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Improved AHD71 Height Determination from GNSS using AUSGeoid09 in New South Wales, Australia

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Abstract

In October 2010, Geoscience Australia released the latest beta version of AUSGeoid09 (beta 0.7), providing an improved geoid model to relate GNSS-derived ellipsoidal heights to the Australian Height Datum (AHD71) and vice versa. This paper quantifies the expected improvement of replacing the current geoid model, AUSGeoid98, with AUSGeoid09 in New South Wales (NSW). Four tests were performed to investigate how well the two geoid models fit known AHD71 heights, based on (1) about 500 AUSPOS solutions, (2) 38 CORSnet-NSW sites, (3) several GNSS-based adjustments, and (4) numerous height control points from these adjustments. It was found that AUSGeoid09 provides a considerably improved fit to AHD71 for GNSS-based height transfer in NSW. The first two tests showed the root mean square (RMS) of residuals improved by factors of 2.7 and 4.1 respectively. The magnitude of N values in NSW will change by up to 0.5 m when AUSGeoid09 is introduced. The adjustment tests confirmed these findings, evidenced by improved variance factors and reduced numbers of flagged residuals. The adjusted height observations showed an improved RMS of the residuals, generally by a factor of about 1.5, but reaching 4.6. In most cases the RMS of the AUSGeoid09-derived height results falls within the expected ±0.05 m accuracy stated by Geoscience Australia.

Keywords: AUSGeoid09, AHD71, GNSS, CORS, geoid undulation, height transfer.

1. Introduction

A vertical datum defines a reference for elevation comparisons and is essential for a wide range of applications such as road and drainage design, floodplain management, agricultural management and surveying in general. Most countries utilise an approximation of the orthometric height system referenced to the geoid. The Australian Height Datum (AHD) was realised in 1971 by setting the observed mean sea level (MSL) to zero at 30 tide gauges situated around the coast of Australia and adjusting about 195,000 km of spirit levelling across the country (Roelse et al., 1971). However, due to dynamic ocean effects (e.g. winds, currents, atmospheric pressure, temperature and salinity), the short duration of tide gauge observations (spanning a period of only 2-3 years for some) and the omission of observed gravity, MSL is not coincident with the geoid at these tide gauge locations. This introduces considerable distortions of up to ~1.5 m into AHD71 across Australia, causing it to be essentially a third-order datum (Morgan, 1992). It should be noted that the Tasmanian AHD (generally referred to as AHD83) was defined separately (in 1979) by setting MSL observations at two tide gauges to zero, and the Tasmanian levelling network was then readjusted in 1983 (ICSM, 2002). For a detailed treatment of height systems and vertical datums in the Australian context, the reader is referred to Featherstone and Kuhn (2006).

Positions obtained by a Global Navigation Satellite System (GNSS) such as GPS, GLONASS or the planned Galileo include height information referred to a reference ellipsoid. These heights are based purely on the geometry of the ellipsoid and therefore have no physical meaning. In most practice, however, heights are required that correctly reflect the flow of water, e.g. for drainage and pipeline design. National height datums such as the AHD are therefore based on orthometric heights, referenced to the geoid or a close approximation of the geoid.

Ellipsoidal heights (h) can be converted to orthometric heights (H) by applying the geoid undulation (N), also known as geoid-ellipsoid separation, geoid height or N value (e.g. Featherstone and Kuhn, 2006; Janssen, 2009a; 2009b):

$$H = h - N \tag{1}$$

In practice, geoid undulation information plays two crucial roles (Rizos, 1997): On the one hand, N values are necessary to convert (non-GNSS) geodetic control information (i.e. orthometric heights) into a mathematically equivalent reference system to which

GNSS results refer (i.e. ellipsoidal heights). On the other hand, N values are required to obtain orthometric heights (i.e. physical meaning) from GNSS-derived ellipsoidal heights (i.e. geometrical meaning).

Generally, N values are interpolated for a given site based on a geoid model of the area of interest. Many countries have generated national geoid models to relate GNSS-derived heights to their national vertical datum.

In October 2010, Geoscience Australia released the latest beta version 0.7 of the new AUSGeoid09 (Featherstone et al., 2011) to the general public. This paper aims to quantify the improvement achieved by replacing the current Australian geoid model, AUSGeoid98, with the new AUSGeoid09.

2. GNSS Height Transfer Considerations for CORS Users

The use of Continuously Operating Reference Station (CORS) networks, such as the rapidly expanding CORSnet-NSW (Janssen et al., 2010), for GNSS real-time and post-processing applications has been growing substantially over the last few years. It is therefore appropriate to illustrate the increased importance of accurate N values in regards to GNSS-based height transfer.

