

An Evaluation of Geoid Models on the Great Dividing Range Escarpment

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ABSTRACT

An evaluation was made of commonly used global and Australian regional geoid models. Absolute and relative comparisons over 46.2 km, using 116 control points (6,670 baselines) and over elevations between 200 m and 600 m show that AUSGeoid98 is the superior geoid model for the conversion of GPS-derived ellipsoid heights to AHD elevations in the test area.

Keywords: Geoid, GPS, height, level

INTRODUCTION

An integral part of most engineering projects is the provision of suitable horizontal and vertical control. This task is often performed using the Global Positioning System (GPS) to provide horizontal coordinates on the national mapping datum (GDA94), and conventional levelling to derive or propagate elevations on the national vertical datum, the Australian Height Datum (AHD).

Conventional levelling can be resource intensive, particularly in undulating terrain. As a consequence, it is often more efficient to use GPS to derive elevations as well as horizontal coordinates. To do this a gravimetric geoid model is used to convert GPS-derived ellipsoid heights to elevations on some vertical height datum such as the AHD. This process has been well documented (Gilliland 1986; Kearsley 1988; Collier & Croft 1997; Featherstone *et al.* 1998).

Many geoid models, both global and specific only to Australia, are available for this purpose. Information is required on the comparative accuracy and reliability of these geoid models so informed decisions can be made as to which geoid model might be suitable to use for particular projects.

Consequently, an empirical evaluation of several commonly used gravimetric geoid models was carried out to determine the suitability of each model for use with GPS heighting. This evaluation was limited to a test site on the Great Dividing Range escarpment near Toowoomba, Queensland.

The geoid models tested were the OSU91A (Rapp *et al.* 1991), EGM96 (Lemoine *et al.* 1998), EIGEN2/EGM96 (Amos & Featherstone 2003), UCPH2/EGM96 (Amos & Featherstone 2003) and PGM2000A (Pavlis *et al.* 2000) global geoid models, and the AUSGeoid93 and AUSGeoid98 geoid models of Australia available from Geoscience Australia. The evaluation included both bi-cubically and bi-linearly interpolated geoid heights for the two Australian regional models. The evaluation also included an assessment of both absolute and relative heighting, although it is recognised that, since gravimetric geoid models are generally deficient in scale due to an inexact knowledge of the total mass of the Earth, the relative verification is more useful to the GPS user.

BACKGROUND

The OSU91A global geoid model has a resolution of approximately 15' x 15' which equates to approximately 27-30 km (Featherstone & Alexander 1996, p.30). Because of this poor spatial resolution, OSU91A is expected to exhibit a bias over the short to medium baselines in this study.

The EGM96 global geoid model also has a grid resolution of 15' x 15' (NIMA 2003). Featherstone *et al.* (2001, p.314) comment that, based on the debatably improved computational methods, amount of input data, and comparisons with a national control data set, the EGM96 global geoid model only provides a marginally better solution over Australia than OSU91A.

The EIGEN2/EGM96 and UCPH2/EGM96 global geoid models are hybrid models. Amos and Featherstone (2003, p.16) found that comparisons between several global

models including EIGEN2/EGM96, UCPH2/EGM96 and EGM96 indicate that these hybrid models provide a small, though statistically insignificant, improvement on EGM96 over the Australia-New Zealand region.

The PGM2000A global geoid model is a combined model that preserves the orbit and land geoid modelling performance of EGM96, although it also includes improved sea surface topography (Pavlis *et al.* 2000). The practical implication of this variation in gravimetric geoid solution is a marginally finer resolution than EGM96 over the Australian oceanic region that may provide a statistically better result than EGM96 in this study.

In general, comparisons between the global geoid models and the empirically derived control data are expected to exhibit a bias over the short to medium baseline lengths due to their coarse geoid height grid resolution, although improved results may be obtained over longer baselines.

The former national gravimetric geoid model, AUSGeoid93, consists of a 10' x 10' grid (approximately 20 km) of gravimetric geoid heights with respect to the WGS84 ellipsoid. This model improved on the long wavelength component of OSU91A, which in practice provides GPS users with a more accurate method of converting GPS-derived ellipsoid heights to elevations on the AHD than using the global models.

The latest in the series of national gravimetric geoid models in Australia is AUSGeoid98. AUSGeoid98 was released on a 2' x 2' (approximately 3.6 km) grid of N values computed in terms of the GRS80 ellipsoid, which is compatible with the

WGS84 ellipsoid used with GPS (Johnston & Featherstone 1998, p.1; Featherstone *et al.* 2001, p.316).

RESEARCH METHODS

Test Site

The location of the test site for the geoid evaluation was on the Great Dividing Range escarpment near Toowoomba, which is approximately 150 km west of Brisbane, Queensland. This area is the subject of a major civil construction project. Currently in the planning phase, the proposal is to build a second range crossing to the north of Toowoomba to alleviate the impact of expected traffic volume increases over the next 10-15 years on the existing highway and local road network through which it passes. The proposed new road corridor is approximately 43 km in length, rising 450 m from the bottom to the top of the range.

Existing permanent marks along the proposed alignment were standard brass plaques set in concrete. New control stations were placed at approximately 500 m intervals along the preferred alignment in early 1999. These marks were 2.4 m galvanised star pickets, driven full depth into the ground or to refusal, with loose concrete collars at surface level for protection. A total of 116 control points were used for this study, consisting of 107 new control stations and 9 existing permanent marks.

