Performance of AUSGeoid09 in NSW

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Abstract

In March 2011 Geoscience Australia released AUSGeoid09, an improved geoid model for Australia to relate GNSS-derived ellipsoidal heights to the Australian Height Datum (AHD71) and vice versa. This paper briefly reviews the theory of GNSS-based height determination and illustrates that the absolute accuracy of N values is increasingly important for users of Global Navigation Satellite System (GNSS) Continuously Operating Reference Station (CORS) networks. In order to quantify the expected improvement of replacing the current geoid model, AUSGeoid98, with AUSGeoid09 in New South Wales (NSW), four tests were performed. These tests investigated 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. In most cases the AUSGeoid09-derived height results fall within the expected ±0.05 m accuracy stated by Geoscience Australia. It is also shown that the magnitude of N values in NSW will change by up to 0.5 m when AUSGeoid09 is introduced in order to provide a better fit to AHD71. The NSW Land and Property Management Authority (LPMA) has adopted AUSGeoid09 for all operations and urges all spatial professionals to do the same.

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. Australia, like most countries, uses an approximation of the orthometric height system referenced to the geoid. The geoid is defined as the equipotential surface that best approximates mean sea level (MSL). A detailed treatment of height systems and vertical datums in the Australian context can be found in Featherstone and Kuhn (2006).

The Australian Height Datum (AHD71) was realised in 1971 by setting the observed MSL to zero at 32 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, 40 years later we know that shortcomings in the AHD71 realisation resulted in MSL not being coincident with the geoid at the 32 tide gauges involved. These shortcomings included not considering dynamic ocean effects (e.g. winds, currents, atmospheric pressure, temperature and salinity), a lack of long-term tide gauge data, and the omission of observed gravity. This has introduced considerable distortions of up to about 1.5 m into AHD71 across Australia. Nevertheless, AHD71 continues to be a practical height datum, providing a sufficient approximation of the geoid for many applications.

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 generally required that correctly reflect the flow of water and must therefore be referenced to the geoid. GNSS-derived ellipsoidal heights (h) can easily be converted to orthometric AHD71 heights (H) if the appropriate geoid undulations (N), also known as geoid-ellipsoid separations or N values, are available (e.g. Featherstone and Kuhn, 2006; Janssen, 2009):

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

Figure 1 illustrates the important role N values play in the conversion of heights. On the one hand, N values are required 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 necessary to obtain orthometric heights (i.e. physical meaning) from GNSS-derived ellipsoidal heights (i.e. geometrical meaning) (Rizos, 1997).

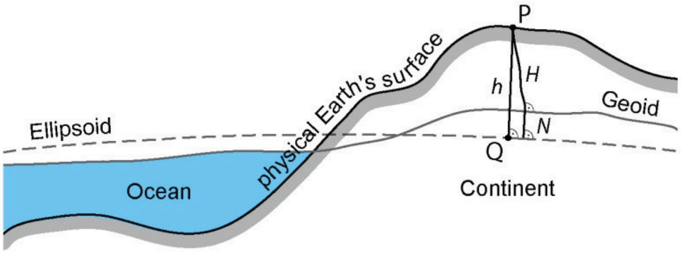

Figure 1: Relationship between ellipsoidal height (h), orthometric height (H) and geoid undulation (N), courtesy of M. Kuhn, Curtin University of Technology.

In practice, a geoid model is used to provide these N values necessary for GNSS-based height determination. This paper highlights the increased importance of N values for users of Continuously Operating Reference Station (CORS) networks and shows that the new AUSGeoid09 geoid model substantially improves GNSS-based access to AHD71 in New South Wales.

Considerations for CORS Users

The use of CORS networks, such as CORSnet-NSW (Janssen et al., 2010), for GNSS real-time and post-processing applications has grown significantly over the last few years. This development has substantially increased the importance of accurate N values in regards to GNSS-based height determination.