In the traditional base-rover field scenario, the published, local AHD71 height of a temporary GNSS reference station is converted to an ellipsoidal height using equation (1). The ellipsoidal height of the rover is then determined via Real Time Kinematic (RTK) or post-processing techniques and converted back to AHD71 using the same equation. The entire process is based on the calculated ellipsoidal height of the reference station.

In the CORS scenario, the height conversion is only applied once, at the rover end, and is based on an observed ellipsoidal height. The ellipsoidal height of most CORS in Australia is determined via Regulation 13 certification performed by Geoscience Australia, a facility accredited by the National Association of Testing Authorities (NATA). Geoscience Australia determines site coordinates in a global (or, more precisely, regional) context based on a week of GNSS data and highly traceable, standardised, scientific processing using the Bernese 5.0 software (Dach et al., 2007). This process provides a direct and consistent connection to the Australian Fiducial Network (AFN) and its successor, the Australian Regional GPS Network (ARGN), exclusively via GNSS observations. The resulting coordinates (latitude, longitude and ellipsoidal height) are stated on Regulation 13 certificates which are valid for five years and provide a Recognised Value Standard for positioning infrastructure with respect to the national datum, GDA94. Through this facility the site coordinates are linked to a standard of measurement in accordance with the National Measurement Regulation 1999 and the National Measurement Act 1960. Consequently, Regulation 13 certificates assist users in establishing some legal traceability of GNSS positions when CORS data are used. In addition, certified Regulation 13 coordinates allow users to obtain consistent GNSS positioning results in the border regions of neighbouring CORS networks, independent of which network is utilised.

As illustrated by Figure 1, in the traditional scenario most of the error in the absolute N values cancels due to the conversion being applied from AHD71 to ellipsoidal height and back again. The absolute N values involved may have relatively large errors *e* but by starting and ending the process with AHD71, the height of the rover is only contaminated by the small difference of these errors (ignoring any GNSS observational errors). However, in the CORS scenario, the height conversion is only applied once (from ellipsoidal height to AHD71) and any error *e* in the absolute N value will therefore fully propagate into the AHD71 height of the rover. Consequently, the absolute accuracy of N values is now more important than ever for AHD71 height determination using GNSS techniques.

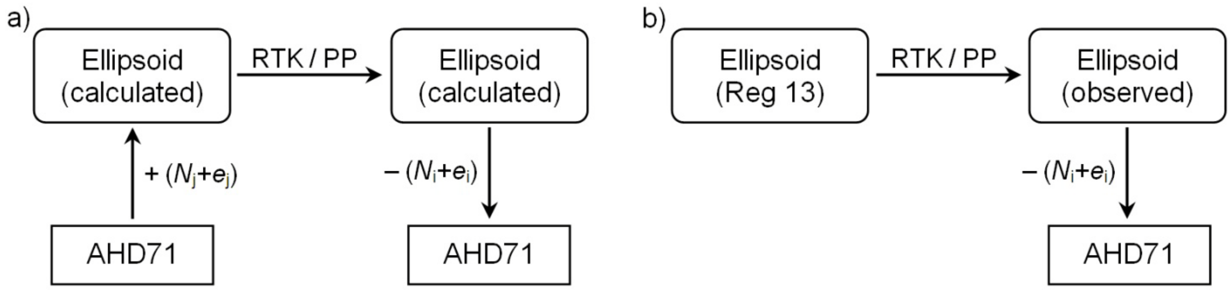

Figure 1: GNSS height transfer methodology using RTK or post processing (PP) in the past (a) and using CORS (b).

3. Recent Geoid Models of Australia

The geoid is defined as the equipotential surface that best approximates mean sea level and is the basis for orthometric heights, while the quasigeoid is the non-equipotential surface that normal heights refer to. The Australian Height Datum is a hybrid of these two vertical datum surfaces because normal gravity, referenced to a mean Earth ellipsoid, was used in the orthometric correction formulae instead of observed gravity (Roelse et al., 1971). The AHD is therefore sometimes called a normal-orthometric height datum. Estimates of the quasigeoid-to-geoid separation over Australia were found to be small enough to assume geoid and quasigeoid to be coincident for the determination of AHD heights from GNSS observations (Featherstone and Kirby, 1998). For consistency, the term geoid is used throughout the present paper.

