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TOWARDS THE NEW AUSGEOID MODEL

W.E. Featherstone, D.M. Sproule, J.M. Goos, J.F. Kirby, M. Kuhn, and S.J. Claessens

Western Australian Centre for Geodesy,
Curtin University of Technology,
GPO Box U1987, Perth WA 6845, Australia

D.Sproule@curtin.edu.au

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ABSTRACT

Since November 1998, all high-precision GPS users in Australia have adopted the AUSGeoid98 gravimetric geoid model to transform GPS-derived ellipsoidal heights to the Australian Height Datum (AHD) and *vice versa*. Since AUSGeoid98 was released by Geoscience Australia (http://www.ga.gov.au/nmd/geodesy/ausgeoid/) based on recommendations by the first-named author, several new theories have been formulated and refined datasets have been released, all of which can improve the Australian geoid model.

This paper reports our latest implementations of these theories and datasets, which comprise a global geopotential model derived from the GRACE (Gravity Recovery And Climate Experiment) dedicated satellite gravimetry mission, gravimetric terrain corrections from the version-2 DEM-9S 9"×9" digital elevation model, approximately 200,000 additional land gravity observations in Geoscience Australia's database, improved gravity data cleaning methods, refined marine gravity data from multi-mission satellite radar altimetry, a least-squares crossover adjustment of ship-track gravity observations, and new GPS data collected by State and Territory geodetic survey agencies at key tide-gauges, some junction points and other benchmarks of the AHD.

The refined gravimetric geoid solution will be fitted to the GPS-AHD data using least-squares collocation so as to deliberately provide a more direct transformation to the AHD that obviates the need to occupy nearby AHD benchmarks during a GPS survey. This pragmatic solution, while not producing a classical equipotential geoid model, does provide a very useful product for GPS users in Australia until the AHD is rigorously redefined. Our results show that the new model will deliver GPS-derived AHD heights with an RMS of less than ~12 cm in an absolute sense over most parts of Australia, which reduces when used in relative mode over shorter GPS baselines. In short, the new model will deliver height results that are commensurate with or better than Australian class LC (third order) geodetic levelling methods.

As with AUSGeoid98, this new product will be released and administered by Geoscience Australia based on our recommendations, hopefully towards the end of 2005.

BIOGRAPHY OF THE PRESENTER

David Sproule holds a degree in Geomatic Engineering (1st Class Hons) from the University of New South Wales (1998), and a PhD in gravimetric geodesy (submitted) also from UNSW. He has worked in the Geodesy Section of AUSLIG (now Geoscience Australia), and is currently a Research Associate in the Western Australian Centre for Geodesy at Curtin University of Technology.

INTRODUCTION AND MOTIVATION

High-precision GPS (Global Positioning System) surveyors in Australia have used AUSGeoid98 [Featherstone et al., 2001; http://www.ga.gov.au/nmd/geodesy/ausgeoid/] since its release in November 1998. For instance, it is embedded in most commercial GPS data processing software. A model geoid height (N) is used to transform a GPS-derived ellipsoidal height (h) to an Australian Height Datum (AHD) height (H) using the simple algebraic relation $H = h - N$. While this is probably the most common use of a geoid model, AUSGeoid98 must also be used for the accurate reduction of terrestrial survey data to the ellipsoid [Featherstone, 1997]. AUSGeoid98 is also accompanied by a grid of vertical deflections, which must be used to apply corrections to some angular geodetic measurement types to relate them to the ellipsoid [Featherstone and Rüeger, 2000]. As such, AUSGeoid98 remains a useful product for a variety of GPS and non-GPS surveyors in Australia, as well as being of use to geophysicists and oceanographers.