General Test Method

GPS observations were used to coordinate the control and transform it onto GDA94. All baselines were measured with dual frequency receivers and geodetic quality

antennas with observation times sufficient to provide a fixed solution on all baselines. A by-product of this was GPS-derived ellipsoid heights for each of the control stations. This network of control stations were also assigned Australian Height Datum derived (AHDd) heights from earlier conventional levelling. Since the control had both ellipsoid heights and AHD heights, an empirical ‘geoid’ height could be calculated at each control station. This empirically derived geoid height was then compared against values obtained from the geoid models under consideration. At this point it is worth acknowledging that AHD itself has some inherent weaknesses (Featherstone *et al.* 2001), but these have been ignored for the purposes of this study.

Precision estimates were attached to the ellipsoid heights and AHD heights based on the results from appropriate adjustments explained in the following sections of this paper. This enabled the error to be estimated for each empirically derived geoid height and to allow statistical comparisons to be made between each gravimetric geoid model.

These comparisons were made between the geoid models and the empirically derived geoid heights in both an absolute and relative sense (explained in detail in the later sections). The main aim was to determine whether GPS, in conjunction with the geoid models being evaluated, could achieve accuracy and precision equivalent to that obtained via conventional levelling in the case study area. Furthermore, the comparisons were also expected to reveal whether any of the prototype gravimetric geoid models being validated were more suitable for GPS heighting than the current national gravimetric geoid model, AUSGeoid98, in the case study area.

Data Acquisition – Reduced Levels

The levelling data was obtained from a series of digital level traverses performed to 3rd order (class LC) specifications in a series of loop closures and adjusted to produce AHDd elevations on the control stations. Results from this adjustment were used to establish an estimated variance (σH^2) of the AHDd heights or reduced levels (RLs). The average variance (σH^2) was calculated and converted to a standard deviation for the RLs (σH) of ± 12.7 mm (or ± 24.9 mm at the 95% confidence level). Individual σH for the control stations ranged up to a maximum of ± 20 mm. These error statistics of the control points were ultimately used to estimate the accuracy of the empirical geoid heights.

Featherstone (2001, p.811) acknowledges that it is difficult to quantify the error present in AHD heights from a tolerance and that the absolute accuracy of the AHD heights is not critical considering that the main use of a geoid model is to convert GPS-derived ellipsoid heights to elevations on the AHD.

Data Acquisition – Ellipsoidal Heights

The ellipsoid height data was obtained from a least-squares adjustment of the network of baselines observed as part of the GPS campaign to coordinate the control. To facilitate the use of all possible baselines in the statistical analysis of each geoid model, a single homogeneous network of ellipsoid heights was computed. Results of this network adjustment were used to assign error statistics to the ellipsoidal heights.

Point positions were also observed at 20 control stations. These data were post-processed by Geoscience Australia's AUSPOS (Geoscience Australia 2004) Online GPS Processing facility to obtain three-dimensional point positions relative to the GRS80 ellipsoid. The GPS baselines were combined with the 20 AUSPOS computed point positions in a single network adjustment.

The adjustment consisted of both a minimally constrained and fully constrained adjustment. The estimated variance for each GPS-derived ellipsoid height (σ_h^2) was obtained from the constrained least-squares adjustment report.

The average variance (σ_h^2) was calculated and converted to a standard deviation for the ellipsoidal heights (σ_h) of ± 13.4 mm (or ± 26.2 mm at the 95% confidence level). Individual σ_h for the control stations ranged between ± 6 mm and ± 28 mm. This precision of the ellipsoid heights was combined with the error estimate for the RLs to estimate the accuracy of the empirical geoid heights.

Empirical Geoid

The empirical geoid heights used as the standard of comparison in the verification of each geoid model were determined by subtracting the RL from the ellipsoidal height at each control point, i.e., $N_{CTRL} = h_{GPS} - H_{AHD}$. The result is empirically derived geometric *estimates* of separations between the GRS80 ellipsoid and the local vertical datum (AHD). These separations are commonly known as 'N values'.

Note that the resultant N values represent the separation between the GRS80 ellipsoid and the AHD, as opposed to separations between the GRS80 ellipsoid and the equipotential geoid (Featherstone *et al.* 2001, p.316). This is because the geoid and the height datum differ due to sea surface topography and other errors. Consequently the empirically derived geoid heights cannot be relied upon as absolutely accurate, however, at present the use of empirical geoid heights to validate geoid models on land is the most practical method available (Featherstone 2004, p.334).

Featherstone (2001, p.811) and Featherstone *et al.* (2001, p.317) comment that it is essential to recognise that the GPS and levelling data used in the verification of gravimetric geoid models are subject to their own error budgets. Accordingly, an estimation of the quality of the empirical geoid heights was calculated by adding the estimated variance of the ellipsoid height (σ_h^2) to the estimated variance of the AHDd height (σ_H^2). This resulted in an estimated variance (σ_N^2) of the empirical geoid height at each control point.

The average variance (σ_N^2) was calculated and converted to a standard deviation for the N values (σ_N) of ± 18.9 mm (or ± 37.1 mm at the 95 % confidence level). These error statistics provide an estimate of the accuracy of the empirical geoid heights.

Geoid Model Interpolation

Whilst other methods are available to interpolate values from gravimetric geoid models, the bi-cubic and bi-linear interpolation methods are most commonly used (Featherstone 2001, p.808). Consequently the evaluation of the two Australian

regional models (AUSGeoid93 and AUSGeoid98) included both bi-cubically and bi-linearly interpolated geoid heights. The bi-linear method alone was used for all global geoid models.