3.1 AUSGeoid91 and AUSGeoid93

Over the last two decades, several geoid models were generated in order to relate GNSS-derived ellipsoidal heights to AHD71 and vice versa. In 1991, the first version of AUSGeoid was computed and released by Geoscience Australia (then known as the Australian Surveying and Land Information Group, AUSLIG). AUSGeoid91 referred to the WGS84 ellipsoid and was based on the OSU89A global geopotential model (Rapp and Pavlis, 1990), the Australian Geological Survey Organisation's (AGSO's) national gravity database of 1980, and the ring integration implementation of the spherical Stokes integral (Kearsley, 1988a; 1988b). It was given on a 10' by 10' grid (i.e. about 18 by 18 km) of geoid undulations.

In 1993, the same gravity data and computational procedures were used by AUSLIG in conjunction with the more recent OSU91A global geopotential model (Rapp et al., 1991) to produce AUSGeoid93 (Kearsley and Steed, 1995). AUSGeoid93 had an estimated accuracy of better than 0.5 m in absolute terms (Steed and Holtznagel, 1994) and about 2-5 ppm in a relative sense (Kearsley, 1988b). At the time there was no attempt to evaluate terrain corrections or to involve a digital elevation model (DEM) in the solution because there was simply no DEM available that was independent of the height data (measured barometrically) supplied with the gravity data. Indeed, the best DEM for Australia at the time was that which came with the nationwide gravity survey.

3.2 AUSGeoid98

In 1998, AUSLIG released AUSGeoid98 which referred to the GRS80 ellipsoid (practically identical to the WGS84 ellipsoid) and was computed using data from the EGM96 global geopotential model (Lemoine et al., 1998) and the AGSO national gravity database of 1996 (containing more than 830,000 observations, i.e. 100,000 observations more than in 1980). A nationwide DEM, given on a 9" by 9" grid (i.e. about 250 by 250 m), was utilised to compute topographic corrections such as gravimetric terrain corrections and their indirect effects, while satellite altimeter observations were used to aid marine gravity anomaly determination, and the geoid model was computed using the 1-dimensional Fast Fourier Transform technique with a modified Stokes integration kernel (Featherstone et al., 2001).

AUSGeoid98 was given on a 2' by 2' grid (i.e. approximately 3.6 by 3.6 km) of geoid undulations, making it a lot denser than its predecessors. With an estimated accuracy of better than 0.4 m in absolute terms and around 3 ppm in a relative sense, it provided a substantial improvement compared to AUSGeoid93. This improvement was particularly evident in mountainous and coastal regions, owing to the benefit of incorporating additional topographic height and satellite-altimeter-derived gravity data (Featherstone and Guo, 2001).

3.3 AUSGeoid09

In October 2010, Geoscience Australia released the latest (and most likely last) in a series of beta versions of AUSGeoid09 (beta 0.7). It covers the same area as AUSGeoid98, i.e. between 108°E and 160°E longitude and 8°S and 46°S latitude, and also refers to the GRS80 ellipsoid but is given on a 1' by 1' grid (i.e. approximately 1.8 by 1.8 km), making it four times denser than its predecessor (Featherstone et al., 2011). Version 1.0 is expected to be released soon. In contrast to previous versions of AUSGeoid, which were gravimetric-only geoids, AUSGeoid09 is a combined gravimetric-geometric geoid, allowing a more direct determination of AHD71 heights from GNSS observations (Brown et al., 2010).

The first component of AUSGeoid09 is the latest gravimetric-only geoid model (AGQG2009) produced by the Western Australian Centre for Geodesy at Curtin University, computed using the 1-dimensional Fast Fourier Transform technique with a modified Stokes integration kernel (Featherstone et al., 2011). It provides the gridded height offset between the GRS80 ellipsoid and the geoid surface. The horizontal position of the grid is given in the Geocentric Datum of Australia (GDA94) (ICSM, 2002).

The second component of AUSGeoid09 is the gridded geometric offset between the geoid (i.e. AGQG2009) and AHD71, calculated by empirical testing using a cross-validation, least-squares collocation technique (Featherstone and Sproule, 2006). This offset is predominantly caused by AHD71 not taking into account sea surface topography including the differential heating of the oceans. The warmer or less dense water off the coast of northern Australia is approximately 1 m higher than the cooler or denser water off the coast of southern Australia. Therefore, AHD71 is about 0.5 m above the geoid in northern Australia and roughly 0.5 m below the geoid in southern Australia (Brown et al., 2010).

