DATA PREPARATIONS FOR A NEW AUSTRALIAN GRAVIMETRIC GEOID

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ABSTRACT

The rationale is given for a new determination of the Australian gravimetric geoid. In preparation for this task, the Australian Geological Survey Organisation's gravity data base has been validated and reformatted. Additional information in the form of digital terrain data are available from the Australian Surveying and Land Information Group's 9" by 9" Digital Elevation Model (DEM), derived from ~5.2 million spot elevations and the ~0.6 million elevations in the gravity data base. Both gravity and terrain data were transformed to give their horizontal position on the GRS80 ellipsoid, which produces a homogeneous data source for subsequent geoid computations. The gravity anomalies were computed using a second-order, free-air correction and normal gravity was computed using GRS80 latitude. Satellite altimeter-derived gravity anomalies are also considered as an additional source of information in offshore areas. The statistical fit of the new EGM96 global geopotential model to geometrical control provided by the Australian Fiducial and National GPS Networks is shown to be an improvement upon the OSU91A model, upon which AUSGEOID93 was based.

INTRODUCTION

The geoid can be described as the equipotential surface of the Earth's gravity field which corresponds most closely with mean sea-level in the open oceans and ignores the effects of sea surface topography. One of its major applications in surveying and geodesy is to transform GPS-derived ellipsoidal heights to orthometric heights. Such use of the geoid in conjunction with GPS can significantly reduce the costs associated with 'conventional' levelling. For example, the field time required to provide height control between two points 100km apart is less than one day with dual-frequency relative GPS, compared with eight to

ten days, or more, for third-order optical levelling methods. Detailed cost comparisons are difficult to ascertain, but this anecdotal example suggests an order of magnitude reduction in survey cost.

The gravimetric method can provide a model of the geoid that is suitable for this coordinate transformation, provided that homogeneous gravity and terrain data coverage is available, which is the case in Australia. A modern gravimetric geoid is computed through a combination of three primary data sources. These comprise:

1. a global geopotential model, which provides most of the long and intermediate wavelength (>100km) geoid undulations;
2. terrestrial gravity observations surrounding the area of interest, which supply most of the intermediate wavelengths (>10km), and;
3. a high resolution digital terrain model, which supplies most of the short wavelengths (<10km).

The pre-processing of gravity and terrain data is of prime importance, because if errors remain in any of these input data, they will propagate into any subsequent geoid solution. An additional consideration is that data preparation can be the most time-consuming component of any practical geoid determination on a continental scale. This process can take many times longer than the geoid computation itself, and should be factored into the total time required to compute a gravimetric geoid.

This discussion is concerned with the requirements for a new determination of the Australian gravimetric geoid, which may supersede the current AUSGEOID93 (Steed and Holtznagel, 1994), and the pre-processing of the data required specifically for this task.

THE NEED FOR A NEW AUSTRALIAN GEOID MODEL

There are a series of geoid models which have been computed for the Australian continent. They are of differing age, resolution and accuracy, are based on various geodetic datums, and were computed by various methods. For a chronological review of these earlier geoid determinations, see Kearsley and Govind (1991). The most recent continent-wide gravimetric geoid models are AUSGEOID91 and AUSGEOID93, which were computed by the Australian Surveying and Land Information Group (AUSLIG) using software developed by Kearsley (1988a and 1988b).

These geoid models are supplied by AUSLIG to all users for a small fee, calculated on a cost recovery basis. AUSGEOID93 is supplied on a 10 arc minute (approximately 20km) grid. This can be reduced to approximately 10km (as implied by the resolution of the Australian gravity data) through a rigorous geoid computation at each of the required points. However, even this resolution has proven to be too low for GPS height determination in some cases (eg. Featherstone and Alexander, 1996).