However, AUSGeoid98 does not meet the accuracy requirements expected by surveyors in all areas of Australia, notably as a replacement for Australian class LC [ICSM, 2002] spirit levelling [e.g., Featherstone and Guo, 2001]. When GPS is used in differential mode, AUSGeoid98 is also used differentially, where geoid errors that are equal at each end of short baselines will cancel out [cf. Kearsley, 1988]. However, as the baseline length increases, this cancelling no longer always applies, and post-survey adjustments are required [e.g., Featherstone et al., 1998a]. A more important driver is the evolution of precise single-point GPS techniques, such as AUSPOS [Dawson et al., 2001] or precise point positioning (PPP) [e.g., Castleden et al., 2005]. Here, GPS is not used in the classical differential mode, so geoid errors will not cancel on differencing.

Featherstone and Dent [2002] used AUSPOS and AUSGeoid98 in the absolute mode, and showed that a ~7 cm bias occurred with respect to the AHD in Hyden, Western Australia. However, inspection of Table 2 (given later) shows that differences of up to ~87 cm may occur. While it is still difficult to separate the source of the error between AUSGeoid98 and the AHD, there is mounting evidence of a fundamental problem with the realisation of the AHD [e.g., Featherstone and Stewart, 1998, Featherstone, 1998, 2002a, 2004, Baran et al., 2005]. Since, by decree of the Intergovernmental Committee on Surveying and Mapping (ICSM), the AHD is to be retained for the “foreseeable future”, it is necessary to continue to address the practical problem of AHD height determination by GPS in Australia.

We aim to address the above problems by the production of a new ‘geoid’ model for Australia. This will comprise two solutions: a scientific gravimetric-only geoid model from improved data, theories and computational techniques; and a practical product for the more direct transformation of GPS heights to the AHD and *vice versa* [cf. Featherstone, 1998]. Both will refer to the GRS80 ellipsoid [Moritz, 1980], so will be compatible with the Geocentric Datum of Australia 1994 (GDA94). A new grid of vertical deflections will also be computed. This paper introduces the data- and theory-driven improvements that are likely to be made to the Australian gravimetric geoid model, followed by a description and initial results of producing the ‘user-friendly’ product for more direct GPS heighting with respect to the AHD.

NEW DATA AND THEORIES

Several new datasets are available to compute the new AUSGeoid: significantly improved global geopotential models from the analysis of the GRACE (Gravity Recovery and Climate Experiment) dedicated satellite gravity mission; additional gravity data from Geoscience Australia’s (GA’s) national gravity database; improved marine gravity data from a least-squares crossover adjustment of GA’s ship-track gravity database; improved marine gravity anomalies from multi-mission satellite radar altimetry; improved and higher-resolution gravimetric terrain corrections and indirect effects from the version 2 DEM-9S digital elevation model of Australia; and new GPS data at several junction points, tide-gauges and other benchmarks of the AHD. The new theoretical developments include consideration of downward-continuation corrections to the satellite-derived and terrestrial gravity data, ellipsoidal corrections to the spherical Stokes formula, implementation of band-pass digital filters (probably by way of modified Stokes’s integration kernels) so as to gain most benefit from the new data sources.

The GGM02 global geopotential model

The long-wavelength component of the new AUSGeoid will come from the GGM02S global geopotential model [Tapley et al., 2005, in press; http://www.csr.utexas.edu/grace/]. This model was derived from the analysis of GRACE mission data, which uses a combination of high-low satellite-to-satellite GPS tracking of two tandem satellites in low-Earth orbits (Figure 1). The twin satellites are equipped with star cameras for external orientation, orthogonal accelerometers to measure non-gravitational orbit perturbations, and a low-low inter-satellite range and range-rate tracking system [e.g., Tapley et al., 2004; Rummel et al., 2002; Featherstone, 2002b]. GGM02S will probably be truncated at a spherical harmonic degree and order somewhere between 70 and 110, which is chosen based on the greater noise levels in the high-degree coefficients and advice from its creators. GGM02S provides a considerable improvement upon all previous satellite-only GGMs, showing centimetre-level geoid precision for wavelengths greater than ~550 km [Tapley et al. 2005].

