	±0.273
AUSGeoid98	~5400	Yes	+3.346	–2.460	+0.000	±0.267
PGM2007A	2160	Yes	+3.055	–2.581	+0.000	±0.230
EGM2008	2160	Yes	+3.087	–2.596	+0.000	±0.228

Table 6 Descriptive statistics of the absolute differences between quasigeoid models and 1013 co-located GPS-AHD points [units in metres]

Quasigeoid	*Degree*	*Bias/tilt removed?*	*Max*	*Min*	*Mean*	*STD*
AUSGeoid98	~5400	No	+0.416	–0.740	–0.027	±0.204
PGM2007A	2160	No	+0.430	–0.583	–0.059	±0.175
EGM2008	2160	No	+0.378	–0.578	–0.060	±0.172
AUSGeoid98	~5400	Yes	+0.392	–0.743	0.000	±0.178
PGM2007A	2160	Yes	+0.358	–0.567	0.000	±0.132
EGM2008	2160	Yes	+0.364	–0.562	0.000	±0.126

Table 7 Descriptive statistics of the absolute differences between quasigeoid models and 243 co-located GPS-AHD points in Western Australia [units in metres]

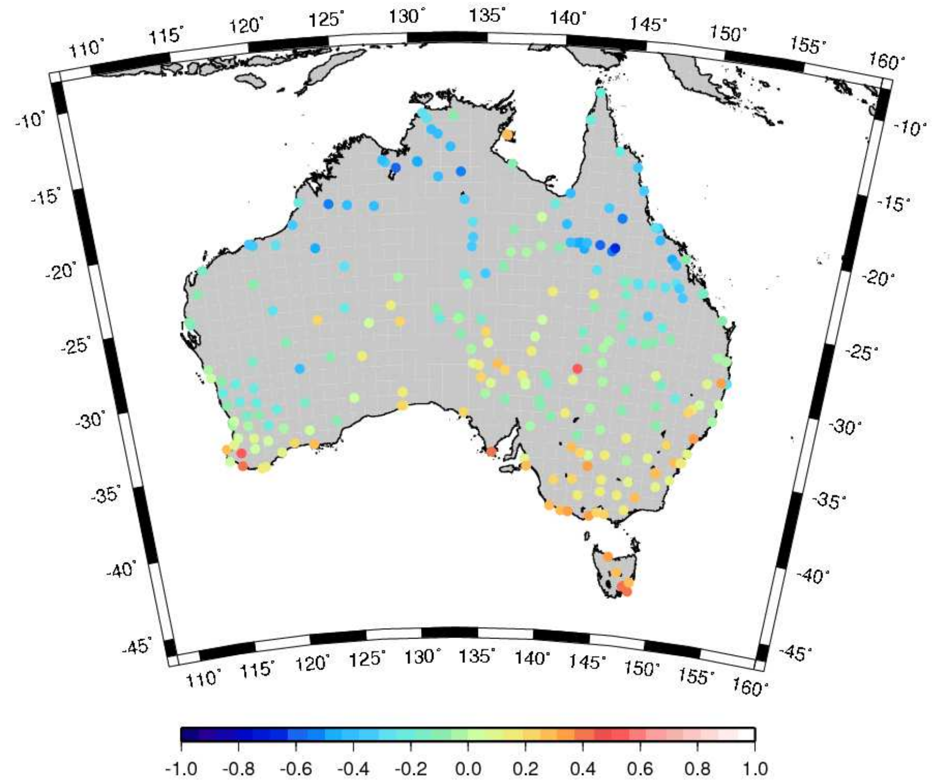

Fig 23. Differences between height anomalies from 254 GPS-levelling observations and EGM2008 [Lambert projection; units in metres]