The absolute accuracy of AUSGEOID93 is estimated to be less than 0.5m (Steed and Holtznagel, 1994). The relative accuracy currently achieved from the Australian geoid in conjunction with GPS varies between 2-3ppm of baseline length in most areas (Kearsley, 1988b). However, some long baselines (>100km) provide 1-2ppm and short baselines (<10km) greater than 4ppm. Moreover, systematic discrepancies of 5-10ppm are encountered in areas of rugged topography, which can be attributed to either terrain effects on the geoid or Australian Height Datum (AHD) errors, which were used to test the gravimetric geoid in these areas. Nevertheless, AUSGEOID93 in conjunction with GPS has proven to be an adequate alternative to third-order optical levelling in many cases (Steed and Holtznagel, 1994; Featherstone and Alexander, 1996).

AUSGEOID93 and its gravimetric predecessors are, in fact, free-air compensated geoids or co-geoids. This is because the full effect of topography has been neglected during their computation. For GPS to be used to its full potential in the more mountainous regions of Australia, the topographic effects should therefore be considered. The justification for this is twofold: The mathematical basis of gravimetric geoid determination requires that the effect of topography is taken into consideration to properly solve the geodetic boundary value problem. Secondly, a detailed digital elevation model (DEM) can provide the short wavelength contributions to the geoid. The omission of detailed topographic data in the existing Australian geoid models is the most likely cause of the deficiencies observed in mountainous regions. As such, the inclusion of Australian elevation data is expected to improve the precision and accuracy of the geoid in these regions.

Another point of concern is the lack of detailed gravity data offshore Australia (see Figure 1), which has restricted geoid determination near its coast (Pearse *et al.,* 1995). In Australia, the coast is densely populated and highly developed, which requires more extensive surveying and thus demands the most reliable geoid solution. The inclusion of satellite altimeter data (Figure 2) is considered as a supplementary data source and is expected to improve the geoid solution near the coast.

Also, a number of theoretical and practical advances in geoid determination have been made in recent years. One such example is the fast Fourier transform (FFT), which can allow a time-efficient computation of a gravimetric geoid. This approach has evolved from the planar FFT (Schwarz *et al.,* 1990), to the spherical FFT (Strang van Hees, 1990), to the multi-band FFT (Forsberg and Sideris, 1993), and the one-dimensional FFT (Haagmans *et al.,* 1993), which is reported to give results identical to numerical integration. The effects of cyclic convolution and windowing in the FFT have also been addressed by Sideris and Li (1993).

This Australian geoid research project is expected to enable the production of a geoid with relative precision of 1-2ppm irrespective of location, an absolute accuracy of 0.1-0.2m, and a spatial resolution of a few kilometres in pertinent regions. These accuracy expectations agree with results achieved in other parts of the world, such as Canada (Sideris and She, 1995), the USA (Milbert, 1992) and Europe (Denker *et al.,* 1995).

Therefore, in view of the deficiencies expected and encountered with AUSGEOID93, in conjunction with the above developments, it is timely to compute a new gravimetric geoid of Australia. This will be achieved through:
1. Testing the latest theories and methodologies against those used at present, in order to establish an optimum approach for Australia.
2. Incorporating satellite altimeter data offshore Australia to improve the geoid solution at the continental edge.
3. Including new digital topographic data, which were not used in any of the previous geoid computations.

The methods, results and data produced as a result of this collaborative project will be supplied to AUSLIG who, in their role as custodians of the Australian geoid, will incorporate it into geodetic infrastructure and distribute it to Australian users. This will ensure that only a single National geoid model will be in use at any one time, and ensure that the GPS user in Australia will have access to the most up-to-date gravimetric geoid model.

AUSTRALIAN GRAVITY DATA
In Australia, the datum adopted for gravity measurements is called Isogal84 (Wellman *et al.,* 1985). This provides a network of absolute gravity values which are tied to the

International Gravity Standardisation Network 1971 - IGSN71 (Morelli *et al.,* 1971). A denser network of gravity observations are supplied relative to these base stations, the majority of which were collected using helicopter surveys in the 1950s, 60s and 70s. It can, therefore, be assumed that all gravity observations on the Australian continent are referred to a common datum.

Barlow (1977) estimates the observation errors (standard deviation) of these relative gravity data to be ±0.3mgal, and the error in their height, observed barometrically, to be ±4-6m. The latter estimate infers an error in the gravity reduction of ±1.2-1.8mgal. This error is, in most cases, an order of magnitude greater than other possible error sources, such as the second-order, free-air correction (mentioned later). This situation will not be improved upon until new gravity surveys are conducted using improved height determination techniques, such as levelling or even a combination of GPS and gravimetric geoid heights.