Bi-cubic interpolation uses polynomials of degree three, in two dimensions, to calculate the appropriate N value at a particular location. Sixteen points are required to use this interpolation method. Bi-linear interpolation uses straight-line interpolation, in two dimensions, to calculate the appropriate N value at a particular position. Only four points are required to use this interpolation method.

Absolute Evaluation

Featherstone (2001, p.809) notes that an error in this type of empirical evaluation ($N_{CTRL} = h_{GPS} - H_{AHDd}$) comes from neglecting the deflection of the vertical. The approximate error can be calculated by multiplying the orthometric height by the cosine of the deflection of the vertical at the point of interest. Applying this principle, a calculation was made to validate the use of the absolute verification method in this study. The largest deflection of the vertical with respect to the GRS80 ellipsoid over the project area is $-8.031''$ and the maximum AHDd height is 708.203 m, which equates to an approximate error of less than 0.001 m. As this is not significant in comparison to the error statistics of the calculated N values, the deflection of the verticals was ignored in all subsequent calculations.

Empirical geoid heights at each control point were calculated by *algebraically* subtracting digitally levelled AHDd heights from GPS-derived ellipsoid heights

($N_{CTRL} = h_{GPS} - H_{AHDd}$). This is illustrated graphically in Figure 2. Note that some drafting licence was taken by depicting the plumbline for H as a straight line, when in reality it is curved and at right angles to the geoid. These empirical geoid heights were then used as a standard of comparison to assess the integrity of gravimetric geoid heights interpolated from each geoid model at these same known control points.

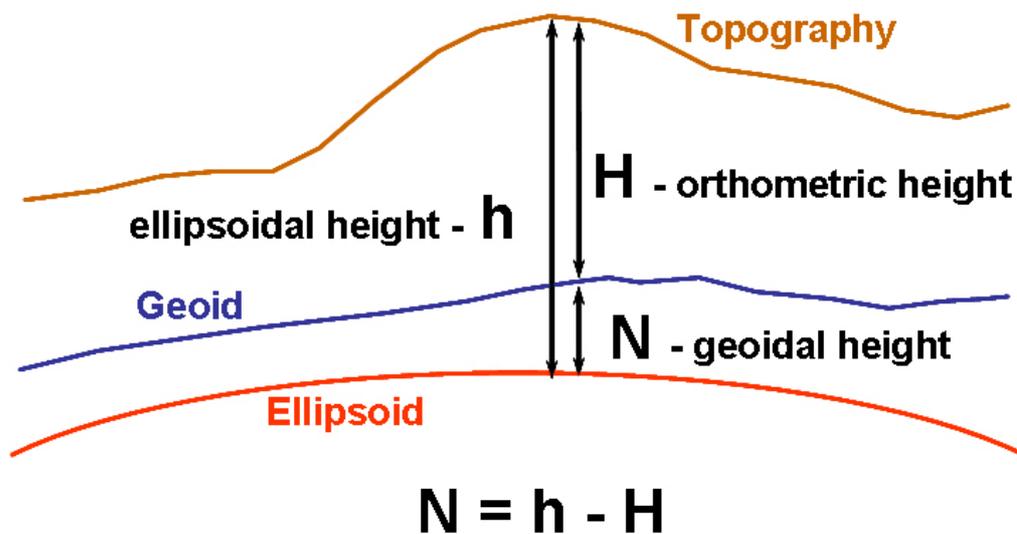


Figure 2. N values for absolute evaluation

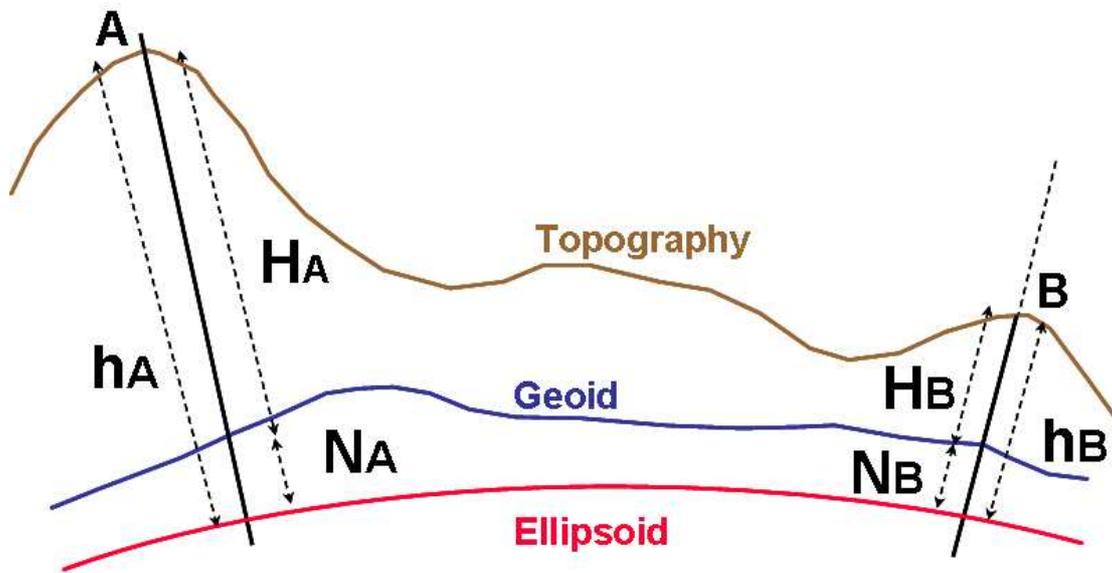
The practical implication of these assessments is that they provide an indication of the suitability of each geoid model for the recovery of AHD heights in an absolute sense, as would be required when conducting a GPS point positioning survey.