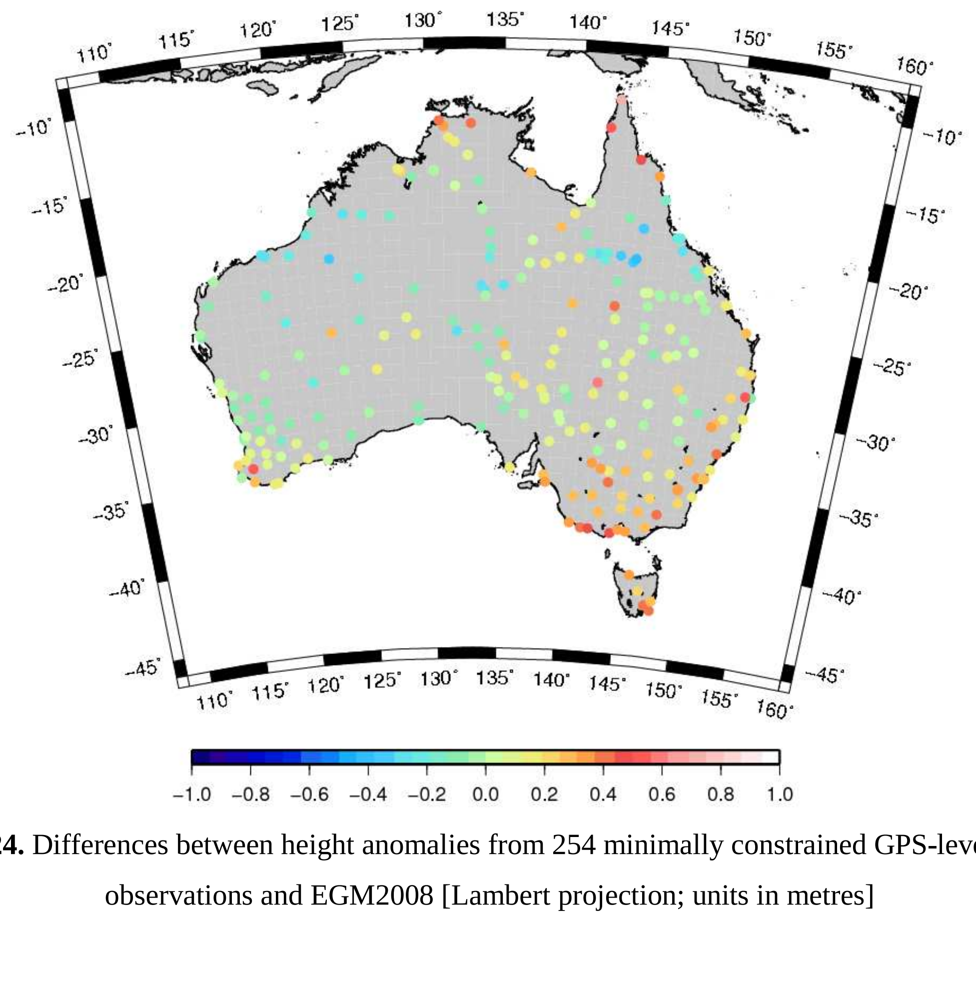

Fig 24. Differences between height anomalies from 254 minimally constrained GPS-levelling observations and EGM2008 [Lambert projection; units in metres]

Comparisons were also made to the regional GPS-levelling data in the SASZ and the SWSZ (Tables 8 and 9 and Fig. 25). The SWSZ data (published in an Appendix to Featherstone (2004)) were inadvertently not supplied to the EGM2008 development team. For the SASZ dataset, the STDs of PGM2007A and EGM2008 are larger than that of AUSGeoid98, but this is reversed when a bias and tilt are removed (see Table 8). In the SWSZ, EGM2008 has the smallest STD, but after removal of a bias and tilt the STD of AUSGeoid98 is the same (see Table 9).

Quasigeoid	*Degree*	*Bias/tilt removed?*	*Max*	*Min*	*Mean*	*STD*
EGM96	360	No	+1.637	–0.401	+0.246	±0.466
AUSGeoid98	~5400	No	+0.313	–0.211	+0.010	±0.117
PGM2007A	2160	No	+0.396	–0.322	–0.044	±0.133
EGM2008	2160	No	+0.402	–0.286	–0.036	±0.127
EGM96	360	Yes	+1.154	–0.732	+0.000	±0.396
AUSGeoid98	~5400	Yes	+0.373	–0.210	+0.000	±0.105
PGM2007A	2160	Yes	+0.394	–0.196	+0.000	±0.102
EGM2008	2160	Yes	+0.374	–0.183	+0.000	±0.100

Table 8 Descriptive statistics of the absolute differences between quasigeoid models and 45 co-located GPS-AHD points in the South Australian Seismic Zone [units in metres]

Quasigeoid	*Degree*	*Bias/tilt removed?*	*Max*	*Min*	*Mean*	*STD*
EGM96	360	No	+1.174	–0.211	+0.512	±0.280
AUSGeoid98	~5400	No	+0.196	–0.277	–0.010	±0.128
PGM2007A	2160	No	+0.160	–0.335	–0.002	±0.120
EGM2008	2160	No	+0.144	–0.305	–0.006	±0.106
EGM96	360	Yes	+0.543	–0.606	+0.000	±0.244
AUSGeoid98	~5400	Yes	+0.097	–0.133	+0.000	±0.046
PGM2007A	2160	Yes	+0.092	–0.138	+0.000	±0.050
EGM2008	2160	Yes	+0.092	–0.130	+0.000	±0.046

Table 9 Descriptive statistics of the absolute differences between quasigeoid models and 48 co-located GPS-AHD points in the South West Seismic Zone [units in metres]

The STDs for EGM2008 are consistently smaller than the STDs for PGM2007A in Tables 5, 6, 7, 8 and 9, both with and without removal of a bias and tilt. Thus, although there is little difference between PGM2007A and EGM2008 in the comparisons with gravity anomalies, EGM2008 is an improvement on PGM2007A in the comparison with GPS-levelling data.

It is interesting to note that the STDs of AUSGeoid98, PGM2007A and EGM2008 are very similar for the regional GPS-levelling data sets in South Australia and Western Australia (see Tables 8 and 9), whereas PGM2007A and EGM2008 agree significantly better with the nation-wide GPS-levelling data sets than AUSGeoid98 (see Tables 5 and 6). This is probably caused by the improved accuracy of the low degrees in PGM2007A and EGM2008 compared to EGM96, which was used in AUSGeoid98, due to the inclusion of GRACE data.

