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AUSGEOID98:
A NEW GRAVIMETRIC GEOID FOR AUSTRALIA

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ABSTRACT

AUSGeoid98 is a new national geoid model that replaces AUSGeoid93. A two-minute grid of geoid-GRS80-ellipsoid separations and the associated deflections of the vertical have been computed for the area bound by 8° S to 46° S and 108° E to 160° E. AUSGeoid98 offers improvements over previous geoid models of Australia, particularly in areas of rugged terrain and coastal regions. It also offers significant improvements over AUSGeoid93 in some local areas, most notably the Adelaide hills. Therefore, AUSGeoid98 will provide surveyors with a greater accuracy when transferring Australian Height Datum (AHD) heights using Global Positioning System (GPS) techniques than was possible with previous geoid models. The AUSGeoid98 grid of geoid values, vertical deflections and *Winter* interpolation software can be downloaded free-of-charge from the Australian Surveying and Land Information Group's (AUSLIG) world wide web-site (www.auslig.gov.au)

INTRODUCTION

The geoid is the equipotential surface of the Earth's gravity field that closely approximates mean sea level and is, by definition, perpendicular to the direction of gravity at all points. Since the mass distribution within the Earth is not uniform and the direction of gravity changes accordingly, the geoid is an undulating surface. On the other hand, the ellipsoid is a mathematical surface obtained by rotating an ellipse about its semi-minor axis. The dimensions and orientation of the ellipsoid are usually chosen to give a "best fit" to the geoid over a given area, which in this case is the whole Earth.

The separation between the geoid and ellipsoid (*N*) is needed to transform ellipsoidal heights (*h*), derived from Global Positioning System (GPS) surveys, to heights (*H*) on the Australian Height Datum (AHD) according to $H = h - N$. The choice of ellipsoid also impacts upon the size of this separation. The geoid-ellipsoid separation used for GPS levelling is generally best determined over large areas using gravimetric techniques. The evaluation of Stokes's integral over the surface of the Earth gives an estimate of the *N*-value at any point. In practical terms, however, this evaluation is not done over the surface of the Earth, but only over the area of interest.

The gravimetrically determined geoid-ellipsoid separation is considered to consist of two components. The first is the long wavelength component given by a global geopotential model, which is derived predominantly from the analysis of artificial Earth satellites. This is the larger of the two components. The second component is the medium and short wavelength contribution, which is evaluated through the use of local gravity and terrain data in a modified version of Stokes's integral. The summation of the two components at each computation point, and including some small correction terms, results in a determination of the full geoid-ellipsoid separation.

This paper describes the production of a new gravimetric geoid model of Australia, called AUSGeoid98. AUSGeoid98 will then be validated using GPS and AHD data across the whole continent and in areas where AUSGeoid93 was found to be deficient.

AUSGEOID98

AUSGeoid98 is the third in a series of national geoid models produced for Australia by the Australian Surveying and Land Information Group (AUSLIG). The computational techniques utilised for AUSGeoid98 are in line with the recommendations and outcomes of Australian Research Council grant A49331318 (eg. Featherstone *et al*., 1997). These include the use of the:

- EGM96 global geopotential model (Lemoine *et al*., 1997);
- GRS80 ellipsoid (Moritz, 1980), which is compatible with WGS84;
- Australian Geological Survey Organisation's (AGSO) 1996 national gravity database;
- AUSLIG / AGSO GEODATA nine-second digital elevation model (Caroll and Morse, 1996);
- Satellite altimeter-derived free-air gravity anomalies offshore (Sandwell *et al*., 1995);
- Theories, techniques and computer software developed by Associate Professor Will Featherstone, Curtin University of Technology (eg. Featherstone *et al*., 1997 and 1998; Kirby and Featherstone, 1998).

AUSGeoid98 (Figure 1) replaces the currently accepted geoid model for Australia, which is known as AUSGeoid93. AUSGeoid93 was the second in a series of national geoids for Australia produced by AUSLIG. It superseded AUSGeoid91 and other geoid models in existence at that time (Kearsley and Govind, 1991). It used the OSU91A global geopotential model produced by Professor Richard Rapp, Ohio State University (Rapp *et al*., 1991), the 1980 AGSO gravity database, and techniques and software developed by Associate Professor Bill Kearsley, University of New South Wales (Kearsley, 1998) with an integration cap radius of 0.5 degrees.