Absolute comparisons were made between the 116 empirical geoid heights and the N values interpolated from each geoid model. The empirical N value (N_{CTRL}) at each control point was subtracted from the gravimetric geoid model N value (N_{GM}) interpolated at each control point, i.e., $\Delta N = N_{GM} - N_{CTRL}$. The result was a residual geoid height difference at each control point.

Relative Evaluation

Relative verification was conducted by *algebraically* subtracting the levelled AHDd height differences from the GPS-derived AHD height differences calculated using each geoid model (i.e., $\Delta H_{GPS} - \Delta H_{AHDd}$) over all possible baselines in the control network. Featherstone and Alexander (1996, p.31) indicate that this is equivalent to comparing the relative accuracy and precision of geoid gradients computed using each gravimetric geoid model to geoid gradients derived empirically from the difference in GPS and levelling data over equivalent baselines.

As noted by Featherstone (2001, p.810) this type of assessment is more informative to the GPS user than the absolute evaluation since most GPS surveys are performed in the relative mode. That is, GPS baselines are observed between control stations to yield a difference in ellipsoid height (Δh), which must be converted to a difference in orthometric height (ΔH) via the appropriate difference in geoid height (ΔN). Accordingly, for relative geoid verification, the difference in orthometric height is *algebraically* subtracted from the difference in ellipsoid height to give the empirical geoid gradient over the baseline as illustrated in Figure 3.



$$\Delta N = \Delta h - \Delta H$$

Figure 3. Relative evaluation

RESULTS AND DISCUSSION

Absolute Evaluation

Figure 4 shows the absolute comparisons with all 116 control points for the global models. ΔN on the vertical axis refers to the algebraic difference between the N values from each of the geoid models (N_{GM}) minus the empirically derived N values (N_{CTRL}). Zero on the graph represents the empirically derived N value. In Figures 4 to 6 inclusive the baseline length on the horizontal axis refers to the location along the control network starting at the western end at 'Athol' (refer to Figure 1) and increasing eastward to 'Helidon'.

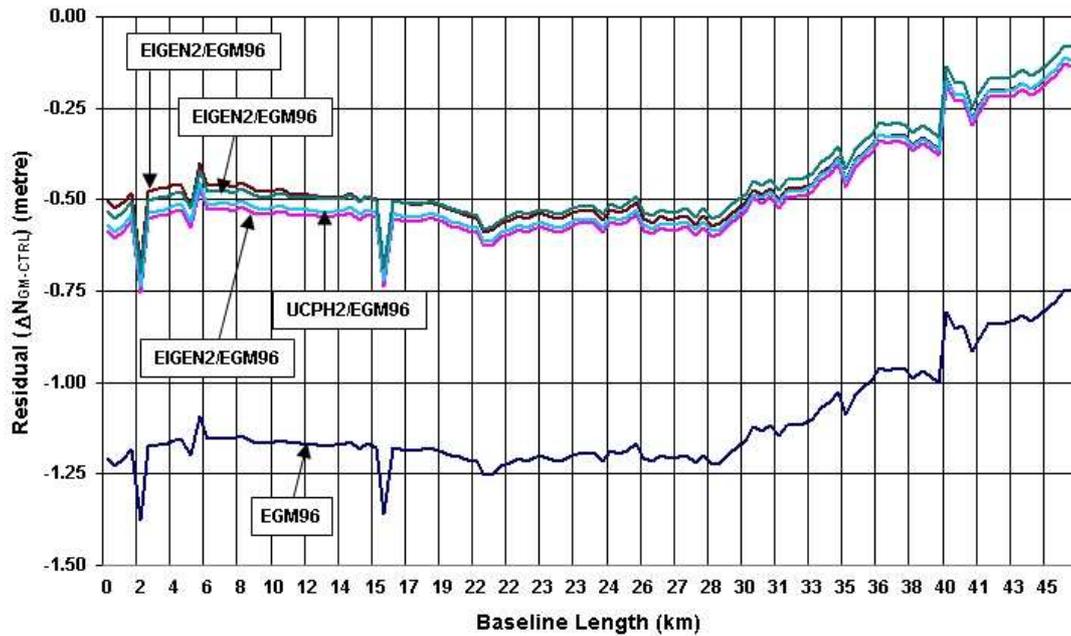


Figure 4. ΔN for global geoid models

The maximum variation between OSU91A, EIGEN/EGM96, UCPH2/EGM96 and PGM2000A is only 0.049 m and hence, these global geoid models are offset by a similar amount from the empirical geoid (but not necessarily parallel to it). It is difficult to draw any conclusions as to which model is more accurate when it is considered that the precision of the empirical N values is ± 37.1 mm at the 95 % confidence level. However, it is obvious that EGM96 exhibits the worst absolute accuracy, (i.e., largest bias in scale) with an average offset 0.649 m worse than the other global geoid models over the test area. This variation may be more significant in this test area than was expected from earlier evaluations by Amos and Featherstone (2003, p.16) (although it is noted that the zero-degree term, which relates the difference between the mass of the earth and the mass of the EGM96 global geopotential model, should account for approximately 0.56 of this offset).

The practical implications of this absolute comparison is that it would be difficult to achieve reliable heights using GPS point positioning over the test area using any of the global geoid models in this study.