Table 10 shows the biases, tilts and directions of the least-squares fitted planes used in the generation of the statistics in Tables 5 to 9. The tilts in the differences with PGM2007A and EGM2008 are slightly smaller than the tilt in the differences with AUSGeoid98 for the nation-wide data sets. The tilts reported here for AUSGeoid98 are slightly larger than those reported by Featherstone and Guo (2001) (~0.26 mm/km for the nation-wide data set of 1013 GPS-levelling observations) and Featherstone (2004) (~0.81 mm/km for the SWSZ data set in Western Australia). This is because the tilts computed in this 'validation' were not constrained to be in a north-south direction, as was the case for Featherstone and Guo (2001) and Featherstone (2004).

Nevertheless, it can be seen from the azimuths in Table 10 that most of the fitted planes are generally close to a north-south direction. This is consistent with the known north-south distortion in the AHD (discussed earlier). As such, PGM2007A and EGM2008 are again implicitly validated because they confirm the known north-south tilt in the AHD. The only exception to this is the South Australian data set, which is discussed next.

Figure 25 (right) shows that the differences between the GPS-AHD heights and height anomalies from EGM2008 in the SASZ follow a north-south trend, similar to the well-known trend in the AHD (cf. Table 7), but more than three times as steep as the trend over the whole of Australia (~0.77/~0.71 mm/km versus ~0.23 mm/km). However, the differences between the GPS-AHD heights and AUSGeoid98 show a very different pattern (Fig. 25 left) with a 'bulge' in the south-east part of the map of up to ~0.3 m. This has caused the azimuth of the least-squares fitted plane to be skewed from the expected north-south direction, which indicates a problem with AUSGeoid98 in this region.

Quasigeoid	*Degree*	*Dataset*	*Bias (m)*	*Tilt (mm/km)*	*Azimuth (deg)*
AUSGeoid98	~5400	Australia-wide (254)	+0.076	+0.281	+3.590
PGM2007A	2160	Australia-wide (254)	+0.068	+0.226	–1.738
EGM2008	2160	Australia-wide (254)	+0.063	+0.221	–1.999
AUSGeoid98	~5400	Australia-wide (1013)	–0.003	+0.267	+2.700
PGM2007A	2160	Australia-wide (1013)	–0.021	+0.232	–9.015
EGM2008	2160	Australia-wide (1013)	–0.025	+0.223	–8.510
AUSGeoid98	~5400	Western Australia (243)	–0.027	+0.178	+14.088
PGM2007A	2160	Western Australia (243)	–0.058	+0.212	–2.758
EGM2008	2160	Western Australia (243)	–0.060	+0.215	+3.190
AUSGeoid98	~5400	South Australia (45)	+0.010	+0.478	+142.366
PGM2007A	2160	South Australia (45)	–0.044	+0.767	–14.166
EGM2008	2160	South Australia (45)	–0.036	+0.708	–21.566
AUSGeoid98	~5400	SW Western Australia (48)	–0.010	+0.922	+22.143
PGM2007A	2160	SW Western Australia (48)	–0.003	+0.902	+31.033
EGM2008	2160	SW Western Australia (48)	–0.006	+0.783	+30.360

Table 10 Bias, tilt and azimuth of maximum positive gradient for planes fitted in a least-squares sense to the differences between GPS-levelling observations and several quasigeoid models. The positive tilt values, coupled with the azimuths show that the differences generally increase northwards.

