# Prospects for the Australian Height Datum and Geoid Model

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**Abstract.** The integrity of the Australian Height Datum (AHD) has remained in some question ever since its adoption in 1971. Indeed, its creators commented that using 30 tide gauges 'placed a strain' on the least-squares network adjustment of the ~97,230 km of spirit levelling used to realise the AHD. Although the AHD seems to have served Australians well, the question remains – can the AHD be improved? Of course, re-levelling an entire continent the size of Australia is prohibitively expensive, especially in the current climate of economic rationalism. Therefore, a proposal is made to enhance and redefine the AHD using the additional levelling data collected since 1971, mean sea level observations made at new tide gauges, models of the sea-surface topography, nation-wide GPS height networks and a regionally refined gravimetric geoid model. This proposal is balanced against the arguments in favour of retaining the existing AHD, coupled with a geoid model that has been warped to fit the existing AHD using nation-wide GPS networks co-located with AHD benchmarks.

**Keywords.** Vertical datum, geoid, height systems, sea-surface topography, orthometric corrections.

## 1 Introduction

While AUSGeoid98 (Featherstone et al. 2001) improves upon earlier Australian gravimetric geoid models, especially in the mountains and close to the coast (eg Featherstone and Guo 2001), it remains inadequate for the *direct* transformation of GPS-derived ellipsoidal heights to the Australian Height Datum (AHD; Roelse *et al*. 1971). As such, users are normally forced to apply post-GPS-survey corrections to fit to local benchmarks on the AHD.

Therefore, the issue has arisen of what is needed in Australia: a 'pure' gravimetric geoid model, a model of the base of the AHD (cf Featherstone 1998), or a total revision of the AHD. Importantly, these issues must not be treated separately. Instead, a more holistic approach to Australian vertical geodesy is needed. This paper presents some of the problems with and prospects for both the AHD and the Australian geoid model. It then presents arguments for and against several strategies for the revision of the AHD and Australian geoid model.

## 2 The Australian Height Datum

Before 1971, no single vertical datum existed for Australia. Instead, numerous *ad hoc* vertical datums, many based on tide gauge estimates of mean sea level at local ports, were used.

The adjustment used to realise the AHD incorporated ~97,230km of two-way spirit levelling observations (termed basic levelling) and was fixed to zero height for mean sea level (MSL) estimated at thirty tide gauges around the mainland (Figure 1). These estimates were made between 1966 and 1968, except at Karumba (1957 to 1960). The spirit levelling network in Tasmania was first adjusted in 1979, then readjusted in 1983 to yield the AHD(Tasmania). This used MSL estimated at the Hobart and Burnie tide gauges in 1972.

Normal orthometric corrections were applied to the levelling data (Roelse et al. 1971). The use of normal - as opposed to observed - gravity and fixing the adjustment of the spirit levelling observations to MSL cause distortions of ~1m in the AHD. In addition, there appears to be a vertical offset of ~0.2m between the AHD on the Australian mainland and Tasmania (Featherstone 2000a). Since the AHD does not appear to be coincident with a single equipotential surface of the Earth's gravity field, differences can be expected between Australian geoid models and GPS-AHD data.

Indeed, these are now being observed (eg Johnston and Luton 2001, Featherstone et al. 2001). However, one must always remember that these differences cannot be attributed solely to errors in the AHD; the geoid model plays a pivotal role.