Furthermore, because the ΔN values in Figure 4 exhibit an obvious non-horizontal linear trend, particularly over the steeper slopes of the range escarpment (meaning the geoid models are not parallel with the empirically derived model over the test area profile), this would limit the effectiveness of any 'block shift' correction being applied to the N values to improve their GPS point positioning capability. This is to be expected because the global models will not define the area along the Great Dividing Range escarpment to the same accuracy as the finer resolution Australian regional models.

Figure 5 shows the absolute comparisons with all 116 control points for the Australian regional models using both bi-linear and bi-cubic interpolated values.

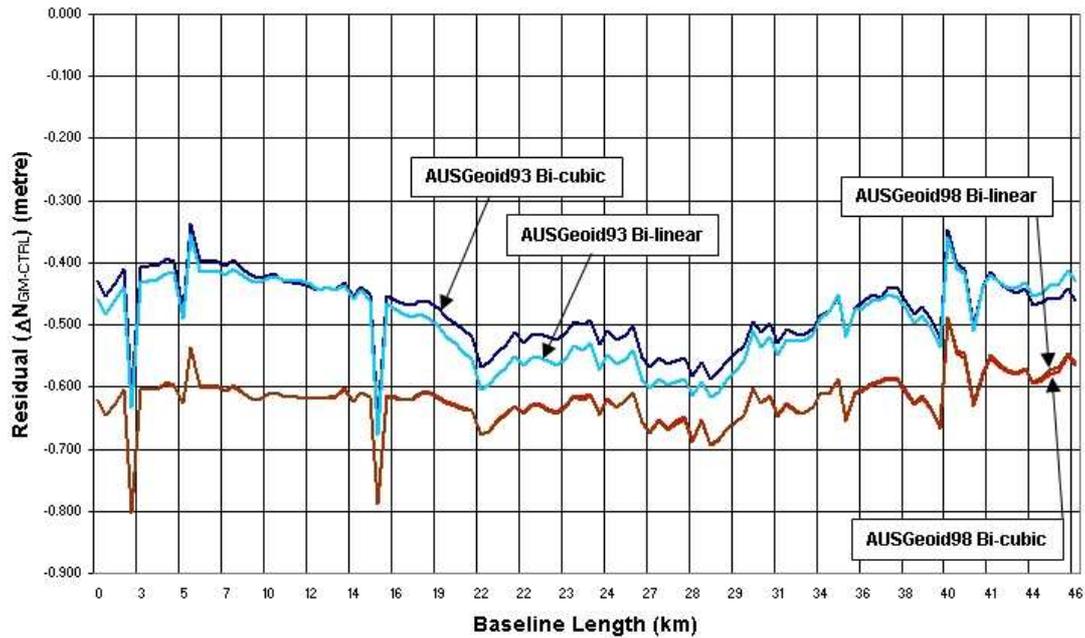


Figure 5. ΔN comparison of bi-linear vs bi-cubic interpolation for Australian geoid models

The residual geoid height differences from AUSGeoid93 are the closest to zero over the test area. This means that for point positioning in the test area, AUSGeoid93 will provide better accuracy than AUSGeoid98. This finding is similar to Featherstone and Guo (2001, table 4, p.86).

A comparison between values shown in Figures 4 and 5 demonstrates that neither regional model can be said to be significantly better or worse than global geoid models. With due consideration to the precision of the empirical N values, it appears that over this test area AUSGeoid93 provides a significant improvement in absolute fit to the control data compared to EGM96. This finding is similar to Featherstone and Guo (2001, table 2, p.85) if results are adjusted to account for the mass difference mentioned earlier.

It is interesting to note in Figure 5 that the regional models are close to parallel with each other over the test area, particularly considering the precision of the empirical N values of ± 37.1 mm at the 95 % confidence level. The variability in the N values interpolated from these models indicates that, like the global geoid models, the regional models are not parallel to the empirical geoid over the range escarpment profile. However, since there is no obvious non-horizontal linear trend as there is with the global models, this indicates that they are significantly more parallel to the empirical geoid than the global geoid models over the test area. The practical implication of this is that these regional models would permit a simple 'block shift' correction to be applied to the interpolated N values to significantly improve the heighting capability of GPS point positioning over the test area. Note though, the use of GPS point positioning to derive accurate elevations on the AHD is not recommended.

There seems to be a slight difference between bi-linear and bi-cubic interpolation for AUSGeoid93 with the bi-cubic method generally providing more accurate results. But there is very little difference between the two interpolation methods for AUSGeoid98. These findings are consistent with results achieved by Featherstone and Guo (2001, table 4, p.86).

Relative Evaluation

As previously noted, gravimetric geoid models are generally deficient in scale due to an inexact knowledge of the mass distribution of the Earth (i.e. the zero-degree term).

This results in a less reliable assessment of the gravimetric geoid model from absolute verification. Thus, the most relevant appraisal of the integrity of gravimetric geoid models from the point of view of the GPS user is by relative verification.

The most relevant analysis from a practical perspective is an evaluation that determines whether GPS heighting can achieve an equivalent accuracy and precision to that obtained by conventional levelling. To verify each gravimetric geoid model in a relative sense, a comparison was made of the misclose over baselines to the equivalent Australian 3rd order levelling specifications ($12 \sqrt{k}$ mm where k is the distance levelled in kilometres), which is equivalent to differential levelling class LC under SP1 specification (ICSM 2002).

Note that the GPS-derived AHD height difference (ΔH_{GPS}) between any two control stations is a function of the N values from the geoid model used. For each baseline from the western most control point to all other control points along the route, the difference between ΔH_{GPS} for each global geoid model and the levelling derived AHD height difference (ΔH_{AHDd}) is presented in Figure 6. The height difference on the vertical axis is defined as $\Delta H_{\text{GPS}} - \Delta H_{\text{AHDd}}$.