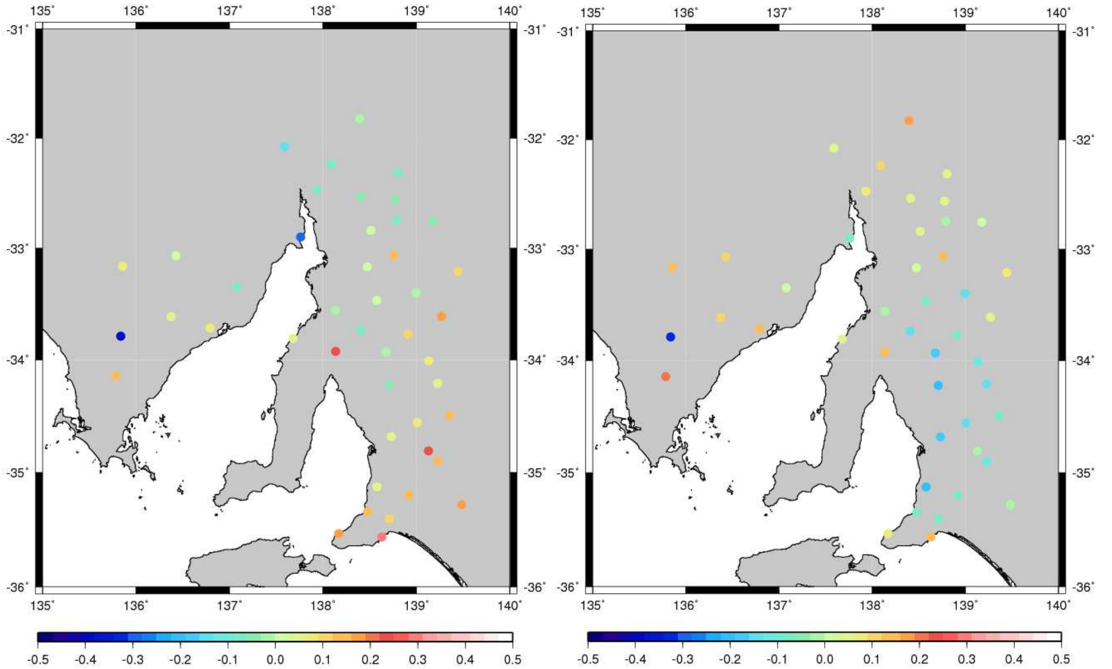

Fig 25. Differences between height anomalies from GPS-levelling observations and AUSGeoid98 (left) and EGM2008 (right) over the SASZ [Mercator projection; units in metres]

This 'bulge' is also apparent in the differences between the GPS-AHD heights and height anomalies computed from EGM96, and the differences in this case are much larger (see Fig. 26). This indicates that EGM96 contains an error in this region, which has propagated into AUSGeoid98, albeit mitigated by local gravimetric data. The residual quasigeoid computed for this region in AUSGeoid98 was around one metre, being one of the largest 'corrections' to EGM96 in that computation. Thus, despite the fact that AUSGeoid98, PGM2007A and EGM2008 give similar standard deviations in the comparison with GPS-levelling data over the SASZ, spatial analysis of the differences appear to indicate that PGM2007A and EGM2008 are the more accurate models in this region.

Historically, the Adelaide region has always been a problematic area for GGMs (see, e.g., Kearsley and Holloway 1989, Zhang and Featherstone 1995, Kirby et al. 1998, Amos and Featherstone 2003). PGM2007A and EGM2008 appear now to be free from this error, which is a positive validation for these models.

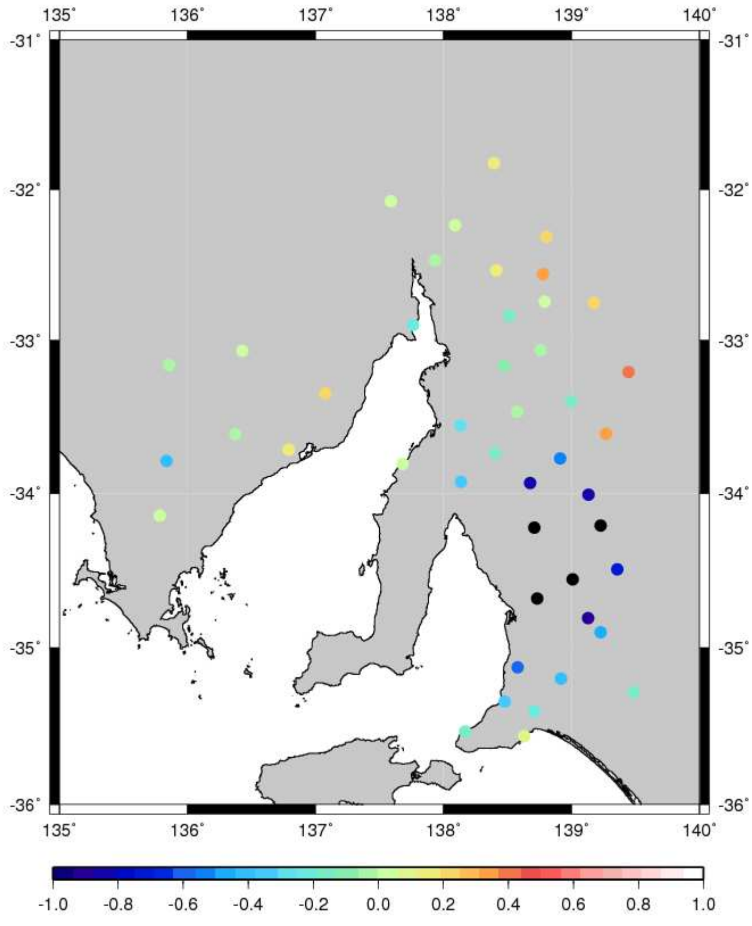

Fig 26. Differences between height anomalies from GPS-levelling observations and EGM96 [Mercator projection; units in metres]

It is obvious from all GPS-levelling comparisons that the slope in the AHD is complicating the evaluation. Removal of a bias and tilt cannot completely account for the deficiencies in the AHD. The main reason for the deficiencies is the fact that the AHD is constrained to 32 tide gauges around the coast. This was overcome for this 'validation' by performing a minimally constrained adjustment on the levelling, fixing the height of one tide-gauge only. All datasets are tied to the Albany tide-gauge on the south coast of Western Australia, except for the SASZ dataset, which is tied to the tide-gauge at Port Lincoln on the Eyre Peninsula in South Australia.