The AUSGeoid09 input dataset includes about 2,600 points across Australia that have both accurate ellipsoidal heights and published Class LC, third order (or better) AHD71 heights provided by the State and Territory government authorities. In addition, in excess of 4,200 junction points have been used on which orthometric heights have been propagated by constraining the Australian National Levelling Network (ANLN) to the orthometric heights at the above mentioned 2,600 GNSS-levelling points. AUSGeoid09 was computed using data from the EGM2008 global geopotential model (Pavlis et al., 2008), the July 2009 release of the national land gravity database from Geoscience Australia (consisting of about 1.4 million gravity observations, i.e. almost twice as many as used for AUSGeoid98) and DNSC08GRA satellite-altimeter-derived gravity anomalies offshore (Andersen et al., 2010). Dynamic ocean topography estimates at 32 tide gauges and a nationwide DEM given on a 9” by 9” grid were also utilised (Featherstone et al., 2011). It is expected that AUSGeoid09 will convert GNSS heights to AHD71 heights to within ±0.05 m across most of Australia, although the accuracy can exceed a decimetre in some areas due to errors in the levelling network, land subsidence, long wavelength geoid anomalies, GNSS errors or a lack of data (Brown, 2010).

It is important to note that the published AUSGeoid models are not strictly geoid models as they express the separation between the GRS80 ellipsoid and the (less than ideal but widely accepted) AHD71, rather than the equipotential geoid (Featherstone, 1998). While the inclusion of the geometric component in AUSGeoid09 contributes to a better fit to AHD71, it causes the N values to deviate from true geoid/quasigeoid undulations.

This paper aims to quantify the expected improvement of replacing AUSGeoid98 with AUSGeoid09 in New South Wales (NSW). Four tests have been performed. Firstly, in excess of 500 AUSPOS solutions were used to investigate how well the two geoid models fit known AHD71 heights across the State. Secondly, a similar analysis was carried out based on 38 sites of the State’s permanently operating GNSS reference station network, CORSnet-NSW. Thirdly, the overall fit of several GNSS-based adjustments was studied, incorporating various ranges in elevation and adjustment area sizes. Lastly, the residuals of the height observations stemming from these adjustments were analysed.

4. Test 1: Analysis based on NSW AUSPOS Solutions

Initial calculations were performed using a large number of AUSPOS (GA, 2009) solutions collected by the NSW Land and Property Management Authority (LPMA) and covering most of the State. The analysis was based on N values derived from a modified version of interpolation software developed by Dr Dru A. Smith of the U.S. National Geodetic Survey (NGS, 2010), which utilises bi-quadratic interpolation and has shown to deliver the same results as both Geoscience Australia’s WINTER (GA, 2007) and GeoLab (Microsearch Corp, 2010), at the 1-2 mm level. N values were interpolated for 513 AUSPOS solutions on established marks with accurate AHD71 heights (C3 or better, including 44% of levelled marks with LCL3 or better). Detailed definitions of the terms class and order can be found in ICSM (2007). The AUSPOS solutions were based on between 3 and 94 hours of GNSS data. It should be noted that about 100 of these AUSPOS solutions were used in the determination of the geometric component of AUSGeoid09.

An improvement by a factor of 2.7 was found in the agreement with expected AHD71 heights when applying AUSGeoid09 to GDA94 ellipsoidal heights as opposed to applying AUSGeoid98, with the root mean square (RMS) dropping from 0.185 m to 0.069 m. The range of residuals for this dataset decreased from 1.27 m (-0.725 m to +0.547 m) to 0.67 m (-0.391 m to +0.275 m), improving by a factor of 1.9. It should be noted that no correlation was evident between the length of the GNSS observation span and the level of agreement with the AHD71 values.

The differences in the N values for the same 513 AUSPOS solutions (AUSGeoid09 minus AUSGeoid98) exhibit a range of 0.93 m (-0.498 m to +0.435 m) with an RMS of 0.185 m. These results indicate that N values will change by a significant amount across the State when moving to AUSGeoid09 in order to provide an improved fit to AHD71. Figure 2 illustrates that large differences occur in some parts of the State, while the values in other areas have hardly changed. In isolated cases it is evident that neighbouring points show very different N values. The North Coast area is known to exhibit a large offset in relation to the national datum (up to about 0.3 m horizontally and 0.5 m vertically) caused by adjustments based on terrestrial data lacking connections to surrounding control performed in the past. It clearly stands out as a block with positive differences while the remainder of the state shows negative values.

In summary, it is evident from the AUSPOS solutions analysed that AUSGeoid09 provides a better fit to AHD71 across NSW than its predecessor AUSGeoid98.