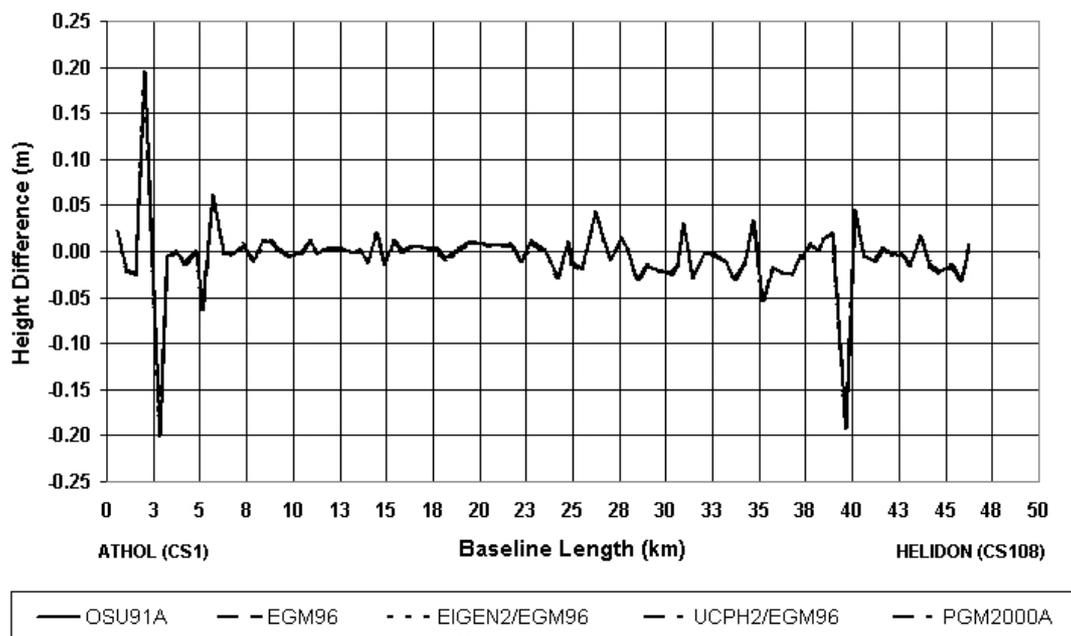


Figure 6. Difference between GPS and levelled height differences

It is impossible to distinguish between the different geoid models at this plot scale. It is concluded that there is no significant difference between the results obtained from the global geoid models. The large spikes indicate differences that are well outside 3rd order level tolerances, and may be due to errors in the levelled AHDd heights at those stations. Note that it is possible to have level loops closing within specification if there are two equal and opposite gross errors in the loop. No other explanation is offered and these anomalies were not investigated further.

As described earlier, the ellipsoid height data was obtained from a combined least-squares adjustment of the network of GPS baselines. This produced a single homogeneous set of ellipsoid heights for the network of control stations. The total number of possible baselines between n control points is given by $n(n-1)/2$. For this study the total number of control points (n) is 116. Therefore the total number of possible baselines available for assessment is 6,670.

The analysis process used to derive data in Figure 6 was extended to all of the 6,670 possible baselines. The difference between ΔH_{GPS} for each global geoid model and the levelling derived AHD height difference (ΔH_{AHDd}) for all 6,670 possible baselines was calculated. Figure 7 shows the magnitude of the relative difference between EGM96 global model and the GPS-AHD control data ($\Delta H_{GPS} - \Delta H_{AHDd}$). As before, the height difference on the vertical axis is defined as $\Delta H_{GPS} - \Delta H_{AHDd}$. As no significant variation was found between any of the geoid models, only the EGM96 scatter plot is reproduced here. The two lines on the graph indicate the 3rd order level specification.

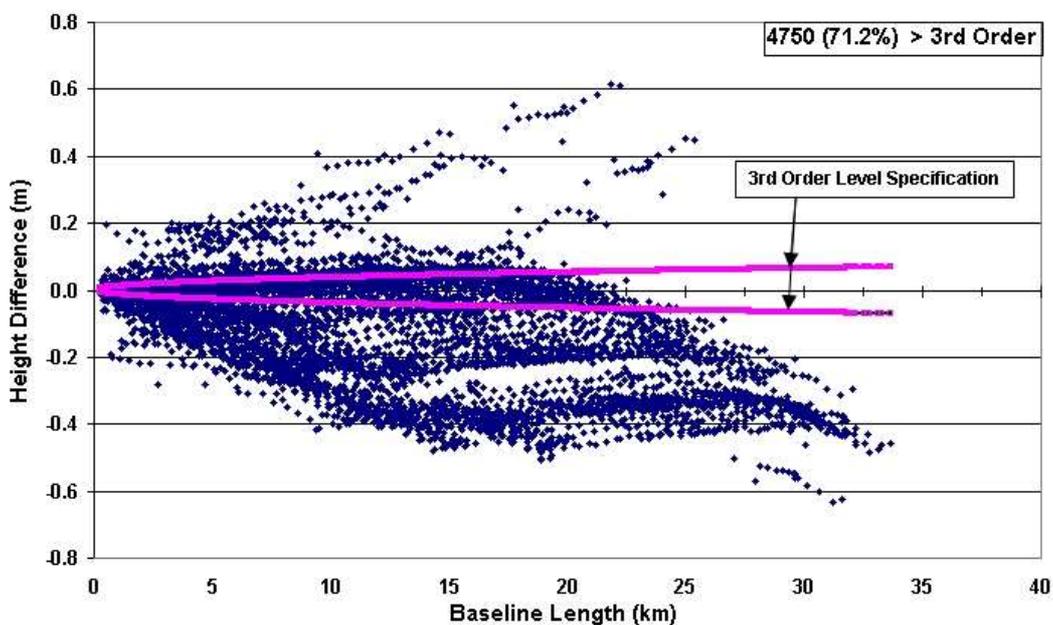


Figure 7. Relative difference between GPS ΔH using EGM96 and levelled ΔH

Figure 7 shows that when using GPS in conjunction with EGM96 (and in fact any of the global geoid models), the majority of the relative height differences are outside 3rd