Table 11 shows the results of comparisons of EGM2008 to the GPS-levelling datasets, where the levelling observations were adjusted using a minimally constrained adjustment. Minimally constraining the levelling observations decreases the STD of the differences with EGM2008 for all datasets, except for the SASZ. In South Australia, the differences between GPS-levelling and EGM2008 show an east-west trend of ~1 mm/km. The reason for this trend is probably erroneous spirit-levelling data in the file used for the adjustment (cf. Steed 2006).

Dataset	*Bias/tilt removed?*	*Max*	*Min*	*Mean*	*STD*
Australia-wide (248)	No	+0.727	–0.437	+0.062	±0.203
Western Australia (243)	No	+0.300	–0.402	–0.007	±0.125
South Australia (45)	No	+0.632	–0.397	+0.391	±0.180
SW Western Australia (48)	No	+0.225	–0.048	+0.063	±0.059
Australia-wide (248)	Yes	+0.710	–0.569	+0.000	±0.182
Western Australia (243)	Yes	+0.400	–0.420	+0.000	±0.102
South Australia (45)	Yes	+0.250	–0.491	+0.000	±0.113
SW Western Australia (48)	Yes	+0.084	–0.097	+0.000	±0.039

Table 11 Descriptive statistics of the absolute differences between EGM2008 and various minimally constrained GPS-levelling datasets [units in metres]

The absolute differences between height anomalies from GPS-levelling and from EGM2008 at two points can be subtracted from one another to compute a relative baseline difference (cf. Featherstone 2001) to evaluate the quasigeoid gradients. This was done for all possible baselines between the 254 GPS-levelling points in the nationwide dataset and the relative differences are plotted against baseline length (Fig. 27). The majority of relative differences fall within the 12 root km misclosure tolerance (ICSM 2007), especially for long baselines, but many fall outside this level. This is probably due to errors in the AHD, most notably the north-south slope.

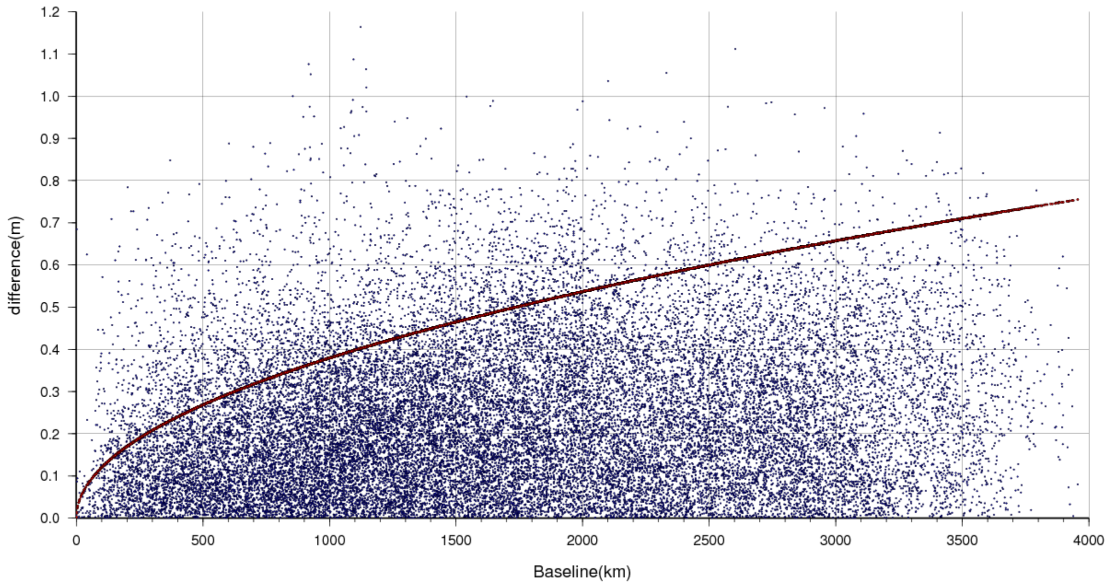

Fig 27. Relative baseline differences between height anomalies from 254 GPS-levelling observations in Australia and height anomalies from EGM2008, where the black line indicates the 12 root km allowable misclose for third-order Australian spirit-levelling

The effect of the north-south slope in the AHD on the relative baseline differences can be seen most clearly in Figs. 28 and 29. Figure 28 shows the relative baseline differences for the 243 GPS-AHD points in Western Australia. The longest baselines in this dataset (>1800 km) are all north-south oriented. Almost all of these show large relative differences. However, after minimally constraining the levelling observations in a readjustment, the relative baseline differences become much smaller (see Fig. 29). This is especially visible in the longest baselines, but holds for all baseline lengths.

Statistics for all GPS-levelling datasets are shown in Tables 12 and 13. Table 12 shows the baseline statistics when 'official' AHD heights are used, and Table 13 shows the baseline statistics when the levelling observations are minimally constrained in a readjustment. Minimally constraining the levelling observations decreases the relative baseline differences for all datasets except the SASZ. As mentioned earlier, the levelling data in this area requires further investigation.