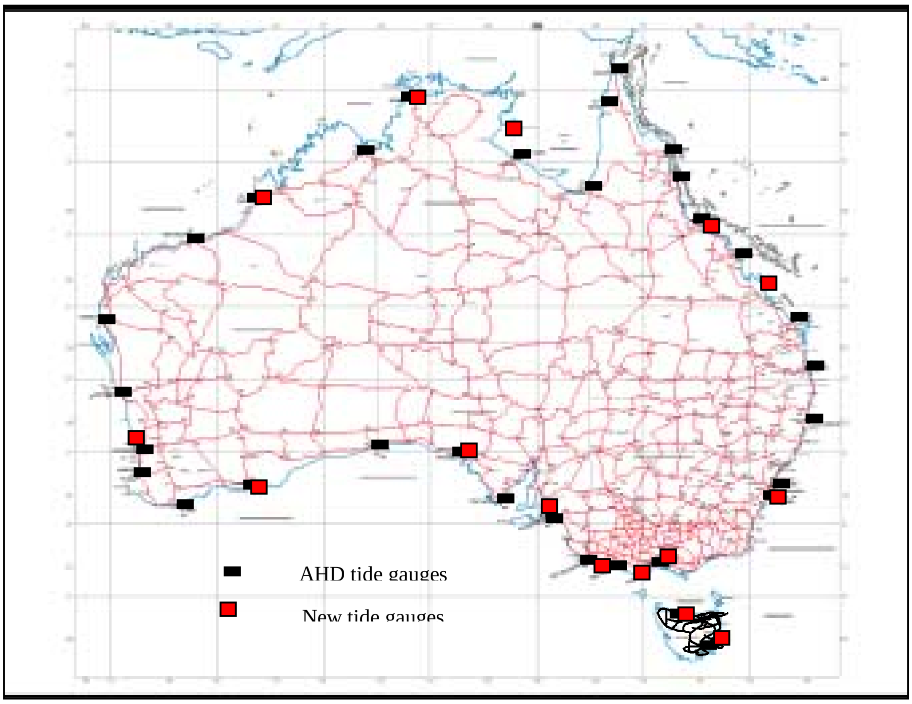


**Fig 1.** The AHD basic levelling network and locations of the tide gauges (from Johnston and Luton 2001)

## 3 AUSGeoid98

Featherstone et al. (2001) describe the production of AUSGeoid98. To summarise, it was computed on a 2′×2′ grid on the GRS80 ellipsoid from EGM96 (Lemoine et al. 1998), the Australian Geological Survey Organisation's (AGSO) land and marine gravity database (Murray 1997), satellite-altimeter-derived gravity anomalies (Sandwell and Smith 1997), and the Australian 27″×27″ digital elevation model (DEM; Carroll and Morse 1996).

The mathematical model used for AUSGeoid98 is a hybrid of the remove-compute-restore technique and the generalised Stokes scheme with a deterministically modified kernel. The degree-360 expansion of EGM96 was used in the remove-compute-restore technique, and the degree-20 spheroid was used for both the reference spheroid and the modified kernel. The residual geoid undulations were computed using the 1D-FFT technique.

Empirical comparisons with 906 GPS-AHD data were used to optimise the integration radius at one-arc-degree. This was found necessary because the use of the entire Australian gravity grid in the 1D-FFT technique gives poor results (eg Forsberg and Featherstone 1998). This is attributed to one or all of errors in the gravity, AHD and GPS data used.

## 4 Differences between AUSGeoid98 and the AHD

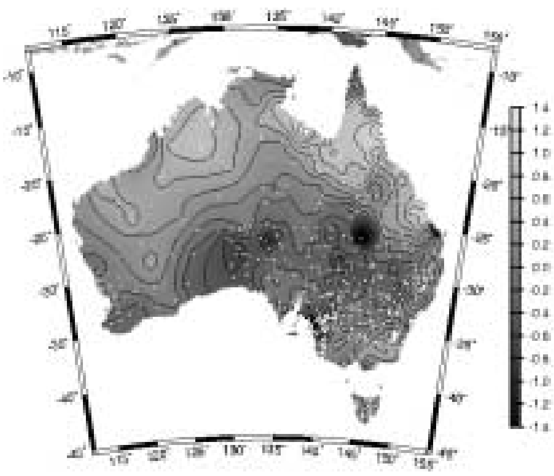

**Fig. 2** Absolute differences (in metres) between 1013 GPS-AHD data (circles) and AUSGeoid98

AUSGeoid98 has been compared with a nation-wide set of 1013 (including the 960 mentioned earlier) GPS-AHD data (Fig 2; Featherstone and Guo 2001). The statistics of the absolute differences are: max=3.558m, min=–2.572m, mean=–0.002m, std=±0.314m. Some of the differences in Fig 2 correlate well with the differences between the free- and fixed-network adjustments of the AHD (Roelse et al. 1971). This suggests distortions in the AHD, but regional errors in AUSGeoid98 cannot be ruled out as the sole explanation for the differences. Nevertheless, there is a significant north-south tilt between the GPS-AHD heights and AUSGeoid98 of (0.0292±0.0014)m/arc-degree (Featherstone and Guo 2001). This is attributed largely to sea surface topography (SST) effects on the tide gauges held fixed to zero height in the realisation of the AHD.

### 4.1 SST effects on the AHD

Sargeant and Featherstone (submitted) investigate the likely effects of SST on the realisation of the AHD by comparing the differences between the free- and fixed-network adjustments (Roelse et al. 1971) with the EGM96 quasi-stationary SST (QSST) model (Lemoine et al. 1998; Figure 3). This is to determine to what extent the fixing of the tide gauges to MSL has introduced the apparent north-south tilt into the AHD.