Mather *et al.* (1976) published one of the earliest discussions on the use of the Australian gravity data for geodetic purposes. Gilliland (1987) subsequently created a continent-wide gravity data base specifically for geoid computations in Australia. The latter discussion relates to the 1980 release of the Australian Geological Survey Organisation - AGSO (formerly the Bureau of Mineral Resources - BMR) gravity data base. Gilliland identified a number of gross errors in these data, which were deleted at that time.

Between 1980 and 1992, nearly 100,000 marine and land gravity observations have been added by AGSO to produce a data base comprising 638,492 observations. The spatial resolution of these data is approximately one observation per 7km in Tasmania and South Australia and one observation per 11km elsewhere. This resolution increases dramatically where detailed gravity surveys have been conducted in areas of geophysical interest (see Figure 1). The 1992 release of the Australian gravity data base has been supplied for use in this geoid project by AGSO. These data have been re-validated at the University of South Australia as part of this project in order to identify errors in the additional observations and any that may have remained following the earlier validation by Gilliland (1987).

GRAVITY DATA VALIDATION

The validation of the Australian gravity data base has proven to be a most time consuming process, taking many months. Several approaches were used to identify gross errors in the 1992 AGSO data release, including the methods employed by Gilliland (1987) and Featherstone (1992). If the suspect data could not be corrected, they were simply deleted from the data base. The approach used to detect erroneous data was based upon the following general scheme:

1. Gravity surveys known to be in error from the earlier validation by Gilliland (1987). These surveys were confirmed by AGSO to still contain errors (Murray, 1994 pers comm).
2. Records where no raw gravity observation was supplied.
3. Records where the height of a station was greater than any elevation given on topographic maps or the AUSLIG spot height data base (described later).
4. Duplicate records.
5. Records with non-numeric characters where numeric characters were expected.
6. Marine observations which appeared to be on land or have a positive elevation, and vice versa.
7. Records with an unexplainable difference between the ground and gravimeter heights.
8. Records with extremely large or small observed values of gravity.

9. Comparisons of free-air and Bouguer gravity anomaly values given in the data base with those recomputed from the observed gravity and station coordinates.

After these numerical tests had been applied, a visual approach was used to identify any further erroneous data. Colour images of the free-air gravity anomalies were produced and points or profiles which appeared to be out of place in relation to nearby anomalies were checked once more by manually editing the data file, and deleted if necessary. This latter approach is quite effective but extremely time consuming.

After these validation procedures, 4091 records were removed to leave 634,401 gravity observations in the new data base. The coverage of the observations in this new data base is shown in Figure 1.

Figure 1. *The coverage of the 634,401 points remaining in the 1992 AGSO gravity data base after removing those observations found to be in error. (Mercator's projection)*

GRAVITY REDUCTION

One stage in the process towards determining a gravimetric geoid is the computation of free-air gravity anomalies, via:

$$\Delta g_{FA} = g_S - \gamma + \delta g_{FAC} + \delta g_{ATM} \qquad (1)$$

where, g_S is gravity observed on the Earth's surface, γ is normal gravity on the surface of WGS84, δg_{FAC} is the free-air reduction, and δg_{ATM} is the atmospheric correction to gravity. The latter two corrections are applied using the height of the gravity observation supplied in the AGSO data base.

Computation of normal gravity

Normal gravity (γ) is evaluated on the surface of the normal ellipsoid using the Somigliana-Pizetti closed formula (Moritz, 1980). Normal gravity refers to a geocentric ellipsoid, and thus requires geocentric geodetic coordinates for its computation. Therefore, the AGD (Australian Geodetic Datum) coordinates of the AGSO gravity observations must be transformed to the Geodetic Reference System 1980 - GRS80 (Moritz, 1980), which is an internationally accepted normal ellipsoid.