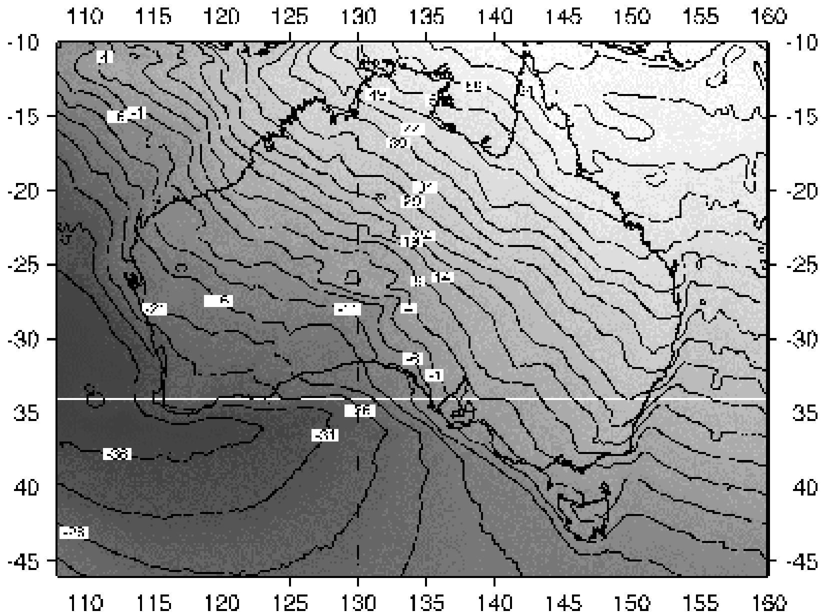

Figure 1. AUSGeoid98 (Rectangular projection from GRS80. 5m contour interval)

AUSGeoid93 had an estimated accuracy of better than 0.5m in absolute terms (Steed and Holtznagel, 1994) and around 2-3 ppm in a relative sense (Kearsley, 1988). The tests described later will show the current estimate of AUSGeoid93's absolute accuracy to be 0.510m. The AUSGeoid93 product has been available from AUSLIG in areas coinciding with AUSLIG's 1:250,000 topographic map series, on a ten-minute WGS84 grid, and in an ASCII format. It was also supplied with Windows-based interpolation software, called *Winter*. The differences between AUSGeoid98 and AUSGeoid93 are shown in Figure 2.

AUSGeoid98 has been released on a two-minute (approximately 4km) GRS80 grid over the area bound by 8° S to 46° S and 108° E to 160° E. It uses the same ASCII format as that used for AUSGeoid93. It is supplied on a 1:250,000 map-sheet basis from the AUSLIG world wide web-site www.auslig.gov.au). The AUSGeoid98 *N*-values refer to the GRS80 ellipsoid, so it can be used to directly transform GPS heights to the AHD and is also compatible with the new Geocentric Datum of Australia (eg. Manning and Steed, 1998). Deflections of the vertical have also been computed from AUSGeoid98 and are supplied in the data format. The AUSGeoid98 *N*-values and vertical deflections can be interpolated using the *Winter* software, which can also be down-loaded from the AUSLIG world wide web-site.