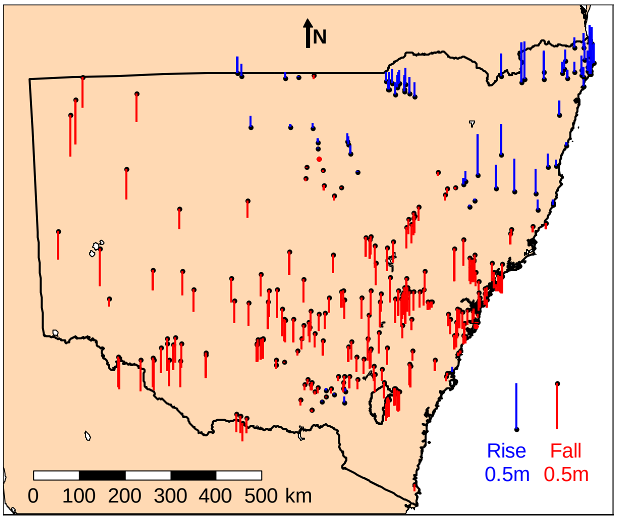

Figure 2: Difference in N values (AUSGeoid09 minus AUSGeoid98) for AUSPOS solutions across NSW.

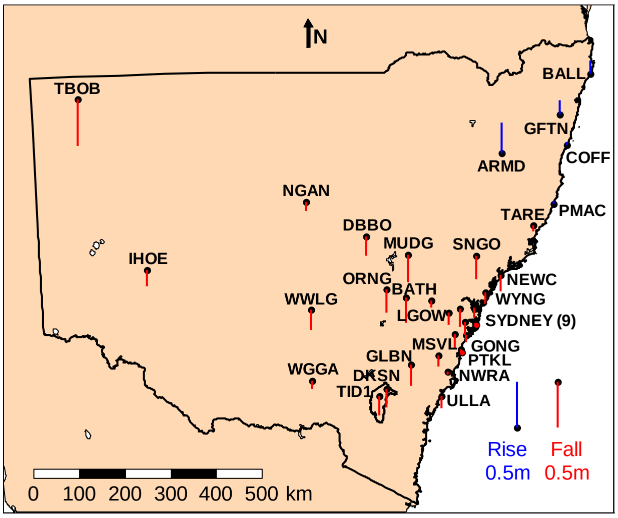

Figure 3: Difference in N values (AUSGeoid09 minus AUSGeoid98) for selected CORSnet-NSW sites.

5. Test 2: Analysis based on Regulation 13 Solutions for CORSnet-NSW Sites

CORSnet-NSW is a rapidly growing GNSS CORS network providing fundamental positioning infrastructure for New South Wales (Janssen et al., 2010). 38 CORSnet-NSW sites with Regulation 13 certified GDA94 coordinates, providing a Recognised Value Standard, and accurate AHD71 heights (mainly A1 obtained by LPMA through a GNSS-based local tie survey) were used for comparable test calculations.

Applying AUSGeoid09 to Regulation 13 GDA94 ellipsoidal heights as opposed to applying AUSGeoid98 revealed an improvement by a factor of 4.1 in the agreement to AHD71 with the RMS dropping from 0.176 m to 0.043 m, thus falling within the expected ±0.05 m accuracy stated by Brown et al. (2010). The range of residuals for this dataset decreased from 0.84 m (-0.519 m to +0.316 m) to 0.24 m (-0.105 m to +0.138 m), improving by a factor of 3.4. The lower RMS and range of residuals in comparison to the previous test involving AUSPOS solutions can be explained by the improved processing methodology employed and the much more consistent quality of the input data. Both Regulation 13 certification and the LPMA local tie survey process are highly traceable and standardised.

The differences in the N values for the same 38 CORSnet-NSW sites (AUSGeoid09 minus AUSGeoid98) exhibit a range of 0.84 m (-0.506 m to +0.329 m) with an RMS of 0.180 m. These values confirm that N values will change by a significant amount across the State when moving to AUSGeoid09. Figure 3 illustrates the varying magnitude of the differences in N values across NSW, showing that results agree very well with the findings from Test 1.

While this dataset contains only a limited amount of data in the north-eastern part of NSW, this area is again identified as a block of positive differences in contrast to the rest of the State.

In summary, the analysis based on 38 CORSnet-NSW sites confirms that AUSGeoid09 provides an improved fit to AHD71 across NSW when compared to AUSGeoid98.