In the traditional base-rover field scenario, the published, local AHD71 height of a temporary GNSS reference station is converted to an ellipsoidal height according to 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 (those following CORS Best Practice Guidelines) is determined via Regulation 13 certification. Geoscience Australia determines these site coordinates in a global (or, more precisely, regional) context based on a week of GNSS data and highly traceable, standardised, scientific processing. 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 Geocentric Datum of Australia (GDA94).

As illustrated by Figure 2, in the traditional base-rover scenario most of the error in the absolute N values cancels due to the conversion being applied twice (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 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 CORS techniques.

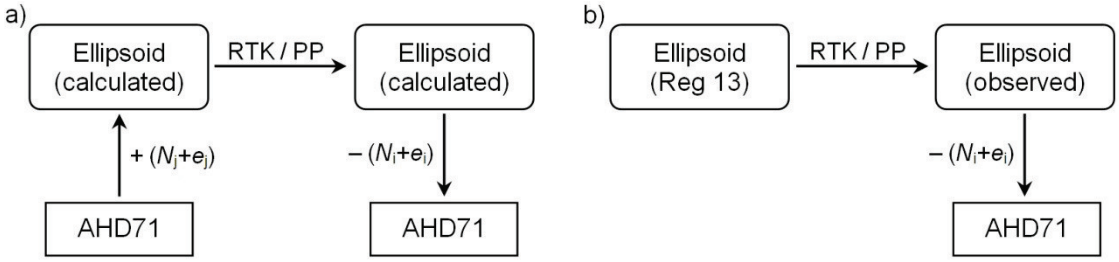

Figure 2: GNSS height transfer methodology using RTK or post processing (PP) in the past (a) and using CORS (b).

AUSGeoid09

In March 2011 Geoscience Australia released AUSGeoid09, a new Australia-wide gravimetric geoid model that has been a-posteriori fitted to the Australian Height Datum. AUSGeoid09 provides an improved means to relate GNSS-derived ellipsoidal heights to AHD71 and vice versa. It is expected to 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 aging levelling network, land subsidence, geoid anomalies, GNSS observational errors or simply a lack of data in some remote locations (Brown, 2010). In comparison, its predecessor AUSGeoid98 only provided an estimated accuracy of better than ±0.4 m in absolute terms (Featherstone and Guo, 2001).

AUSGeoid09 covers the same area as AUSGeoid98 (between 108°E and 160°E longitude and 8°S and 46°S latitude) and also refers to the GRS80 ellipsoid. However, it is given on a 1' by 1' grid (about 1.8 by 1.8 km), making it four times denser than its predecessor (Featherstone et al., 2011). In contrast to previous versions of AUSGeoid, the new AUSGeoid09 combines an improved version of the standard "gravimetric geoid" model with a new additional "geometric" component, colloquially referred to as the "sliver" by its makers.

The first component of AUSGeoid09 is the latest gravimetric geoid model produced by the Western Australian Centre for Geodesy at Curtin University (Featherstone et al., 2011). It provides the gridded height offset between the GRS80 ellipsoid and the geoid surface. It is a product far better than the one used in AUSGeoid98.

The second, and new, component of AUSGeoid09 is the gridded geometric offset between the gravimetric geoid and AHD71, the "sliver", calculated by empirical testing. This offset is mainly caused by AHD71 not taking into account sea surface topography, which includes the differential heating of the oceans. The warmer or less dense water off the coast of northern Australia is about 1 metre 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 introduction of the geometric "sliver" component largely takes care of this 1-metre trend across Australia (0.6-metre trend across NSW), thereby providing a better overall fit to AHD71 (Figure 3).