Since GGM02S represents the Earth's external (to the topographic masses) gravity field, additional downward continuation corrections are needed to compute the geoid beneath the continental landmass [e.g., Sjöberg 1999]. For this purpose, we will use the version 2 DEM-9S 9"×9" (~250m) digital elevation model (DEM) of Australia [Hutchinson, 2001] generalised (i.e., area-weighted means) onto a grid commensurate with the Nyquist frequency of a degree-70-110 expansion of GGM02S. This will be supplemented by a global DEM; possibly one derived from the Shuttle Radar Topography Mission (SRTM).

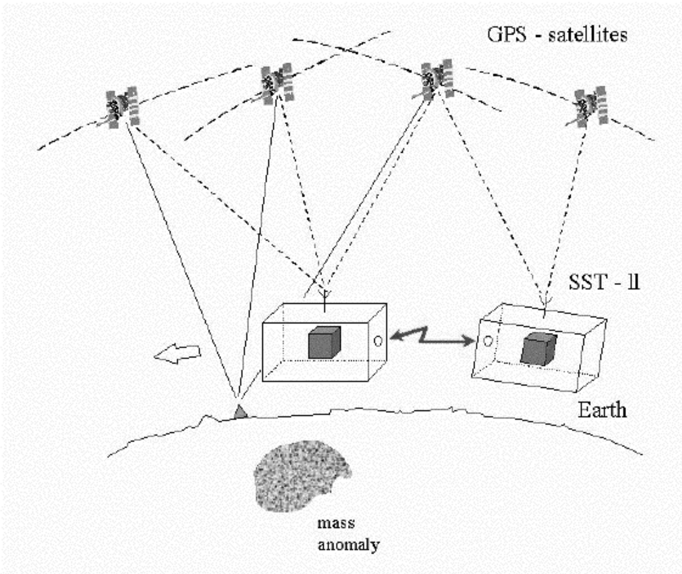

Figure 1. The GRACE concept of satellite-to-satellite tracking in the low-low mode combined with satellite-to-satellite tracking in the high-low mode [from Rummel et al., 2002]

Another benefit of using a high-degree satellite-only GGM is that it avoids the unknown correlations with the terrestrial gravity data encountered when using combined GGMs (i.e., those derived from a combination of satellite and terrestrial data) in regional geoid computation, as well as reducing the truncation bias [Vaníček and Sjöberg, 1991]. Alternatively, the truncation bias may be computed explicitly for a modified Stokes kernel [e.g., Featherstone et al., 2004]. As a refinement to AUSGeoid98, the new AUSGeoid uses a more accurate treatment of the degree-zero term (0.56m), where the difference in potential is now taken into account to better define the scale of the geoid model. The degree-one term remains inadmissible assuming that both GGM02S and GRS80 are co-located at the geocentre. Finally, an ellipsoidal correction to the gravity anomalies computed from the GGM02S spherical harmonic coefficients [Hipkin, 2004] will be applied. As these ellipsoidal corrections only apply up to degree 70-110, additional corrections may be needed to the geoid contribution from the terrestrial gravity data.

Land Gravity Data

Since AUSGeoid98 was computed, ~200,000 land gravity observations have been added to GA's land gravity database [Murray, 1997]. These are mainly in the form of spatially dense regional surveys in prospective areas of economic resource deposits (Figure 2). As such, improvements in the new AUSGeoid model can be expected in these areas. However, most of these new gravity surveys have been positioned with GPS and an unspecified geoid model, which gives rise to a 'circular argument' in that the same data will be used to compute a geoid model. Nevertheless, the GPS-geoid-derived heights are probably more accurate than the barometric heighting used for most of the gravity database, and most of the benefit will come from more data being used to compute mean gravity anomalies for the Stokes integration. The land gravity data will be processed in largely the same way as for AUSGeoid98, but the terrain corrections (described later) will be of higher spatial resolution. We will also consider downward continuation of these gravity anomalies through the topography. Ideally, this should use a topographic mass-density model, but since one is not yet available for Australia, we will have to assume a value of 2670 kgm^{-3}.