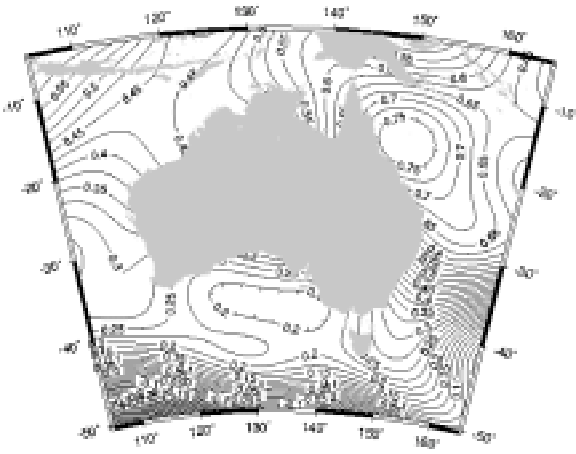

**Fig. 3** EGM96 QSST to degree 20 (contours in metres).

The horizontal geodetic coordinates of the 30 mainland tide gauge sites were used to compute EGM96 QSST values, which were then compared with the differences between adjustments of the AHD (Fig 4). Importantly, this analysis is independent of AUSGeoid98, though the low-frequency EGM96 geoid has been used during the estimation of the QSST (Lemoine et al. 1998).

In Figure 4, there is some broad level of agreement between the EGM96 QSST and the differences between the adjustments of the AHD. The high-frequency differences are due on or both of to the omission error in the degree-20 QSST model and the generally complicated coastal SST (Hipkin 2000). While acknowledging these limitations, linear regression was applied to the differences between the free and fixed adjustments of the AHD (Figure 5) and to these differences after application of the EGM96 QSST (Figure 6).

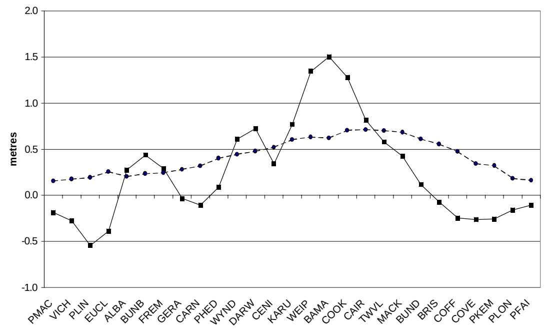


**Fig. 4** Differences (in metres) between the free and fixed adjustments of the AHD at 30 tide gauges (squares; cf Fig 1) and the values of the degree-20 EGM96 QSST (circles).

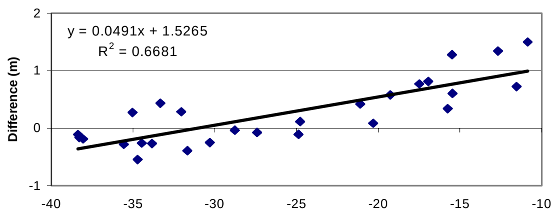


**Fig 5.** Linear regression of the differences (in metres) between the free and fixed adjustments of the AHD as a function of latitude

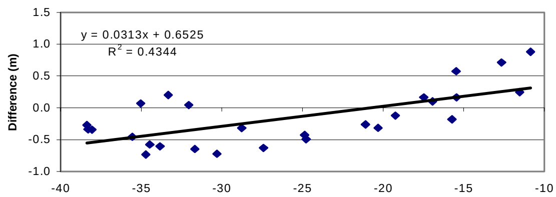


**Fig 6.** Linear regression of the differences (in metres) between the free and fixed adjustments of the AHD after applying the EGM96-20 QSST model as a function of latitude

Comparing the regression and correlation coefficients in Figures 5 and 6 (note the different scales) shows that the application of the EGM96 QSST model removes ~0.5m of the north-south tilt. It is plausible that the remainder is due to systematic north-south levelling errors. Johnston and Luton (2001) use the ellipsoidal heights of the AHD tide gauges and AUSGeoid98 to arrive at the same conclusion. When these two studies are taken together, this indicates that the north-south tilt is in the AHD and not necessarily in AUSGeoid98.

### 4.2 Known problems with AUSGeoid98

As stated, the differences in Figure 1 should not be attributed solely to problems in the AHD; errors in AUSGeoid98 alone could account for them. Since computation of AUSGeoid98 in early 1998, some potential problems have been discovered, as follows.