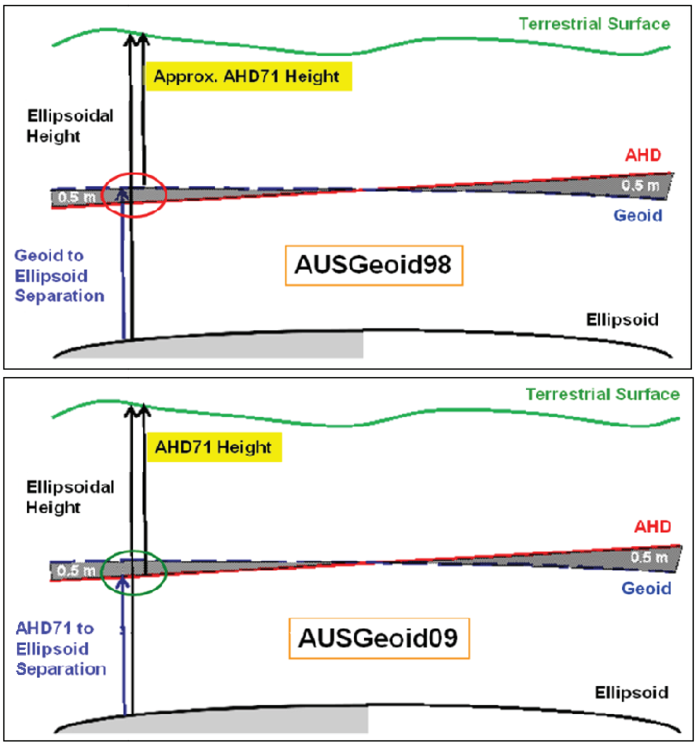

Figure 3: AUSGeoid09 provides improved access to AHD71 due to the introduction of the geometric "sliver" component (adapted from Brown et al., 2010).

Performance of AUSGeoid09

In order to quantify the expected improvement of replacing AUSGeoid98 with AUSGeoid09 in New South Wales (NSW), we carried out four tests. These tests utilised beta version 0.7 of AUSGeoid09 which is identical to the final product in NSW. Firstly, we used more than 500 AUSPOS solutions to investigate how well the two geoid models fit known AHD71 heights across the State. Secondly, we performed a similar analysis based on 38 CORSnet-NSW sites. Thirdly, we studied the overall fit of several GNSS-based adjustments, incorporating different adjustment area sizes and various ranges in elevation. Lastly, we analysed the residuals of the height observations stemming from these adjustments. This section summarises the tests performed and presents the results obtained. For a more detailed analysis the reader is referred to Janssen and Watson (2010).

Test 1: AUSPOS Solutions

The first test investigated 513 AUSPOS solutions (GA, 2009) collected by the NSW Land and Property Management Authority (LPMA) on established marks with accurate AHD71 heights (C3 or better, including 45% 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.

AUSGeoid09 and AUSGeoid98 N values were interpolated for each solution to determine the agreement with published AHD71 heights. Since the differences to the known AHD71 values will sometimes be positive and sometimes be negative, the root mean square (RMS) is used to quantify the average agreement. The RMS of n residuals (x_1 to x_n) is calculated by the square root of the mean of the sum of the squared residuals:

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}} \tag{2}$$

Applying AUSGeoid09 to GDA94 ellipsoidal heights rather than AUSGeoid98 resulted in an improvement by a factor of 2.7, with the RMS dropping from 0.185 m to 0.069 m. The achieved overall accuracy is therefore only slightly worse than the expected accuracy of ±0.05 m stated by Brown (2010). 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 magnitude of N values in NSW will change by up to 0.5 m when AUSGeoid09 is introduced (Figure 4), thereby providing a much better fit to AHD71 across NSW. 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 a large, sparse survey control network. It clearly stands out as a block with positive differences while the remainder of the state shows negative values.