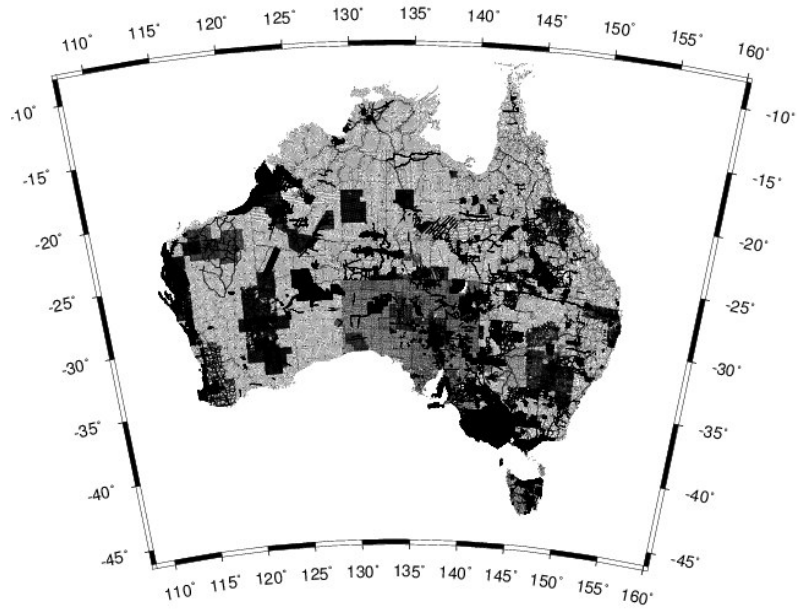

Figure 2. Spatial coverage of the 1,117,054 Australian land gravity observations in the 2004 data release from Geoscience Australia (Lambert conformal conical projection)

We also apply improved gravity data cleaning procedures. The land gravity anomalies have been validated in the short wavelengths by two complementary methods [Sproule and Featherstone, 2005]: a comparison between the gravity observation elevations with the DEM-9S heights, which revealed ~120 gross errors; and a comparison of each gravity observation with those interpolated from around it, which revealed ~65 gross errors. This is testament to the quality of the original data, in that only 0.02% of all observations were rejected. We will also detect the more serious long-wavelength systematic errors in the land gravity anomalies through comparisons with GRACE data [cf. Featherstone, 2005]. These will probably be accounted for through the use of modified integration kernels as high-pass digital filters [Featherstone et al., 1998b; Vaníček and Featherstone, 1998; Featherstone, 2003a]. The long-wavelength errors pose a more serious problem because they have a relatively larger effect on the geoid [Vaníček and Featherstone, 1998].

Ship-track gravity data

Featherstone [2003b] shows that the marine gravity data used in AUSGeoid98 had not been crossover adjusted. This was through a comparison of the ship-track gravity anomalies with those derived from satellite radar altimetry (Figure 3). A crossover adjustment is needed to account for linear drift in marine gravimeters, which causes gravity observations to differ at the same point when observed at different times [e.g., Wessel and Watts, 1988]. The crossover adjustment minimises these crossover differences by estimating biases and tilts to the ship-track gravity using least squares methods. We are in the final stages of completing this adjustment, which proved to be rather problematic because of the way in which GA's marine gravity records are stored. While Petkovic et al. [2001] performed an adjustment of GA's ship-track gravity data, this fitted the ship-tracks to satellite altimeter data, thus probably introducing errors in the coastal zone [cf. Featherstone, 2003b]. Our crossover-adjusted data will be used to constrain satellite-altimeter-derived gravity anomalies in the coastal zone (described next).