The JGP95E DEM (Lemoine et al. 1998, Chap. 2) was used to compute gravimetric terrain corrections and to construct mean gravity anomalies for EGM96. To the west of 140°E, JGP95E is based on the TerrainBase DEM, which in turn was computed from Australian gravity observation elevations. As such, it is subject to aliasing and improper sampling of the topography due to the logistics of collecting gravity data (Featherstone and Kirby 2000). To the east of 140°E, JGP95E was constructed from NIMA's topographic map holdings. Figure 7 shows the disparity at 140°E between the JGP95E and TerrainBase DEMs over Australia. The differences around the western Australian coast are probably due to pixel registration errors.

Version 1 of the GEODATA 9″ DEM (Carroll and Morse 1996) was used in AUSGeoid98. However, a 27″×27″ grid was needed to compute terrain corrections (Kirby and Featherstone 1999). This was attributed to instabilities in the planar algorithm used (cf Martinec et al. 1996). It has since been found (Kirby and Featherstone 2001) that these were caused by gross errors in the DEM. These have been removed in version 2, and new terrain corrections have been computed on a 9″×9″ grid. Importantly, the Australian DEM should be used in any revision of EGM96 to avoid the discrepancy in Figure 7.

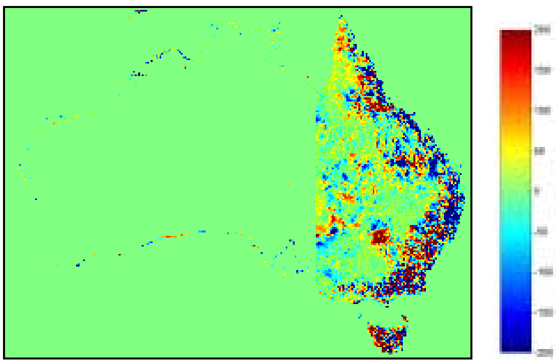

**Fig 7.** Differences (in metres) between TerrainBase and JGP95E DEMs over Australia

Of more concern is the highly variable quality of AGSO's gravity database (Murray 1997). This is inevitable given the size of the Australian continent and the 40+ years taken to compile the database. The largest source of error is in the elevations estimated for the gravity observations on land. A majority of the heights were determined using barometers, which are probably only precise to 4-6m. These were tied to spirit-levelling traverses, where available. However, a substantial part of the gravity data was collected is before the establishment of the AHD in 1971. In addition, the horizontal geodetic datum of the gravity observations is ambiguous and not well documented.

More recently, GPS and (generally unspecified) geoid models have been used to coordinate gravity surveys. This provides a 'catch 22' situation, since the gravity anomalies computed from these GPS-controlled gravity surveys are subject to the accuracy of the geoid model used. Referring to Figure 1, the differences between AUSGeoid98 and GPS-AHD data reach ~3.5m. This introduces additional errors into any geoid model computed from these GPS-levelled gravity measurements. However, the primary problem with the AGSO database is that there are no records with which to trace the origin of the gravity observations, heights and datum. This will probably remain a restriction to Australian geoid determination for many years, until new surveys are conducted.

The AGSO marine gravity data are also problematic. The main limitation is that not all ship tracks have been crossover adjusted. Some crude data editing was used for AUSGeoid98 (Featherstone et al. 2001). However, Claessens et al. (2001) show that erroneous ship-track data remain near Perth. This is of concern since the satellite altimeter gravity anomalies were 'warped' to fit the marine gravity data in coastal regions (Kirby and Forsberg 1998). While Featherstone and Guo (2001) show that this inclusion of satellite altimeter gravity anomalies generally improves the fit of AUSGeoid98 to GPS-AHD data in coastal regions, there is scope for improvement if the problematic ship tracks can be corrected. However, the ship-track records are not currently stored in the AGSO database in such a way that a crossover adjustment can be applied.

One alternative is to reject the ship-track data altogether and rely instead on the satellite altimeter-derived gravity anomalies alone. However, during the AUSGeoid98 project, this approach was shown not to improve the situation. This is probably because of the degradation of the satellite altimeter data close to the coasts, due to the combined effects of the rougher sea surface state, backscatter and off-pointing of the radar to the land, poorly modelled shallow-sea tides, and poorly known coastal SST. The objection to this approach is that some reliable ship-track data may be rejected needlessly.

Finally, topographic mass-density data are not available for the entire Australian continent. This affects both the computation of the geoid (Tziavos and Featherstone 2000) and Helmert orthometric corrections (Allister and Featherstone 2001). It also prevents the rigorous downward continuation of gravity data and causes aliasing during gravity gridding. In other countries, topographic corrections can reduce this aliasing by removing high-frequency topographic signals before gridding. In Australia, however, the topographical corrections are relatively small, whereas there are large density contrasts that are not associated with topography. A digital density model may remedy this problem. However, since this is unlikely to become available in the near-term, one solution is to use normal height system and compute a quasi-geoid model in Australia.