The majority of all relative baseline differences is below the formal precision threshold of third-order levelling (12 root km in Australia; ICSM 2007). The differences are likely to be affected more by errors in the levelling than by errors in EGM2008. Therefore, true validation of EGM2008 from comparisons to GPS-levelling data cannot be claimed.

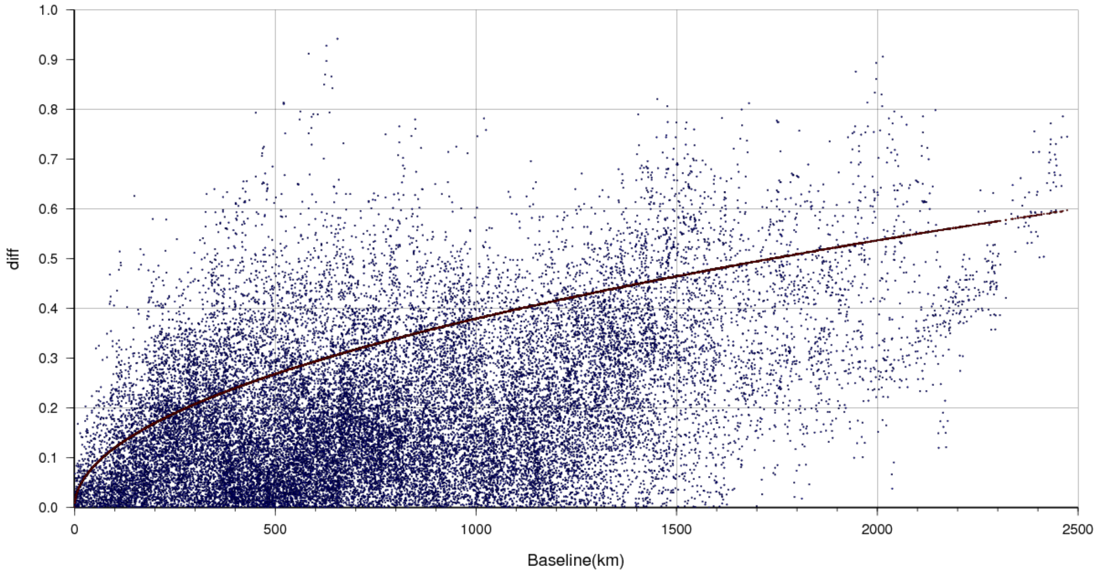

Fig 28. Relative baseline differences between height anomalies from 243 GPS-levelling observations in Western Australia and height anomalies from EGM2008, where the black line indicates the 12 root km allowable misclose for third-order Australian spirit-levelling

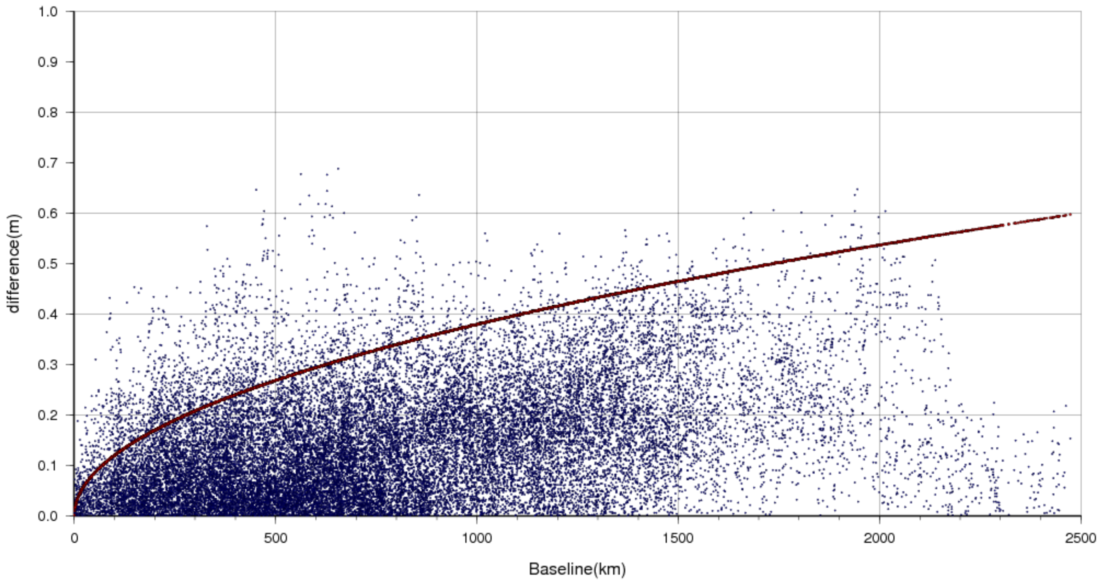

Fig 29. Relative baseline differences between height anomalies from 243 minimally constrained GPS-levelling observations in Western Australia and height anomalies from EGM2008, where the black line indicates the 12 root km allowable misclose for third-order Australian spirit-levelling