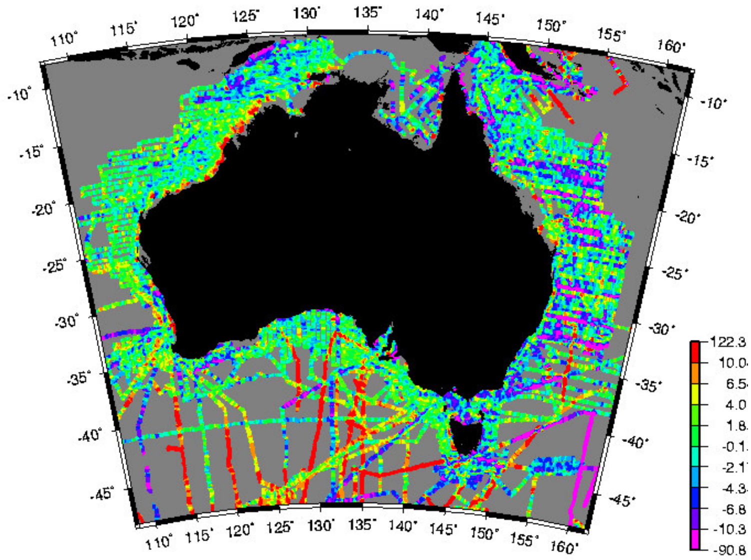

Figure 3. Differences between satellite altimeter gravity anomalies and GA marine gravity anomalies (units in mGal; Lambert conformal conical projection) [from Featherstone, 2003b]

Marine gravity data from satellite altimetry

Marine gravity anomalies can be deduced from sea surface heights measured by echoed radar signals transmitted from a variety of satellite radar altimetry missions (Figure 4). A variety of techniques exist [see the review by Featherstone, 2003b], each of which yields slightly different results from largely the same data sources. AUSGeoid98 used Sandwell and Smith's [1997] version 7.2 grid of altimeter-derived marine gravity anomalies, which has since been upgraded to [http://topex.ucsd.edu/WWW_html/mar_grav.html]. However, the new grid from the Danish Space Research Institute and NASA's Goddard Space Flight Centre is probably superior, which will be released in August 2005. Moreover, it will probably include re-tracked altimeter data [cf. Deng et al., 2002], which improves the gravity anomalies in the coastal zone (cf. the larger differences in Figure 3). However, some discrepancies between the crossover-adjusted ship-track data and altimetry data are likely to remain in the coastal zone, so will have to be merged using least squares collocation [cf. Kirby and Forsberg, 1998].

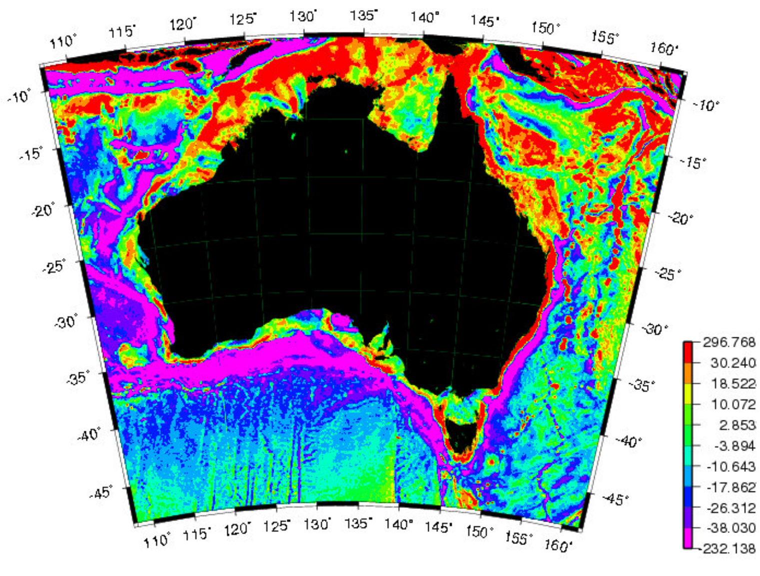

Figure 4. Marine gravity anomalies around Australia derived from multi-mission satellite radar altimetry (units in mgal; Lambert conformal conical projection)

New gravimetric terrain corrections

AUSGeoid98 used gravimetric terrain corrections computed from the version 1 GEODATA DEM of Australia [Carroll and Morse, 1996]. However, the version 1 DEM had to be generalised from a 9"×9" grid to a 27"×27" grid to avoid some spuriously large terrain correction values [Kirby and Featherstone, 1999]. It has since been discovered [Kirby and Featherstone, 2001] that this was due to incorrect stream-flow data in the version 1 DEM. This DEM was corrected and revised to give the version 2 DEM-9S model [Hutchinson, 2001]. This has permitted the computation of a new grid of gravimetric terrain corrections at the full 9"×9" spatial resolution [Kirby and Featherstone, 2002]; see Figure 5.