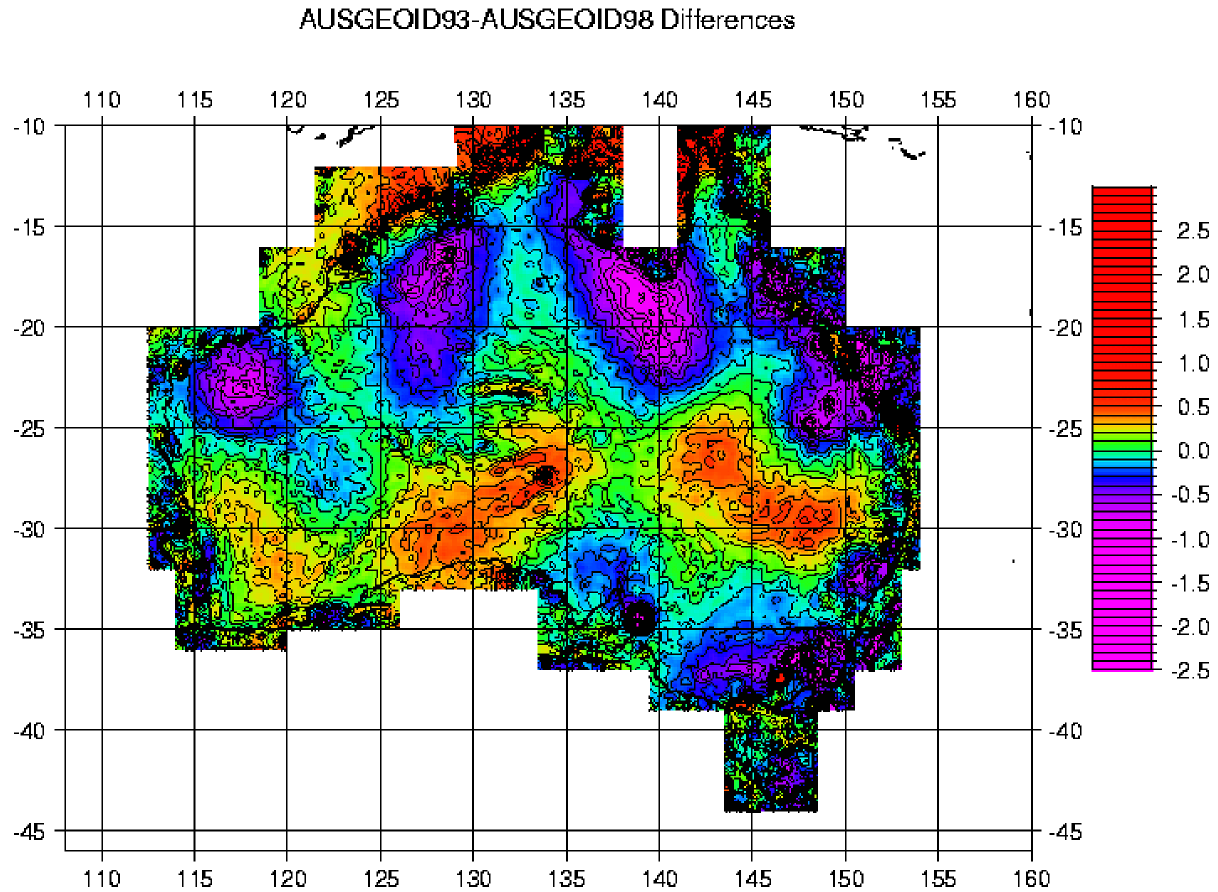

Figure 2. Differences between AUSGeoid98 and AUSGeoid93 (Rectangular projection from GRS80. 0.25m contour interval)

AUSGEOID98 COMPUTATION AND IMPROVEMENTS

Ausgeoid93 is deficient mainly in areas of large terrain gradients (cf. Figure 2). This can be attributed to a number of effects. For instance, gravity observations are typically recorded along roads and tracks in areas of rugged terrain. These usually follow valleys or areas of least height variation. Therefore, very few gravity observations are taken at points of maximum or minimum height in a given area. As such, the gravity anomalies and resultant geoid are biased by these observation techniques (ie., the observed gravity value does not truly represent the mean gravity value of an area). A similar, though opposite, effect occurs in central Australia where observations were often performed by helicopter surveys. These points were located on hilltops where convenient landing spots were identified.

To counter these biasing effects, the AUSLIG/AGSO nine-second digital elevation model (DEM) has been used to reconstruct more representative mean free-air gravity anomalies. In addition, gravimetric terrain corrections (eg. Zhang *et al*., 1997), also based on the AUSLIG/AGSO DEM, have been computed on a twenty-seven second grid to avoid the instability in the terrain correction equation (Zhang *et al*., 1998). These terrain effects were not considered in AUSGeoid93, which explains why AUSGeoid98 has made improvements in areas of rugged terrain.

Another area in which AUSGeoid98 has been improved is in near coastal regions through the use of gravity anomalies derived from satellite altimeter missions. AUSGeoid98 uses these data via a "draping" technique (Kirby and Forsberg, 1998), which is based on a least squares collocation algorithm, to adjust the offshore satellite altimetry gravity values onto marine gravity tracks. This also allows a smooth transition from near coastal land gravity observations to the marine observations. This approach removes the continental edge effects previously seen in AUSGeoid93 (cf. Figure 2).