Dataset	*Mean baseline length*	*Max*	*Min*	*Mean*	*STD*	*Percentage baselines below 12 root km*
Australia-wide (254)	1,700,060	+1.116	–1.182	+0.042	±0.341	81.86%
Western Australia (243)	783,286	+0.893	–0.942	–0.047	±0.241	81.43%
South Australia (45)	415,100	+0.546	–0.689	–0.090	±0.158	65.76%
SW Western Australia (48)	530,677	+0.448	–0.394	+0.094	±0.118	76.77%

Table 12 Descriptive statistics of the relative baseline differences between EGM2008 and various GPS-AHD datasets [units in metres]

Dataset	*Mean baseline length*	*Max*	*Min*	*Mean*	*STD*	*Percentage baselines below 12 root km*
Australia-wide (254)	1,700,060	+1.164	–1.052	+0.081	±0.276	89.03%
Western Australia (243)	783,286	+0.592	–0.688	–0.019	±0.178	93.04%
South Australia (45)	415,100	+0.954	–1.029	–0.090	±0.240	52.63%
SW Western Australia (48)	530,677	+0.273	–0.203	+0.043	±0.073	97.25%

Table 13 Descriptive statistics of the relative baseline differences between EGM2008 and various minimally constrained GPS-levelling datasets [units in metres]

3.4 Comparisons with Australian vertical deflections

The results of comparisons of vertical deflections computed from PGM2007A and EGM2008 to a set of 1080 historic astrogeodetically observed vertical deflections over Australia are shown in Table 14 and Figs. 30 and 31. The results for AUSGeoid98 and PGM2007A agree exactly with the statistics given by Pavlis et al. (2007). This validation is probably the strongest from the Australian data, even though the vintage of the Australian astrogeodetic observations are not ideal because they were mostly observed over 40 years ago. Nevertheless, because vertical deflections are higher order derivatives, they sense high-frequency variations in the gravity field and are thus better for validating GGMs in the high degrees (Jekeli 1999).

PGM2007A and EGM2008 seemingly slightly outperform AUSGeoid98 in Table 14. This may partly be because the `HARMONIC_SYNTH.f` software uses the height of the astrogeodetic observation to evaluate a Helmert deflection directly at the surface of the Earth, so is more compatible with the astrogeodetic observations that yield Helmert deflections. On the other hand, AUSGeoid98 deflections are Pizzetti vertical deflections at the geoid because they were computed from the horizontal gradients of AUSGeoid98. As such, the curvature and torsion of the plumbline through the topography is neglected, which will account for part of the worse comparison for AUSGeoid98 in Table 14.

Deflection	*Model*	*Degree*	*Max*	*Min*	*Mean*	*STD*
north-south (ξ)	AUSGeoid98	~5400	+17.83	–7.76	–0.25	±1.28
north-south (ξ)	PGM2007A	2160	+17.79	–6.95	–0.17	±1.24
north-south (ξ)	EGM2008	2160	+17.69	–6.99	–0.62	±1.17
east-west (η)	AUSGeoid98	~5400	+9.11	–12.65	–0.17	±1.36
east-west (η)	PGM2007A	2160	+8.77	–11.35	–0.10	±1.18
east-west (η)	EGM2008	2160	+8.70	–11.34	+0.10	±1.28

Table 14 Descriptive statistics of the differences between 1080 astrogeodetic observations of vertical deflections and AUSGeoid98, PGM2007A and EGM2008 [units in arc seconds]