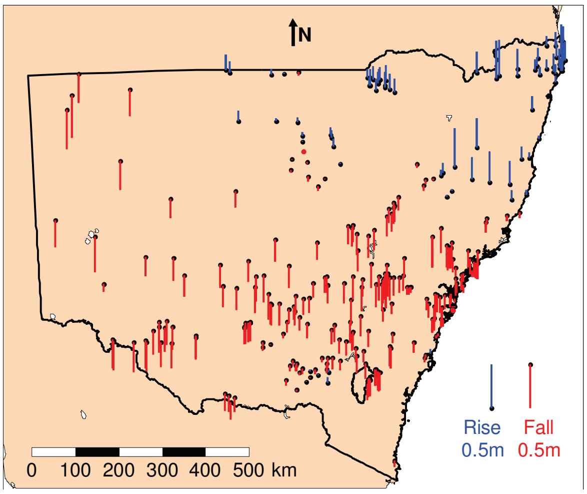

Figure 4: Difference in N values (AUSGeoid09 minus AUSGeoid98) for AUSPOS solutions across NSW.

Test 2: 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 and accurate AHD71 heights (mainly A1 obtained by LPMA through a GNSS-based local tie survey) were used to perform a similar test. Using AUSGeoid09 resulted in 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 accuracy of ±0.05 m stated by Brown (2010). The test confirmed that the magnitude of N values in NSW will change by up to 0.5 m when AUSGeoid09 is introduced (Figure 5). 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.

The higher accuracy achieved in comparison to Test 1 is due to improved processing methods (Regulation 13 vs. AUSPOS) and the much more consistent quality of the input data (7-day vs. 6-hour or so datasets). The Regulation 13 certification and LPMA's local tie survey process are highly traceable and standardised, while the AUSPOS dataset was collected over many years with differing processing parameters. Both tests show that AUSGeoid09 provides an improved fit to AHD71 across NSW when compared to AUSGeoid98.

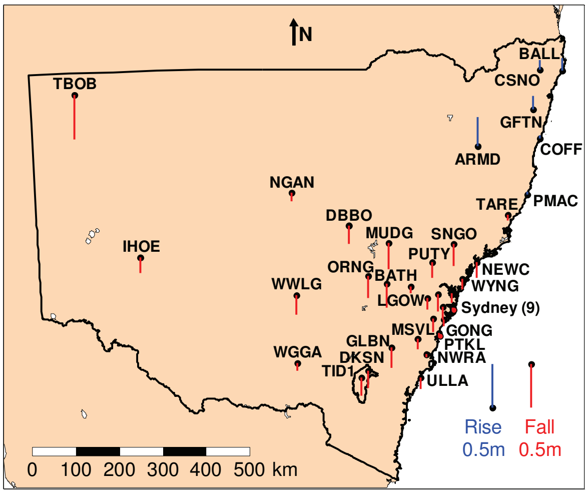

Figure 5: Difference in N values (AUSGeoid09 minus AUSGeoid98) for selected CORSnet-NSW sites.

Test 3: Constrained 3D Network Adjustment Fit

To investigate the performance of the new geoid model in practice with regards to GNSS-based adjustments in NSW, seven 3-dimensional network adjustments were run using AUSGeoid98 and AUSGeoid09. All height control points were tightly constrained in the adjustment to their accurate (LCL3 or B2, or better), predominantly optically levelled AHD71 heights. Therefore, the adjustment was highly constrained in height. The resulting variance factor and flagged residuals were inspected to get an indication of the overall fit of each adjustment to AHD71.

The seven adjustments were chosen carefully to incorporate different adjustment area sizes, ranging from small (20 by 20 km) to state-wide (1,000 by 800 km) with average baseline lengths varying between 2 and 130 km. The datasets included various ranges in elevation: small (290 m), moderate (380 m to 620 m) and large (1,000 m to 2,200 m). The number of sites included in each adjustment varied from 18 to 155 sites, incorporating between 33 and 567 baselines (each baseline component being represented as a separate observation). Table 1 summarises relevant information about these adjustments, while Figure 6 illustrates their location and extent in NSW.