order levelling specifications for the baselines. Furthermore, the relative differences from each of the global models exhibit a general negative trend or bias. This information is more easily quantified in tabular form. Statistics of the relative differences between the empirical geoid gradients and gravimetric geoid gradients interpolated from each global geoid model over all 6,670 possible control baselines are shown in Table 1. Note that the values in the right hand column are ‘raw’ percentages and have not been adjusted to account for the errors in h and N.

Table 1. Statistics for *relative differences* ($\Delta H_{GPS} - \Delta H_{AHDd}$) using global geoid models

Model	Max. (m)	Min. (m)	Mean (m)	σ (m)	% > 3rd Order
OSU91A	0.575	-0.564	-0.079	0.157	77.38%
EGM96	0.616	-0.632	-0.101	0.166	71.12%
EIGEN2/EGM96	0.607	-0.624	-0.099	0.163	71.62%
UCHPH2/EGM96	0.611	-0.625	-0.099	0.165	71.57%
PGM2000A	0.610	-0.625	-0.099	0.164	71.36%

It can be seen that no global model satisfied the 3rd order specifications with any degree of reliability. For all global models, greater than 70% of baselines were outside the 3rd order level specification.

Similar descriptive statistics for the relative differences between the empirical geoid gradients and gravimetric geoid gradients from each bi-cubically and bi-linearly interpolated geoid model of Australia over all 6,670 possible control baselines are shown in Table 2.

Table 2. Statistics for *relative* differences ($\Delta H_{GPS} - \Delta H_{AHDd}$) using Australian regional geoid models

Model	Max. (m)	Min. (m)	Mean (m)	σ (m)	% > 3 rd Order
AUSGeoid93 (Bi-cubic)	0.319	-0.272	0.020	0.078	67.92%
AUSGeoid93 (Bi-linear)	0.323	-0.279	0.015	0.093	71.08%
AUSGeoid98 (Bi-cubic)	0.295	-0.311	-0.005	0.055	39.19%
AUSGeoid98 (Bi-linear)	0.301	-0.315	-0.006	0.057	41.33%

There is little difference between statistics from the bi-linear and bi-cubic interpolation although, as expected, for both regional models bi-cubic gave slightly better results. AUSGeoid98 produced more accurate results than AUSGeoid93.

A greater percentage of the baselines for both AUSGeoid93 and AUSGeoid98 satisfied 3rd order specifications when compared to the global models, although AusGeiod93 is only marginally superior to the best of the global models (EGM96). This can be seen graphically by comparing the scatter plot shown in Figure 7 with similar plots for the regional geoids shown in Figures 8 and 9.

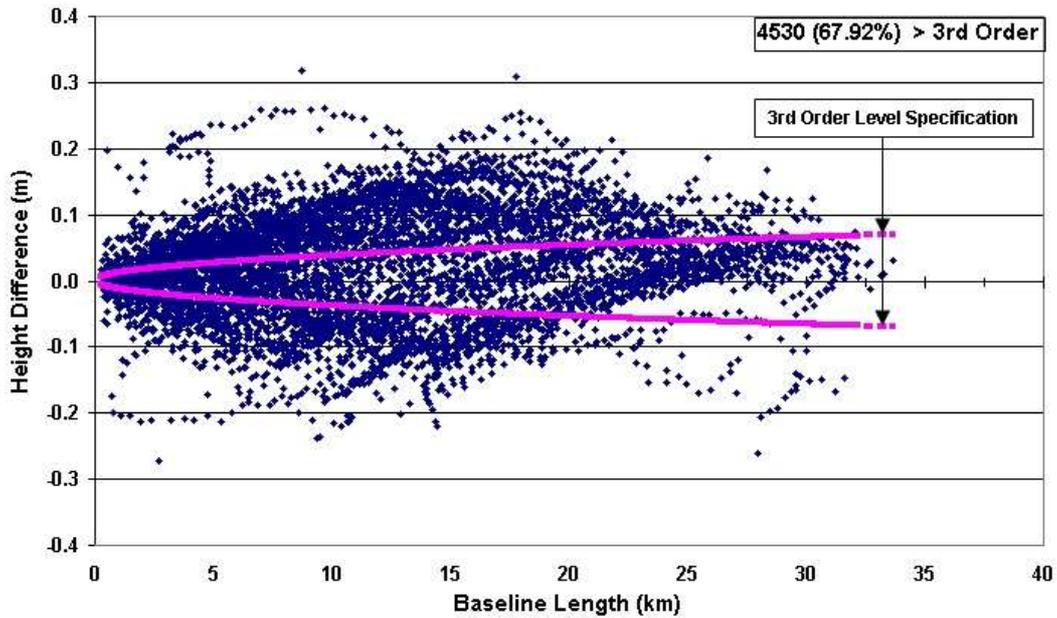


Figure 8. Relative difference between GPS ΔH using AUSGeoid93 (bi-cubic) and levelled ΔH

The relative differences demonstrate that, when using GPS in conjunction with AUSGeoid93, the majority of relative height differences are outside the equivalent 3rd order tolerance. It should be accepted though that some of the larger height differences may be due to the variations seen in Figure 6.