6. Test 3: Adjustment Analysis (Overall Fit)

In order to get an indication of the performance of the new geoid model in practice with regards to GNSS-based adjustments in NSW, seven 3-dimensional GeoLab (Microsearch Corp, 2010) network adjustments were run using AUSGeoid98 and AUSGeoid09. The original geoid files were converted to GeoLab geoid files using software developed in-house which has been tested and validated over 15 years.

Height control points used for these adjustments had accurate (i.e. LCL3 or B2, or better), predominantly levelled AHD71 height values that were converted to ellipsoidal values before the adjustment using the selected geoid model. All heights known accurately were tightly constrained in the adjustment and the resulting variance factor and flagged residuals were inspected to get an indication of the overall fit of the adjustment to AHD71 across NSW. Three of these adjustments (1, 2 and 4 in the list below) originally, in production, had to be run with rotation parameters and a scale factor in order to achieve a satisfactory fit to the existing height control. However, the following comparison is based on adjustments without rotation and scale parameters.

The following seven GNSS-based adjustment datasets were examined:

1. South Coast, a small adjustment covering a small area with a small variation in height.
2. Oxley Highway, a small adjustment covering a small area and showing a large variation in height.
3. Singleton, a large adjustment covering a small area with a moderate variation in height.
4. Bellingen, a large adjustment covering a small area with a large variation in height.
5. Bland, a large adjustment covering a moderately sized area and exhibiting a moderate variation in height.
6. South-west NSW, a large adjustment of a high-precision GNSS network covering a large area with a moderate variation in height. Most of the observations are also included in the state-wide NSW adjustment (see below).
7. NSW, a large state-wide adjustment of the State's high-precision GNSS network covering a large area, extending to all borders of the State. It exhibits a large variation in height and is constrained by 11 Australian National Network (ANN) stations.

Table 1 summarises relevant information about these adjustments, while Figure 4 illustrates their location and extent in NSW. It should be noted that each baseline component is represented as a separate observation.

In general, the utilisation of AUSGeoid09 improved the variance factor (Table 2) and reduced the number of flagged residuals (Table 3), indicating a better adjustment result in comparison to using AUSGeoid98. The smaller adjustments (1 and 2) showed a large improvement in the overall fit, evident by the variance factor improving by factors of 2.3 and 4.6, while the number of flagged residuals was significantly reduced from 13 to 2 and from 7 to 0 respectively. The improvement is more prominent for adjustment 2 which exhibits a much larger variation in height across the area. Owing to the higher density of AUSGeoid09, this could be expected.

The overall fit of the larger adjustments also improved but by a much smaller factor, only showing slight improvements in variance factor and the number of flagged residuals. Adjustments 3 and 4 cover equally small areas and contain rather short baseline lengths. Both show a minimal improvement when using AUSGeoid09, although adjustment 4 exhibits a much larger variation in height.

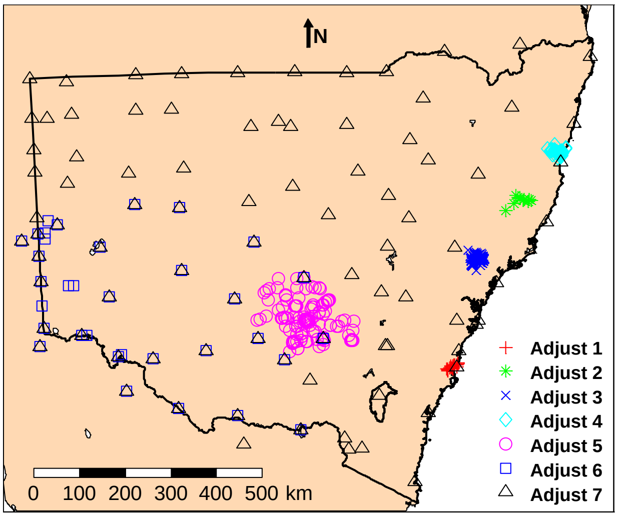

Figure 4: Location and extent of the GNSS-based adjustment datasets investigated.

Adjustment 5 covers a larger area and shows identical variance factors of 1.00 in both cases, while the number of flagged residuals increases from 0 to 1 when using AUSGeoid09. This does not necessarily mean that AUSGeoid09 performs worse than AUSGeoid98 in this case but may indicate that errors in the AHD71 and GNSS heights at the points involved may be compensated by errors in AUSGeoid98. This is discussed further in the next section.