These terrain corrections use Moritz's [1968] algorithm, which includes an implicit downward continuation since the terrain corrections are computed at the geoid. An alternative is to compute the terrain corrections at the Earth's surface, followed by downward continuation of the terrain corrected gravity anomalies to the geoid [e.g., Vaníček et al. 1999]. These approaches remain open to debate in the geodetic literature [e.g., Jekeli and Serpas, 2003], so will be compared in the Australian context. The indirect effects associated with the terrain corrections and downward continuation will be computed from the version 2 DEM-9S model.

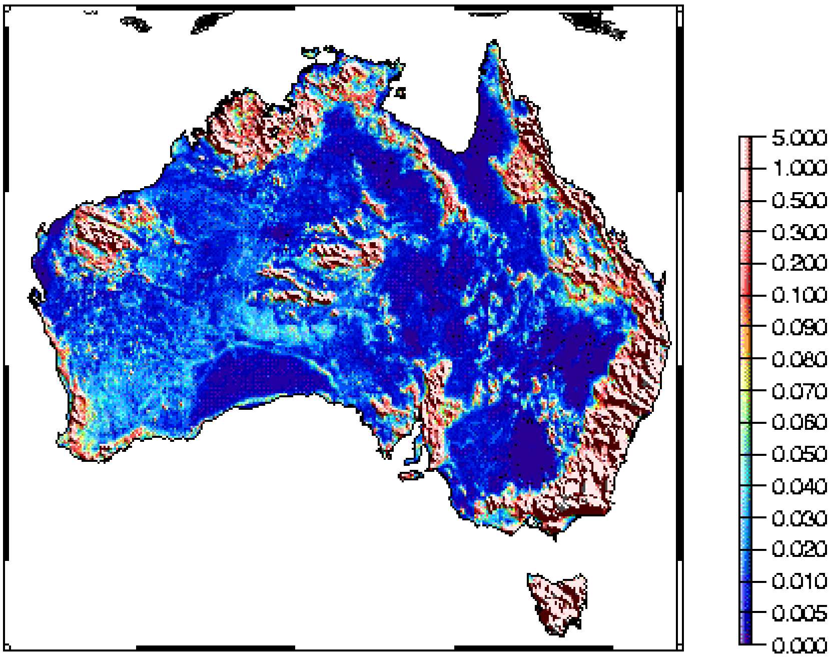

Figure 5. Image of the 9 arc-second terrain corrections over Australia, illuminated from the north-east (units in mGal. Mercator projection) [from Kirby and Featherstone, 2002]

New GPS-AHD data

The ICSM has embarked on a nation-wide programme to occupy all the junction points and 32 tide gauges of the AHD using GPS. This project is still underway, and not all junction points have been occupied as yet. As such, high-quality GPS data at other benchmarks on the AHD have been used here. The 254 GPS-AHD data, provided by GA in 2004, are mapped in Figure 6. These data will be used in two stages: first to test the gravimetric-only geoid model on land, which will also involve a minimally constrained readjustment of the AHD to avoid distortions introduced by fixing all tide gauges to zero height [Roelse et al., 1971; Featherstone, 2002a, 2004]; and second to produce a surface designed specifically for the direct transformation of GPS ellipsoidal heights to the AHD and *vice versa* [cf. Featherstone, 1998; Featherstone and Sproule, 2005]. The latter technique will be described in a subsequent section. Table 1 shows the fit of AUSGeoid98 to these new GPS-AHD data in comparison to the older set of 1013 points used in the validation of AUSGeoid98 [Featherstone et al., 2001; Featherstone and Guo, 2001]. This shows that the new GPS-AHD data appear superior.