This was achieved using a seven-parameter transformation, with Higgins's (1987) constants, and the procedures outlined by Featherstone (1995). This also produces a gravity data base which is compatible with the Geocentric Datum of Australia or GDA (Manning and Harvey, 1994). These data will be resupplied to AGSO, thereby allowing them to provide future gravity data releases on this new geocentric datum. More importantly, if the gravity data are not transformed to the datum on which the geoid is desired, small but systematic errors will be introduced during the gravity reduction that propagate into the geoid heights (Featherstone, 1995).

The free-air reduction

The free-air gravity reduction (δg_{FAC}) accounts for the decrease in observed gravity with increasing elevation above the geoid. A linear approximation of 0.3086mgal/m is commonly used, but this is not always representative of the actual decay of gravity with elevation near the Earth's surface. Instead, a second-order free-air correction is used, which causes the free-air gravity anomalies to vary by up to 0.31mgal from those computed using a linear correction in Australia (Featherstone, 1995).

The atmospheric correction

The atmospheric correction (δg_{ATM}) accounts for the gravitational attraction of the atmospheric masses above the gravity meter. This is also necessary because the value of normal gravity includes a component due to the Earth's atmosphere, and without this correction the gravity anomalies will be underestimated. Also, the gravity anomalies derived from a global geopotential model (described later) include the effect of the atmosphere, so the correction must be applied to terrestrial anomalies to ensure compatibility. The correction term in Featherstone (1992) was used, which is a least-squares-fit polynomial to the average atmospheric attraction of two standard atmospheric models.

The simple Bouguer reduction

Bouguer anomalies can be of value in geoid determination as they are expected to be relatively smooth and thus suitable for interpolation. The simple or slab Bouguer anomaly is given by:

$$\Delta g_{BA} = \Delta g_{FA} - \delta g_{BC} \qquad (2)$$

where the Bouguer correction is 0.1119mgal/m for a mean topographic density of 2670kg/m^3. As with the free-air reduction, this is also a function of the observation elevation given in the gravity data base.

A refined Bouguer anomaly takes into account the effect of the short wavelength topography close to the observation point. Gravimetric terrain corrections have not been applied to the entire gravity data base by AGSO. As such, a digital elevation model (DEM),

which is described later, is expected to remedy this deficiency. These corrections will be computed for the entire continent and applied to the gravity observations. The values of these terrain corrections will also be supplied to AGSO.

Thus, in geoid studies, the geodetic coordinates of the gravity, and terrain, observations should be referenced to GRS80 so as to ensure that the input data are provided on the same datum that the geoid is desired. This is also compatible with the Geocentric Datum of Australia. For the Australian gravity data-base, free-air gravity anomalies are computed on GRS80, after a horizontal coordinate transformation from the AGD, and use a second-order, free-air reduction and atmospheric correction. The formulae given in Featherstone (1995) require that normal gravity need only be computed once, which saves computer time, especially in the case of a data set as large as that over Australia. Another way to increase the processing time is to reduce the amount of reading and writing to disc, which can slow the processing time for large data sets. The restriction of reading and writing time can be reduced further by storing the gravity and terrain data as binary files, which a computer can read and write more quickly than ASCII files.

SATELLITE ALTIMETER GRAVITY

It is evident in Figure 1 that the gravity coverage offshore Australia is poor in relation to that of the land. The marine data are of varying spatial density and even absent in many areas. The gravity coverage can be of prime importance for geoid determination, because in order to determine the geoid height of a single point, gravity data surrounding that point are required. This point has been illustrated by, for example, Sideris and She (1995).

In previous studies of the Australian geoid, the optimal extent of the gravity data about each computation point can vary depending on each author's opinion, cf. Kearsley (1988a) and Gilliland (1994). Using a gravity data set which extends uniformly offshore will allow the optimum gravity data area for the Australian geoid to be studied further. The lack of data near the coast has already impeded some preliminary investigations by Pearse *et al.* (1995). Recently, it has become possible to supplement the AGSO marine gravity data with gravity anomalies derived from satellite altimetry.