For adjustments 6 and 7 the number of flagged residuals is reduced by one, while improvements in the variance factor are minimal. These adjustments cover very large areas with average baseline lengths of 130 km, reaching up to 270 km and 390 km respectively. It can therefore be expected that distance-dependent error sources mask the improvement achieved by using AUSGeoid09 to some degree.

Table 1: Summary of the GNSS-based adjustment datasets used in this study.

Adjustment	Extent (km)	Height Range (m)	Number of Sites	Number of Obs	Number of Hgt Constraints	Baseline Length (km)	Average Bsl Length (km)
1: South Coast	21 x 18	7 – 296	18	159	12 (67%)	0.4 – 12	5
2: Oxley Hwy	53 x 35	116 – 1,208	13	108	6 (46%)	0.03 – 53	16
3: Singleton	33 x 42	30 – 442	87	631	55 (63%)	0.6 – 30	5
4: Bellingen	40 x 27	2 – 1,041	107	565	63 (59%)	0.3 – 23	2
5: Bland	212 x 162	167 – 544	155	1,075	70 (45%)	0.1 – 67	12
6: SW NSW	633 x 553	20 – 645	34	752	26 (76%)	8 – 270	128
7: NSW	1,000 x 800	2 – 2,229	89	1,721	11 (12%)	3 – 393	130

While 76% of the marks included in adjustment 6 are tightly constrained to their known AHD71 heights, only 12% of sites are constrained in the state-wide adjustment 7. The other five adjustments include height constraints on 45% – 63% of the marks involved. From the limited amount of data analysed here, no correlation is evident between the number of constrained AHD71 heights included in the adjustment and the improvement gained by utilising AUSGeoid09.

In summary, based on these seven adjustments, further evidence is given that AUSGeoid09 considerably improves access to AHD71 compared to AUSGeoid98 across NSW.

Table 2: Variance factors obtained for the adjustments investigated.

Adjustment	AUSGeoid98	AUSGeoid09	Improvement Factor
1: South Coast	2.68	1.19	2.3
2: Oxley Hwy	2.50	0.54	4.6
3: Singleton	1.11	1.05	1.1
4: Bellingen	1.19	1.12	1.1
5: Bland	1.00	1.00	1.0
6: SW NSW	0.28	0.24	1.2
7: NSW	0.63	0.63	1.0

Table 3: Number of flagged residuals obtained for the adjustments investigated. N/A indicates that an improvement factor could not be calculated due to a zero entry.

Adjustment	AUSGeoid98	AUSGeoid09	Improvement Factor
1: South Coast	13	2	6.5
2: Oxley Hwy	7	0	N/A
3: Singleton	0	0	N/A
4: Bellingen	2	1	2.0
5: Bland	0	1	N/A
6: SW NSW	1	0	N/A
7: NSW	2	1	2.0

7. Test 4: Adjustment Analysis (Height Observation Residuals)

In a further attempt to investigate the application of AUSGeoid09 in practice, a second test was performed based on the seven adjustments mentioned above. In this analysis, only one observed AHD71 height was held fixed (located in the centre of the adjustment area), while the others were introduced as observations and allowed to float. Therefore, the adjustment was minimally constrained in height. For the marks that had accurately known AHD71 heights, the adjusted heights (obtained by applying AUSGeoid98 or AUSGeoid09) were compared against their known AHD71 values by analysing the residuals of the height observations after the adjustment. The values of these residuals indicate how well the geoid model fits the AHD71 heights.

For each of the adjustment datasets described above, the height observation residuals for each geoid model are summarised in Table 4. It is evident that the use of AUSGeoid09 considerably improves the residuals in most cases with improvement factors generally larger than 1.5. By far the largest improvement is evident for adjustment 2 with improvement factors of 4.6 for the RMS and 6.0 for the range of the residuals, although it should be remembered that the sample size is very small for this adjustment.

In most cases the RMS of the AUSGeoid09 results falls within the expected ±0.05 m accuracy stated by Brown et al. (2010), although the range of residuals remains rather large. However, adjustments 6 and 7 show larger RMS values. This was expected because these two adjustments cover large areas and contain relatively long average baseline lengths of 130 km. While the RMS shows improvement, the range of residuals slightly worsens in these two cases. This is not surprising because these baselines were processed with 1990's-era commercial GNSS software having limited modelling options, and distortions in AHD71 are more prominent over longer distances.

It should also be remembered that errors in the AHD71 and GNSS heights at the analysed points contribute cumulatively to the overall error in the residual comparison of these adjustments. This may be compensated by errors present in AUSGeoid98, giving a falsely accurate answer for AUSGeoid98 residuals and leading to a seemingly smaller accuracy gain when AUSGeoid09 is used. Nevertheless, the overall indication is that AUSGeoid09 improves considerably upon AUSGeoid98.