The above procedures were used, together with a spline algorithm, to generate a two-minute grid of mean gravity anomalies over Australia and its offshore seas. The gravity anomalies implied by the EGM96 global geopotential model (Lemoine *et al*., 1997) were then subtracted to yield residual gravity anomalies, ready for a Stokesian integration. The one-dimensional Fast Fourier transform (FFT) technique (Haagmans *et al*., 1993) was used to perform this integration, which produced a grid of geoid undulations based on EGM96. Importantly, the use of the one-dimensional FFT gives a large computational efficiency and has thus allowed a high-resolution geoid to be computed.

A modification to the Stokes integration kernel (Featherstone *et al*., 1998) is also used in this process. This modification allowed the gravimetric geoid to fit the geometric geoid control (ie., GPS and AHD heights at discrete points) with a lower standard deviation (see Table 1). In addition to providing a theoretical advantage, this improvement has been verified for three different cap sizes.

Gravimetric geoids created for Canada and the United States (eg. Sideris and She, 1995) using FFT techniques, apply no cap to limit the amount of gravity data used in the geoid computation. While this appears to work effectively under those circumstances, our tests indicate that a less than optimum result is achieved in Australia with this technique. This is evident from the geoid statistics over a variety of cap sizes in Table 1, where the fit worsens as the cap size increases. For instance, the 180 degree cap yields a standard deviation of 1.113m, whereas the 1 degree cap yields a standard deviation of 0.364m.

This degradation of the geoid results with increasing integration cap size is probably due to noise in the gravity observations and associated height data. The Australian gravity database was collected primarily for geophysical interpretation rather than for physical geodesy applications and, as such, the accuracy of the height observation associated with each gravity point is less than optimum.

A number of other corrections have also been used in AUSGeoid98, including

- the indirect effect correction (Wichiencharoen, 1982), which has also improved AUSGeoid98 in areas of large terrain variation; and
- a zero-degree bias term of 0.937m (Kirby and Featherstone, 1997), which accounts for the differing masses of the Earth and the EGM96 model. This agrees very well with the value of 0.940m, which is the mean offset from the uncorrected gravimetric N-value and the geometrically derived N-value across the Australian data set.

AUSGEOID98 VALIDATION RESULTS

Two separate forms of gravimetric geoid validation on land are possible. The first is an absolute comparison of gravimetric geoid-ellipsoid separation with the geometric (GPS minus AHD) geoid-ellipsoid separation. This has been completed at 906 points across Australia. The points chosen have ellipsoidal heights derived from a three-dimensional least-squares adjustment of GPS data spanning Australia, and constrained to the Australian Fiducial Network (AFN) and the Australian National Network (ANN). This adjustment was completed using the NEWGAN geodetic adjustment software (Allman, 1993). The points also have third-order, or better, optically levelled AHD heights.

Table 1 shows the standard deviation of the 906 geoid height residuals for a variety of different integration cap radii, with and without the use of a kernel modification. The optimum cap radius of 1.0 degree with a modified kernel yields the smallest standard deviation of 0.364m, while the use of an unmodified kernel yields a standard deviation of 0.402m. AUSGeoid93 yields a standard deviation of 0.510m. Therefore, it is clear that the use of a modified integration kernel and a limited integration cap provide an optimum AUSGeoid98 solution, which also improves upon AUSGeoid93.

Cap radius (degrees)	Modified kernel	Unmodified kernel
0.2	0.403	
0.25	0.395	
0.3	0.389	
0.4	0.379	
0.5	0.373	
0.6	0.370	
0.7	0.367	
0.8	0.366	
0.9	0.364	0.395
1.0	**0.364**	**0.402**
1.1	0.364	0.411
1.2	0.364	
1.3	0.365	
1.4	0.366	
1.5	0.368	
180	1.113	
AUSGeoid93	0.510	

Table 1. Standard deviations of the differences between gravimetric geoids and GPS-AHD data for various cap radii and with and without a kernel modification (units in metres)

The second form of gravimetric geoid validation on land uses relative comparisons over baselines. This tests the relative accuracy of the geoid-ellipsoid separation (ie., the gradient) as opposed to the absolute accuracy of these values. This test is more useful to the majority of users who will use AUSGeoid98 for height transfer using GPS. While the tests completed thus far show a general improvement in the relative accuracy of AUSGeoid98, these are by no means exhaustive and further tests are in progress.