In satellite altimetry, a timed radar pulse is used to measure the position of the instantaneous sea surface, given the position of the satellite in its orbit. This gives an estimate of the position of the geoid (neglecting oceanographic effects), which is used to determine marine gravity anomalies. More specifically, the measured geoid profiles are differentiated once to give deflections of the vertical, which are then converted to gravity anomalies using the planar fast Fourier transform. A degree-40 global geopotential model is also removed then restored as part of this process (Sandwell, 1992). A higher degree geopotential model will subsequently be removed from all gravity data, as only residual gravity anomalies are required.

It is acknowledged that the satellite altimeter geoid profiles are possibly a more useful and direct source of information for this study, and that the effect of sea-surface topography on the derived gravity anomalies may propagate into the geoid. However, due to the errors committed when gravity data are not available surrounding each geoid computation point, we expect improvements upon the existing gravimetric geoid near the coast of Australia.

Several satellite altimeter missions have recently been combined to produce a global marine gravity field of high resolution (Sandwell *et al.,* 1995). This comprises altimeter data from SEASAT, an average of 62 GEOSAT Exact Repeat Mission profiles, unclassified GEOSAT Geodetic Mission data south of 30°S, an average of the first sixteen 35-day-repeat

cycles of ERS-1, and fast delivery profiles from the ERS-1 Geodetic Mission. These combined data are available via anonymous ftp (file transfer protocol on the Internet) and are thus freely available for offshore Australia (Figure 2). Computer programs, supplied with these data, allow the user to extract gravity anomalies over any marine area. For this study, the extent of gravity data extracted will simply be increased or reduced as required.

Figure 2. *The coverage of every 20th satellite-altimeter-derived gravity anomaly offshore Australia. (Mercator's projection)*

The satellite altimeter gravity data are of a greater spatial resolution (approximately 2-4km) than the majority of observations in the 1992 AGSO gravity data base (approximately 7-11km). The greater observation density south of 30S is due to the unclassified GEOSAT Geodetic Mission data. Therefore, in principle, the marine geoid can be computed with a higher spatial resolution than the current continental geoid, AUSGEOID93.

A detailed investigation is currently nearing completion to compare the AGSO marine data with the satellite altimeter gravity. Preliminary results indicate that the marine gravity anomalies agree at the 5-10mgal level. This estimate, however, includes errors which may reside in the ship-borne observations, the altimeter measurements, or both.

DIGITAL TERRAIN DATA

Detailed terrain information was not used during the computation of the AUSGEOID93 model, which could explain the deficiencies experienced in mountainous regions. Therefore, it is important to evaluate the role of terrain effects on the Australian geoid. Terrain data are necessary in gravimetric geoid determination because the gravitational effect of topographic masses outside the geoid have to be mathematically condensed onto, or below, the geoid in order to satisfy the boundary value problem of physical geodesy (Heiskanen and Moritz, 1967). Also, high resolution terrain data can provide additional short wavelength geoid information and help smooth the gravity field prior to gridding.

The terrain effect on the gravimetric geoid is applied in two stages: Firstly, the gravimetric terrain correction (Moritz, 1968) is added to the terrestrial observations for a complete gravity reduction. Then, a co-geoid is computed from these gravity data, which must be converted to the geoid using a correction for the indirect effect of the gravity reduction (Wichiencharoen, 1982).

AUSLIG has made available its digital spot AHD height data base for this project comprising 5,143,063 records. These data cover the whole continent and have been derived from published 1:100,000 topographic map sheets and unpublished 1:100,000 map production material. Spot heights shown on these maps have been combined with selected points on contours to produce a data base which represents the significant terrain features. The vertical accuracy of these spot heights is estimated to be ±10m or better as this information is derived from 20m contours which are positioned accurate to within half a contour interval of their true position. The gravity station elevations can provide an additional source of 634,401 spot heights with an estimated accuracy of ±4-6m (Barlow, 1977). These data have not previously been included in the AUSLIG spot height data base. This was confirmed by simply comparing the horizontal coordinates of each data source.

The horizontal coordinates of the AUSLIG spot height data are supplied as easting and northing on the Australian Map Grid (AMG), and must be transformed to GRS80 for compatibility. This was achieved by using the procedures described in Featherstone (1995). These data were then concatenated with the validated gravity station elevations and interpolated onto a 1' by 1' (~1.8km) grid over the whole continent using the surface fitting algorithms of Smith and Wessel (1990).