In summary, all four tests have shown that AUSGeoid09 will substantially improve the access to AHD71 for GNSS-based height transfer in NSW.

Table 4: Results of the height observation residual analysis.

Adjustment	Parameter	AUSGeoid98	AUSGeoid09	Improvement Factor
1: South Coast (11 marks)	**RMS (m)**	0.061	0.024	2.6
	Range (m)	0.166	0.070	2.4
2: Oxley Hwy (5 marks)	**RMS (m)**	0.157	0.034	4.6
	Range (m)	0.299	0.050	6.0
3: Singleton (53 marks)	**RMS (m)**	0.039	0.029	1.3
	Range (m)	0.159	0.104	1.5
4: Bellingen (60 marks)	**RMS (m)**	0.081	0.053	1.5
	Range (m)	0.477	0.340	1.4
5: Bland (68 marks)	**RMS (m)**	0.077	0.049	1.6
	Range (m)	0.321	0.281	1.1
6: SW NSW (24 marks)	**RMS (m)**	0.150	0.087	1.7
	Range (m)	0.389	0.408	1.0
7: NSW (9 marks)	**RMS (m)**	0.190	0.144	1.3
	Range (m)	0.308	0.411	0.7

8. Concluding Remarks

Geoscience Australia has recently released the latest (and most likely last) beta version of AUSGeoid09 which will soon replace the currently used AUSGeoid98 geoid model for Australia. AUSGeoid09 allows a more direct determination of AHD heights from GNSS observations, owing to the inclusion of a geometric component. It has been shown that the AUSGeoid09 product provides a considerably improved fit to AHD71 across NSW when compared to its predecessor.

Analyses based on more than 500 AUSPOS solutions across the State and 38 CORSnet-NSW sites showed that AUSGeoid09 substantially enhances the quality of GNSS-based determination of AHD71 heights in NSW. The RMS of residuals improved by factors of 2.7 and 4.1 respectively, while the ranges of the height residuals improved by factors of 1.9 and 3.4 respectively. It was also shown that N values in NSW will change significantly in magnitude, by up to 0.5 m, when AUSGeoid09 is introduced.

An investigation of several GNSS-based adjustments, incorporating various ranges in elevation and adjustment area sizes, revealed that the utilisation of AUSGeoid09 generally improved the overall adjustment fit. This was evidenced by improved variance factors and reduced numbers of flagged residuals, although this improvement was smaller for larger adjustments covering large areas.

The residuals of the height observations stemming from these adjustments were also analysed and showed that AUSGeoid09 improved the residuals, generally by a factor of about 1.5, reaching maximum values of 4.6 for the RMS and 6.0 for the range of the residuals.

In most cases the AUSGeoid09 results fall within the expected ±0.05 m accuracy stated by Brown et al. (2010), considering the existence of errors in both AHD71 and GNSS heights at the analysed points and possible compensation of these errors by errors present in AUSGeoid98.

The improvement achieved with AUSGeoid09 can be explained mainly by the larger and higher-quality input dataset, improved modelling and the increased density of AUSGeoid09. It should be emphasised that the inclusion of the geometric component makes AUSGeoid09 a hybrid model, contributing to a better fit to AHD71 but also causing the N values to deviate from true geoid/quasigeoid undulations. It is important to understand that AUSGeoid09 provides a correction surface between the GRS80 ellipsoid and the AHD71, not the geoid. AHD71 continues to be a practical but less than ideal height datum, and a strategy to update it needs to be discussed at the national level. In the meantime, AUSGeoid09 provides a considerable improvement upon AUSGeoid98 for GNSS-based height transfer in New South Wales.

Upon release of Version 1.0, LPMA will adopt AUSGeoid09 for all operations. This will also include the generation of DEM products obtained by airborne LiDAR and photogrammetry. Initial investigations conducted by LPMA indicate that using AUSGeoid09 significantly improves elevation data products. Even over large extents (500 km^2) the AUSGeoid09-derived DEM values agree with local AHD71 ground control points at the few-centimetre level, causing the final correction to AHD71 to be minimal. The CORSnet-NSW infrastructure is increasingly being utilised to determine the aircraft trajectory for LiDAR surveys (Colombo et al., 2010). Users who derive their initial ellipsoidal heights using AHD71 and a geoid model can expect that AUSGeoid09 will serve them very well and the elevation products will represent local AHD71 much better than in the past.

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