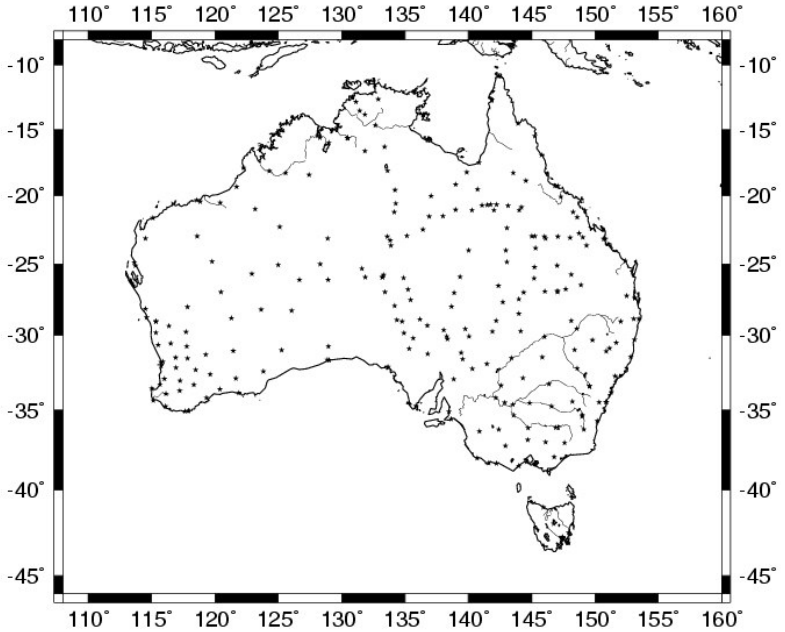

Figure 6. Spatial coverage of the 254 co-located GPS and AHD heights (Mercator projection)

	Data	Mean	Max	Min	Std
Old GPS-AHD data [Featherstone and Guo, 2001]	1013	-0.2	355.8	-257.2	31.4
New GPS-AHD data [Featherstone and Sproule, 2005]	254	7.6	86.5	-72.1	28.6

Table 1. Descriptive statistics of the fit of AUSGeoid98 to the old and new GPS-AHD data (units in cm)

GRAVIMETRIC GEOID COMPUTATION

The new gravimetric geoid model will be computed along the same lines as AUSGeoid98 [Featherstone et al., 2001], but with the new data and consideration of additional geoid correction terms. To summarise, the new AUSGeoid will use: the satellite-only GGM02S global geopotential model; gravimetric terrain effects computed from the full 9"×9" spatial resolution of the version 2 DEM-9S Australian digital elevation model; additional land gravity data that has been screened for short- and long-wavelength errors; marine gravity anomalies merged from crossover-adjusted ship-track observations and satellite altimetry data. It may also be necessary to supplement data gaps to the north of Australia using gravity data synthesised from the EGM96 global geopotential model. The geoid undulations residual to GGM02S will be computed using the fast Fourier transform FFT) technique together with a deterministically modified Stokes kernel [Featherstone et al., 1998b], which may also involve the separate computation of the truncation bias [cf. Featherstone et al., 2004]. Additional corrections will include downward continuation of GGM02S and terrestrial gravity anomalies, ellipsoidal corrections and optimised data filtering using modified kernels [Featherstone, 2003a].

PRODUCTION OF THE AHD TRANSFORMATION SURFACE

Featherstone [1998, 2000] gives the arguments for and against producing a surface specifically for the direct transformation of GPS heights to the AHD. As stated in the Introduction, the ICSM has decided to retain the AHD for the "foreseeable future". Accordingly, it is necessary to seek an interim solution, whereby the gravimetric geoid model is adjusted/warped to better fit the AHD using GPS-levelling data [cf. Featherstone, 2000]. Indeed, this pragmatic solution is being used in several other counties, such as the USA [Smith and Roman, 2001] and the UK [Iliffe et al., 2003]. However, it does avoid the issue of distortions in the AHD, which will ultimately have to be addressed, especially when the GRACE and GOCE (Gravity field and steady-state Ocean Circulation Explorer) dedicated satellite gravity missions start to deliver 1 cm geoid models at distances over 100 km [e.g., Rummel et al., 2002].