Other DEMs of Australia are available from the Australian National University (ANU) of 0.05° (~5km) and 0.025° (~2.5km) resolution, which were generated using ANUDEM, the elevation-specific gridding technique of Hutchinson (1989). These DEMs were designed primarily for hydrological analyses and use approximately 400,000 AGSO gravity station elevations, 83,000 benchmarks, 19,000 trigonometric heights, 65,000 spot heights digitised from 1:250,000 topographic maps, and are supplemented with digitised breaklines (watercourses and lakes) to minimise the occurrence of spurious drainage features during the gridding process. The accuracy of these DEMs is dependent upon the roughness of the topography and errors are estimated to vary from ±10m in areas of low relief to ±100m in areas of rugged or complex terrain (Hutchinson and Dowling, 1991).

An 18" by 18" (~500m) grid DEM has been derived by AUSLIG using only its spot height data, mostly without breaklines, and is available for approximately 60% of Australia. In small specific areas, a 3" by 3" (~80m) DEM has also been produced by AUSLIG using the spot height data, without breaklines.

More recently, AUSLIG and AGSO, in cooperation with the ANU and the Australian Heritage Commission (AHC), have produced a new continental 9" by 9" (~250m) digital elevation model using ANUDEM to grid the spot height and gravity elevation data (Kennard,

1995 pers comm). Supplementary information has come from breaklines. The complete 9"
by 9" DEM product was supplied by AUSLIG towards the end of 1996.

GPS AND LEVELLING DATA

Relative carrier-phase GPS observations in conjunction with precise geodetic levelling can
provide external control with which to test a gravimetric geoid, especially if the geoid is to
be used subsequently for the recovery of AHD heights from GPS. The Australian Fiducial
and National GPS Networks (AFN and ANN) have recently been completed and their three-
dimensional coordinates, including geoid-ellipsoid separations, are available on the
Internet. The majority of AHD heights used to derive these geometrical geoid heights were
observed by third-order spirit levelling.

Figure 3 shows the very long wavelength (>500km) component of the Australian geoid
derived from GPS and AHD data at the 59 optically levelled AFN and ANN stations. This
geoid model was derived using the surface fitting algorithms of Smith and Wessel (1990),
and is estimated to be accurate to approximately ±0.4m.

Figure 3. *The geometrical geoid of Australia derived using 59 GPS and optically levelled
AHD heights at AFN and ANN stations (dark circles) over Australia. (Contours in metres
relative to GRS80. Mercator's projection)*

Of the 75 geometric geoid heights originally supplied, several of the stations were given AHD heights whose origin was unknown. Checks were made with each State and Territory surveying authority as to the accuracy and origin of the AHD data. It transpired that many discrepancies existed, some up to 4m, between the State/Territory and Federal holdings. In these cases, precedence was given to the AHD data of a higher class and order, and it was assumed that the States and Territories had more up-to-date data in their jurisdiction. Most alarmingly, five of the original stations had not been derived from terrestrial survey methods. Instead, they had been derived from GPS and AUSGEOID93, thus biasing some earlier comparisons (eg. Zhang and Featherstone, 1995).

At the same time as checking the ANN and AFN data, States and Territories were asked to supply any local GPS networks that had been co-located with AHD benchmarks. These will provide data with which to test the shorter wavelength behaviour and to give some measure of the accuracy of the new geoid in these regions. If any readers have such data available for our use, we would be pleased to receive them.

GLOBAL GEOPOTENTIAL MODELS

A global geopotential model is a set of spherical harmonic coefficients which describe the long wavelength characteristics of the geoid and gravity field on a global scale. These are computed through the analysis of satellite orbits, and higher resolution models are produced with the combined use of terrestrial gravity and satellite altimetry data. The spatial resolution is implied by the spherical harmonic degree of expansion (M) of that model, where one arc degree on the Earth's surface is equivalent to an expansion of $M=180$.