## 5 Prospects

From the above results and discussion, there is increasing evidence for a north-south tilt in the 1971 realisation of the AHD, and there are numerous data-related problems with AUSGeoid98. Despite the existence of improved mathematical models for the computation of the geoid, the primary limitation remains the quality and availability of the data. Resurveying (levelling and gravimetry) a continent the size of Australia is currently prohibitive, especially in these times of economic rationalism. Therefore, alternative strategies must be sought that will make the best use of the existing data. Importantly, the AHD and the Australian geoid must be treated in a more holistic way, rather than treating them largely separately as has been done in the past.

### 5.1 Fitting a geoid model to the AHD?

A pragmatic solution to the discrepancies in Figure 1 is to combine AUSGeoid98, or preferably a revised gravimetric geoid model, with GPS-AHD heights. This gives a *direct* transformation of GPS-derived ellipsoidal heights to the AHD and *vice versa*. It also avoids the user having to post-process GPS-AUSGeoid98-derived heights to make them compatible with existing benchmarks. The desire for this type of model is based upon the many arguments presented in Featherstone (1998). This approach was applied successfully in Western Australia (Featherstone 2000b). Such combined models are being used in other countries, most notably in the USA (eg Smith and Roman 2001).

However, this combined approach is affected very dramatically by errors in one or both of the GPS and AHD data used. As such, claims of the performance of these combined geoid-type models should be treated with great scepticism, especially if the same data have been used to both create and test the models. As stated, the AHD contains distortions of ~1m and a north-south tilt of ~1.5m (Figure 5). Therefore, a 'pure' gravimetric geoid model, which may be a better representation of *the* equipotential geoid, will have to be distorted by these amounts to fit the existing AHD.

Nevertheless, this approach is currently being investigated over the whole of Australia with a view to providing a 'user-friendly' model of the separation between GRS80 and the AHD. This new geoid-type model may be released some time in 2002. However, in the longer term, this should only be considered as an interim solution until the gravimetric geoid is refined further, the AHD is revised, or both.

### 5.2 Total revision of the AHD?

As well as the systematic errors described earlier, numerous gross errors exist in the AHD. Therefore, a redefinition is probably warranted. For example, an additional 30 years of new and repeat levelling data, and additional (Figure 1) and longer-term tide gauge records have been collected. A readjustment including these new data could use the tide gauges as checks or even constraints on the new AHD. If multiple tide gauges are to be used (as was the case for the 1971 adjustment), then SST models should be considered. That is, the adjustment is constrained to the SST values at the tide gauges, rather than be held fixed to zero height at MSL. The use of a constraint is to allow for the problems with coastal SST models (Hipkin 2000).

However, before any readjustment, the height system should be decided upon. Allister and Featherstone (2001) show that Helmert orthometric corrections using topographic mass-density data can be significant. As stated however, there is no nation-wide density model for Australia. Therefore, the use of a normal height system becomes a more attractive option, especially since it avoids unrealistic hypotheses of the Australian topographic mass-density, which is known to vary rapidly from gravity observations in topographically smooth regions. If a normal height system is chosen, then the focus will also have to change to Australian quasi-geoid determination. As per the above section, the geoid or quasi-geoid model would probably have to be refitted to this new vertical datum. However, the GPS-quasi/geoid data can be included as a check, or even included as a complementary data source in the adjustment. However, the latter requires careful consideration of the correlations among the various data sources used.

Clearly, there are many technical issues that need to be considered to produce a new AHD. The principal argument against a total revision is the inconvenience that will be caused to its numerous users.

### 5.3 An AHD based on GPS and a geoid?

The above use of GPS and the geoid in vertical datum definition can be taken further, where only GPS ellipsoidal heights minus a regional geoid model define the vertical datum. That is, no levelling or MSL data are used. Such a proposal is currently receiving attention in Canada and New Zealand. This approach has merit in the future since significant advances in gravimetric geoid determination are expected due to satellite gravity gradiometry (eg CHAMP, GRACE and GOCE). However, given the relatively poor quality the Australian gravity data, this solution does not appear to be practical for Australia in the near term.

*Acknowledgments.* The Australian Research Council has funded geoid and vertical datum research in Australia through grants A49331318, A39938040 and DP0211827.

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