For the interim solution, we have adapted existing software to achieve this data combination using least squares collocation (LSC) interpolation. LSC is essentially identical to Kriging [Dermanis, 1984], which is a well-known spatial data interpolation algorithm. It takes into account the spatial distribution and errors in the data being interpolated. Featherstone and Sproule [2005] used LSC in a cross-validation mode to empirically determine the correlation length (2,500 km) and data noise (14 mm) to optimally interpolate the residuals between AUSGeoid98 and the new GPS-AHD data to generate a surface (Figure 7) that, when applied to AUSGeoid98, provides a model for the more direct transformation of GPS heights to the AHD. Table 2 gives the descriptive statistics showing that the warped AUSGeoid98 gives a better transformation accuracy. This will be improved by the use of the new gravimetric geoid model and the addition of more GPS-AHD data that have a better spatial distribution.

	Mean	Max	Min	Std
AUSGeoid98 only	7.6	86.5	-72.1	28.6
Fitted model [Featherstone and Sproule, 2005]	0.0	46.2	-48.3	11.8

Table 2. Descriptive statistics of the fit of AUSGeoid98 and the fitted model to the new GPS-AHD data (units in cm)

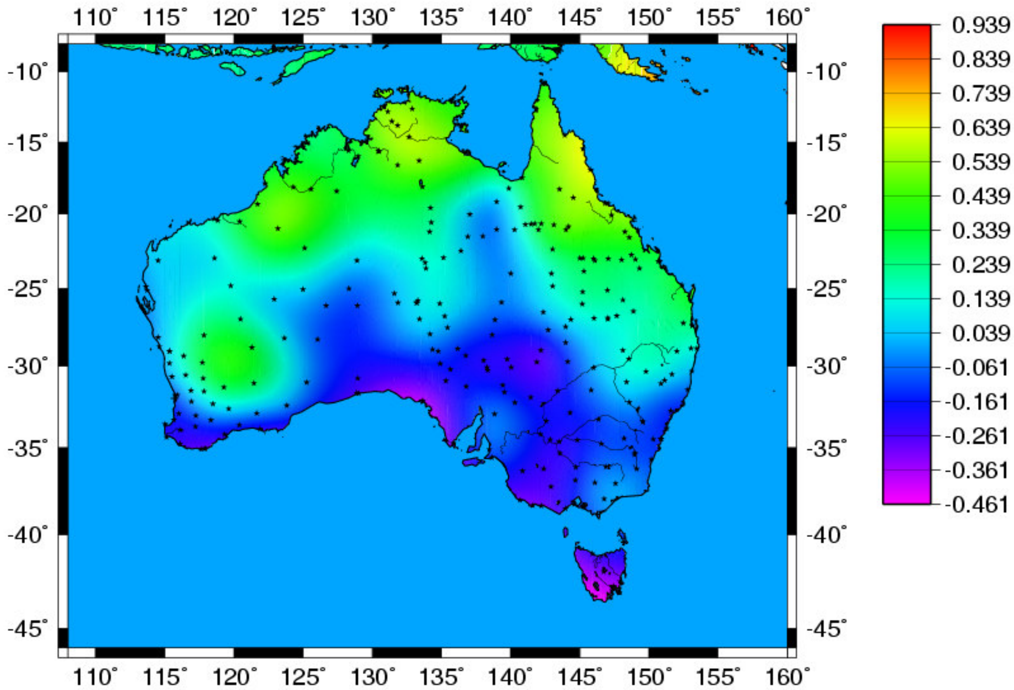

Figure 7. The LSC-predicted surface used to adjust AUSGeoid98 such that it provides a more direct transformation of GPS ellipsoidal heights to the AHD (units in metres).

CONCLUDING REMARK

We have summarised our recent activities to produce a new AUSGeoid model. These procedures will be implemented to produce a new gravimetric-only geoid model, which will then be adjusted to fit the AHD using LSC. Hopefully, GA will release the new model later in 2005, probably as AUSGeoid2005.

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