Geoid heights and gravity anomalies can easily be computed from a set of geopotential coefficients using the algorithms of either Rapp (1982) or Rizos (1979). In the following study, we have used the routines of Rapp as these can produce a geoid height at a discrete point, whereas Rizos's routine, while more efficient, computes geoid heights on a regular grid because of its use of recursive relationships for the associated Legendre polynomials (Heiskanen and Moritz, 1967). By using Rapp's routine, we avoid the need to interpolate geoid heights from a grid which is necessary when using Rizos's routine.

Several global geopotential coefficient models are freely available via the Internet from the International Geoid Service (IGeS) in Italy (Brovelli and Migliaccio, 1994), for example. More recently, the United States Department of Defense and NASA's Goddard Space Flight Center have used a combination of public domain and confidential military data to produce the latest global model (Rapp and Nerem, 1995). Several preliminary models were tested by the global community under the auspices of the International Association of Geodesy's International Geoid Service prior to the release of the final EGM96 in September, 1996. These, and other geopotential models already stored in Australia, that are currently available for use in this project are listed in Table 1.

In modern geoid determination, a global geopotential model is combined with terrestrial gravity and terrain data surrounding each geoid computation point. By using a global model as a higher degree reference field for Stokes's integration reduces some of the errors encountered in gravimetric geoid computation (eg. Vanìcek and Sjöberg, 1991). When using this approach, one must avoid adding the long wavelength component of the gravity field to the geoid solution twice (Kearsley, 1988a). The remove-restore technique is now considered a routine step during geoid determination that avoids these scenarios.

The gravity anomalies implied by a particular degree of expansion geopotential model are subtracted from the terrestrial gravity anomalies to produce residual gravity anomalies.

These are then used to compute residual geoid heights based upon this model using some implementation of Stokes's integral. The corresponding geoid component from the same degree of expansion of the same geopotential model is subsequently restored to produce the co-geoid.   Smaller corrections are then applied for the indirect effect of the gravity reductions to convert the co-geoid to the true geoid.

BEST FITTING GEOPOTENTIAL MODEL

If the geoid heights supplied by a global geopotential model are a close fit to geometrically derived geoid heights, it is reasonable to expect that this model is also a good fit to the long wavelength component of the geoid.   Therefore, a comparison of the geoid heights with GPS/levelling control will indicate the goodness of fit of the global model to the geoid in Australia.   This was achieved using the control data for the AFN and ANN GPS networks, 59 of whose AHD heights are known from optical levelling.

Similar comparisons of the fit of OSU86E and OSU89A to the Australian gravity field have been studied by Kearsley and Holloway (1989) and Kearsley and Govind (1991), respectively.   These tests demonstrate that OSU89A is the superior model of those tested at that time.   Since then, the OSU91A, GFZ93A/B, GFZ95 and EGM96 (Figure 4) global geopotential models have been released, the first four of which have been tested by Zhang and Featherstone (1995).   The OSU91A model is used in the computation of AUSGEOID93 (Steed and Holtznagel, 1994), but it was not reported whether OSU91A on its own was superior to previous models.   Also, the EGM96 model was released in September, 1996.   Therefore, the differences between the global models available and the 59 control stations in Figure 3 have been computed and are listed in Table 1.

Figure 4. *The degree-360 expansion of the EGM96 geoid in Australia. (Contours in metres relative to GRS80. Mercator's projection)*

Table 1 illustrates that the statistical comparisons are significantly improved for the high degree and order global geopotential models. Also, the level of agreement generally improves for the more recent models, which is indicative of the improved data and methods used in their computation. The agreements for the post-1990 models are very similar when considering that the GPS and optical levelling data are also in error, possibly by as much as ±10-20cm. This makes it very difficult to choose the best fitting model based on these tests alone. Therefore, an independent confirmation will come from a comparison of gravity anomalies implied by the geopotential models with free-air gravity anomalies of the validated Australian gravity data. This is currently in progress and will be published in a forthcoming bulletin of the International Geoid Service.