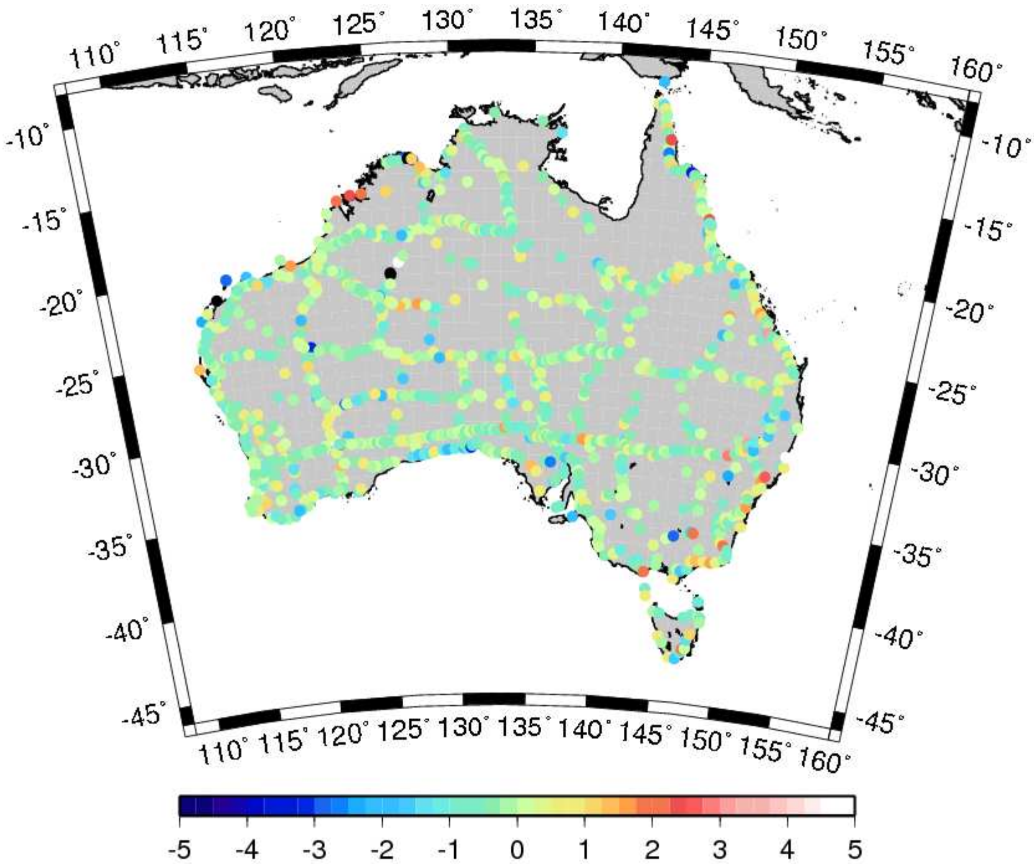

Fig 30. Differences between north-south vertical deflections from 1080 astrogeodetic measurements and EGM2008 [Lambert projection, units in arc seconds]

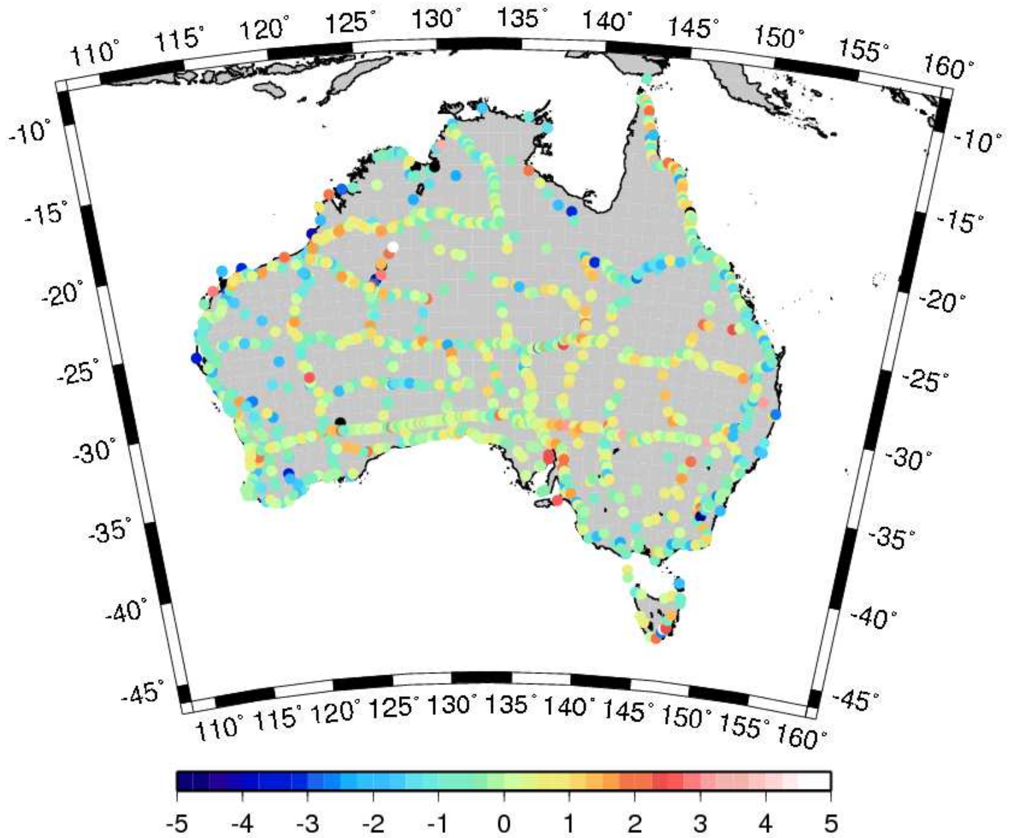

Fig 31. Differences between east-west vertical deflections from 1080 astrogeodetic measurements and EGM2008 [Lambert projection, units in arc seconds]

4. Conclusion

The tide-free combined global geopotential model EGM2008 and its preliminary version PGM2007A were compared with Australian land, marine and airborne gravity observations, co-located GPS-levelling, the AUSGeoid98 regional gravimetric quasi-geoid model, and astrogeodetic deflections of the vertical. The results show that we cannot legitimately claim to truly validate EGM2008. Instead, these global models confirm the already-known problems with the Australian data, as well as revealing some previously unknown problems. If one wants to claim validation, then EGM2008 is validated because it can confirm the errors in our regional data. Simply, EGM2008 is a good model over Australia.

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