AUSGeoid93 has removed a small amount of the short wavelength trend exhibited by the global models, has converted the negative medium wavelength trend to a positive trend and removes most of the long wavelength trend exhibited by the global models. However, as can be seen from Figure 8 and Table 2, a small positive long wavelength trend remains.

Figure 8 shows that the majority of relative differences using AUSGeoid93 are outside the equivalent 3rd order specification for baselines up to about 25km, but for baselines greater than about 25km, results are generally within the equivalent 3rd order specification.

The relative differences shown in Figure 9 confirm that when using GPS in conjunction with AUSGeoid98 the majority of relative height differences are within the equivalent 3rd order specification. And there seems to be very little significant bias to the results.

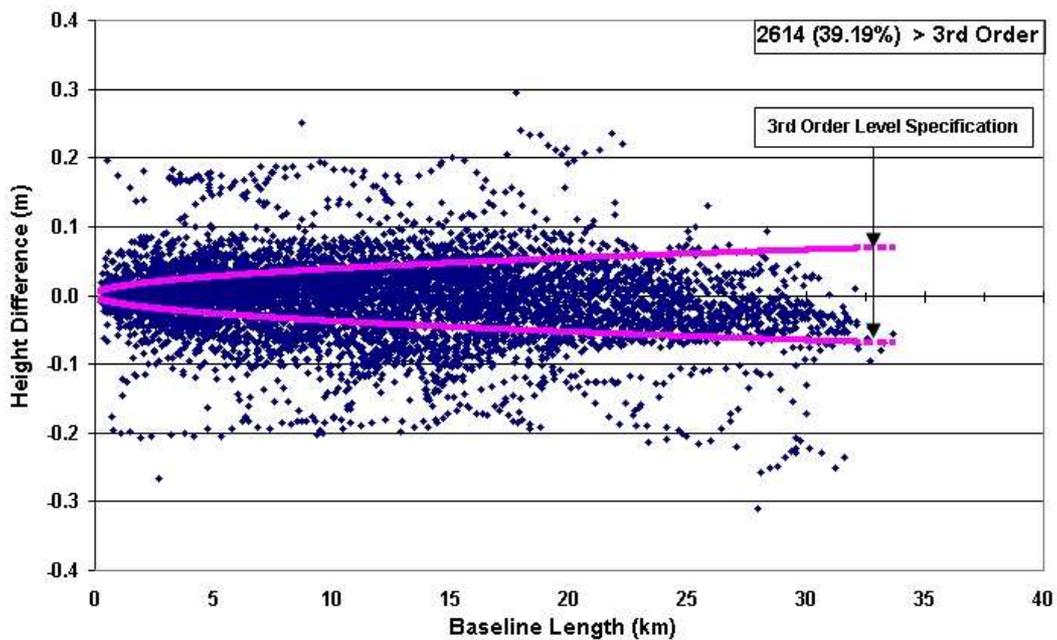


Figure 9. Relative difference between GPS ΔH using AUSGeoid98 (bi-cubic) and levelled ΔH

The majority of relative differences using AUSGeoid98 are outside the equivalent 3rd order specification for baselines up to approximately 5km. For baselines greater than about 5km, the majority of results are within the equivalent 3rd order specifications.

CONCLUSION

This study compared the accuracy and reliability of several geoid models against empirically derived geoid heights to determine the suitability of each geoid model for use with GPS heighting over the Great Dividing Range escarpment at Toowoomba.

Notwithstanding the fact that the use of GPS point positioning to derive accurate elevations on the AHD is not recommended, the conclusion to be drawn from the absolute comparison is that it would be difficult to achieve reliable heights from GPS point positioning over the test area using any of the global or regional geoid models evaluated in this study. If one had to be chosen, then AUSgeoid93 using bi-cubic interpolation would yield most accurate results in the test area. Either regional model with either interpolation method would be suitable for heighting if marks with known RLs were measured and a 'block shift' used to account for the bias.

The use of geoid models for GPS differential heighting was evaluated over the full 46.2km range escarpment profile, against 116 control points, using all 6,670 possible baselines and over heights varying from 200m to 600m. The conclusion was that GPS differential heighting used in conjunction with the global geoid models (OSU91A, EGM96, EIGEN2/EGM96, UCPH2/EGM96 and PGM2000A) would be inadequate

for converting GPS-derived ellipsoid heights to elevations on the AHD over the Great Dividing Range escarpment at Toowoomba.

Evaluations of bi-cubically and bi-linearly interpolated regional geoid models lead to the conclusion that bi-cubically interpolated N values generally provides a superior and more stable statistical fit to the control data than bi-linear interpolation. This is attributed to the grid spacing of the geoid model grids as it is less reliable to bi-linearly interpolate from a coarse grid such as AUSGeoid93 than a finer grid such as AUSGeoid98.

Evaluation of GPS used in conjunction with the bi-cubic and bi-linear interpolations of AUSGeoid93 and AUSGeoid98 regional geoid models led to the conclusion that AUSGeoid98 is the superior model for converting GPS-derived ellipsoid heights to elevations on the AHD over the Great Dividing Range escarpment at Toowoomba and hence, should be used with GPS heighting on local projects such as the Toowoomba range bypass.

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