Table 1. *Statistical comparisons between the global geopotential models currently available for computing the Australian geoid and the 59 optically levelled AFN and ANN stations. AUSGEOID93 is also included for the purpose of comparison. M is the degree of spherical harmonic expansion. (all units in metres)*

model	reference	M	max.	min.	mean	st d	rms
GEMT1	(Marsh *et al.*, 1987)	36	7.463	-4.051	1.237	2.616	2.894
GEMT2	(Marsh *et al.*, 1990)	36	5.639	-3.531	0.975	2.138	2.350
GEMT3	(Lerch *et al.*, 1994)	50	3.699	-2.814	0.535	1.576	1.664
JGM-1S	(Nerem *et al.*, 1994)	60	4.502	-2.969	0.738	1.803	1.948
JGM-2	(*ibid.*)	70	2.557	-2.654	0.086	1.124	1.128
JGM-3	(Tapley *et al.*, 1996)	70	2.634	-2.714	0.091	1.129	1.133
GRIM3-L1	(Reigber *et al.*, 1985)	36	4.844	-3.532	0.626	1.978	2.075
GRIM4-S1	(Schwintzer *et al.*, 1991)	50	5.629	-3.816	1.219	2.260	2.568
GRIM4-C4	(Schwintzer *et al.*, 1995)	72	3.088	-2.606	0.366	1.404	1.451
OSU81	(Rapp, 1981)	180	1.551	-2.115	-0.366	0.810	0.889
OSU86E	(Rapp & Cruz, 1986)	360	0.984	-1.643	-0.304	0.586	0.660
OSU86F	(*ibid.*)	360	0.954	-1.608	-0.291	0.584	0.653
OSU89A	(Rapp & Pavlis, 1990)	360	1.720	-0.679	0.220	0.476	0.525
OSU89B	(*ibid.*)	360	1.712	-0680	0.198	0.476	0.515
OSU91A	(Rapp *et al.*, 1991)	360	1.189	-0.989	0.074	0.476	0.482
GFZ93A	(*ibid.*)	360	1.306	-0.400	0.531	0.399	0.664
GFZ93B	(Gruber & Anzenhofer, 1993)	360	1.235	-.643	0.315	0.410	0.517
GFZ95A	(Gruber *et al.*, 1995)	360	0.955	-0.563	0.110	0.342	0.360
EGM96	(Rapp & Nerem, 1995)	360	0.851	-0.913	-0.017	0.409	0.410
AUSGEOID 93	(Steed & Holtznagel, 1994)	n/a	1.184	-0.676	0.154	0.419	0.447

However, EGM96 does appear to be a better fit to the geometrically derived geoid in Australia than OSU91A (cf. Figures 3 and 4). As OSU91A provided the basis for AUSGEOID93 (Steed and Holtznagel, 1994), this implies that a recomputation using only EGM96 will provide an improvement upon AUSGEOID93. It is most interesting to note the improved agreement offered by EGM96 rather than AUSGEOID93. This is unexpected because AUSGEOID93 includes detailed Australian gravity data. However, recall that the GPS and AHD data are in error which may be misleading.

Using only the comparisons in Table 2, however, the GFZ95A model appears to give the best fit to the geometrical (GPS/levelling) geoid in Australia, which implies it will form the most suitable base for a new gravimetric geoid. However, this is yet to be confirmed using tests with gravity data. Despite the improved agreement of GFZ95A here, EGM96 is still expected to be superior, simply because of the additional data and refined techniques that were used in its computation, especially for the very long wavelengths.

CONCLUDING REMARKS

The preparation of terrestrial gravity and terrain data prior to a modern gravimetric geoid determination is a most time consuming process. In this Australian geoid project, the data processing took several months, which is far in excess of the time required to compute a gravimetric geoid given pre-processed data, irrespective of which computational method is used.

The reformatted and validated gravity data is now being used in the current computation of the new Australian gravimetric geoid. Other issues concerning the testing and selection of optimal computational procedures to derive the geoid from these data, and the size of computation area over which gravity data should be used, can now be studied in more detail with some assurance that the raw data being used in the next geoid solution are as free from error as possible.

One point to note, which is of most relevance to those users undertaking their own geoid accuracy tests, is that the use of GPS and AHD data to validate the gravimetric geoid on land are themselves subject to error. Therefore, these control data should not be used as an unequivocal indicator of the accuracy of any gravimetric geoid.

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