Figure 3 shows the baseline comparisons in some of the areas around Australia where height transfer using GPS was previously known to deliver poor results when using AUSGeoid93. These areas include the Adelaide hills, southern ACT, the Brisbane area, the Cairns area, the Perth area, and the southern

NSW region. A total of 46 baselines were used in the analysis.

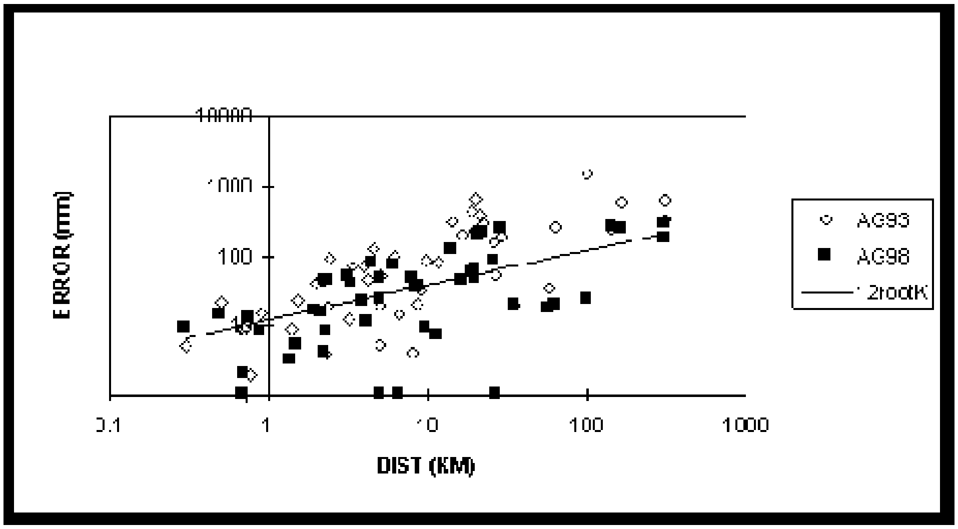

Figure 3. Baseline comparisons between AUSGeoid93, AUSGeoid98 and GPS-AHD data (logarithmic scale)

From Figure 3, considerable improvement can be seen over some of the baselines and a general improvement over several others. However, some baselines show no improvement over AUSGeoid93. A number of factors contribute to this. Firstly, errors in the AHD and GPS heights at the points being used as control contribute additively to the overall error in the baseline comparison. Secondly, errors in AUSGeoid93 may compensate for this to give a falsely accurate answer. Nevertheless, the overall indication is the AUSGeoid98 improves upon AUSGeoid93.

In addition to the results summarised in Figure 3, the average error over all 46 baselines in these ‘problem areas’ has been computed. The average of the allowable error under the 12√ km (mm) third-order levelling specification is 48.6mm. GPA and AUSGeoid98 produces an average error of 57.2mm, which is just outside these third-order specifications. However, GPS and AUSGeoid93 yields an average error of 155.7mm, which is well outside the third-order specifications. Accordingly, this represents a 272% average improvement when using AUSGeoid98 for height transfer using GPS in these areas. Recall, however, that these comparisons are also subject to an error budget associated with the GPS and AHD data at either end of each baseline.

While it is noted that these baselines have been deliberately chosen in areas where a significant improvement was expected, these results indicate that, on average, the user’s ability to obtain accurate AHD height results from GPS surveys will be improved with AUSGeoid98. It is also expected that when a similar analysis is completed in areas of relatively smooth terrain, the achievable results will generally lie within the third-order specifications.

CONCLUDING REMARKS

A considerable improvement in AHD height determination using GPS and AUSGeoid98 has been made over AUSGeoid93. This can be seen in both the absolute and relative comparisons. The recommendations of the previously mentioned ARC research have been implemented and the software developed from this research has been adopted. Clearly, AUSGeoid98 will allow users to more confidently calculate AHD heights using GPS surveying measurements. The refinement of the Australian geoid model will also open the door for an evaluation of the AHD and the future demands put on this datum by the surveying and mapping industry.

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Biographical Notes

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Will Featherstone, BSc(Hons1), DPhil(Oxon), FRAS, MIEMSAust, MISAust, MMSIAust, is currently Associate Professor of Geodesy at Curtin University of Technology. He is active in the administration and promotion of the profession in his roles as Federal Councillor of the Institution of Surveyors, Australia and President of the Australasian Surveying and Mapping Lecturers' Association.

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