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

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

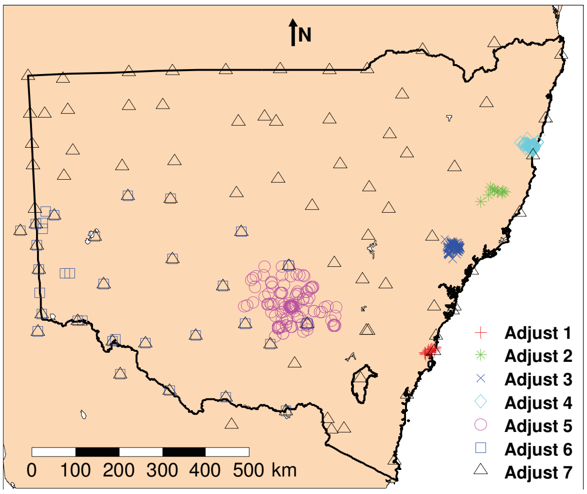

Figure 6: Location and extent of the seven GNSS-based adjustment datasets investigated.

In general, AUSGeoid09 improved the variance factor, indicating a better adjustment result in comparison to AUSGeoid98 (Table 2). The number of flagged residuals was also reduced in most cases. The smaller adjustments (1 and 2) showed a large improvement in the overall fit. Here the variance factor improved 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 displays 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 increased but only showed slight improvements in the variance factor and the number of flagged residuals. Adjustments 6 and 7, covering very large areas with baseline lengths reaching up to 390 km, showed minimal improvements in the variance factor, while the number of flagged residuals was reduced slightly to 0 and 1 respectively. It can be expected that distance-dependent error sources mask the improvement achieved by using AUSGeoid09 to some degree in these cases. In summary, the seven adjustments give further evidence that AUSGeoid09 considerably improves access to AHD71 across NSW compared to AUSGeoid98.

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

Test 4: Minimally Constrained 3D Network Adjustment Fit

The final test was based on the same seven GNSS-based adjustment datasets. In this analysis, only one observed AHD71 height was held fixed (located in the centre of each adjustment area), while the others were introduced as observations and allowed to float. Therefore, the adjustment was minimally constrained in height. For those 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 in practice.

The use of AUSGeoid09 considerably improved the residuals, with RMS improvement factors generally larger than 1.5 (Table 3). By far the largest improvement is evident for adjustment 2 with an improvement factor of 4.6 for the RMS, although it should be remembered that the sample size is very small for this adjustment.

Table 3: 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

In most cases the accuracy of the AUSGeoid09 results falls within the expected accuracy of ±0.05 m. Only adjustments 6 and 7 show larger values, reaching 0.09 m and 0.14 m respectively. This was expected because these two adjustments cover large areas and contain relatively long average baseline lengths of 130 km. 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 needs to be emphasised that the RMS values stated in Table 3 should be interpreted as the average accuracy achievable in these adjustments. As the range of the obtained height residuals illustrates, the residuals continue to show considerable variations, although the improvement of using AUSGeoid09 is obvious.

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 determination in NSW.

Concluding Remarks

In March 2011 Geoscience Australia released AUSGeoid09, an improved geoid model for Australia. This paper has briefly reviewed the theory of GNSS-based height determination and illustrated that the absolute accuracy of N values is increasingly important in the era of expanding CORS networks.

Tests based on more than 500 AUSPOS solutions across the State, 38 CORSnet-NSW sites and seven carefully selected adjustment datasets have shown that AUSGeoid09 substantially improves access to AHD71 for GNSS-based height determination in NSW when compared to its predecessor, AUSGeoid98. This improvement is due to the larger and higher-quality input dataset, improved modelling and the increased density of AUSGeoid09, as well as the inclusion of a geometric component. This allows a more direct determination of AHD71 heights from GNSS observations. In most cases the AUSGeoid09 results fall within the expected accuracy of ±0.05 m stated by Geoscience Australia.

It is important to understand that AUSGeoid09 provides a correction surface between the GRS80 ellipsoid and 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, LPMA has adopted AUSGeoid09 for all operations (including CORSnet-NSW) and urges all spatial professionals to do the same.

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