Evaluating the Performance of AUSGeoid2020 in NSW

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ABSTRACT

Presently, Australia is transitioning to a modernised national datum in order to meet the increasing demands placed by modern satellite-based positioning technology on the underlying geodetic framework. The much improved Geocentric Datum of Australia 2020 (GDA2020) was gazetted in October 2017 and is to replace the current national datum (GDA94) in practice by 2020. This also includes a new quasigeoid model, AUSGeoid2020, to provide an improved connection between ellipsoidal heights derived from Global Navigation Satellite System (GNSS) observations and the Australian Height Datum (AHD). In September 2017, Geoscience Australia finalised the release version of AUSGeoid2020. As NSW is preparing to enable GDA2020, this paper quantifies the expected improvement of using AUSGeoid2020 in conjunction with GDA2020 ellipsoidal heights over using the current AUSGeoid09 in conjunction with GDA94 ellipsoidal heights to access AHD. Three tests are performed in order to investigate how well the two quasigeoid models fit known AHD heights across the State, based on (1) 138 CORSnet-NSW sites, (2) seven GNSS-based adjustments of varying extent and size, and (3) numerous height control points from these adjustments. It is found that the AUSGeoid2020 product provides a considerably improved fit to AHD across NSW when compared to its predecessor. However, the rigorous uncertainty values provided with AUSGeoid2020 appear to be overly conservative, resulting in the AUSGeoid2020 uncertainty grid having only limited practical value at this stage.

KEYWORDS: *AUSGeoid2020, GDA2020, Australian Height Datum, CORSnet-NSW, datum modernisation.*

1 INTRODUCTION

The Geocentric Datum of Australia 1994 (GDA94) has been our national datum since its adoption in 2000, providing fundamental positioning infrastructure for Australia (ICSM, 2014a). Significant improvements in positioning technology in the recent past now enable centimetre-level positioning capability via Global Navigation Satellite System (GNSS) techniques such as Network Real Time Kinematic (NRTK) and Precise Point Positioning (PPP) (e.g. Janssen and Haasdyk, 2011; Rizos et al., 2012), while decimetre-level accuracy will soon be available to the mass-market. These developments have revealed that GDA94 is not capable of providing the required quality of datum into the future. Consequently, Federal, State and Territory Governments have worked towards modernising Australia's datum for some time. In the context of NSW, progress made in this regard has been reported on many occasions during recent years (e.g. Haasdyk and Roberts, 2013; Haasdyk and Watson, 2013; Haasdyk et al., 2014; Gowans et al., 2015). These efforts are now becoming reality as Australia is transitioning to a modernised national datum in order to meet the increasing demands placed on the geodetic framework by modern satellite-based positioning technology (e.g. Gowans, 2017; Janssen, 2017).

The Geocentric Datum of Australia 2020 (GDA2020) is a new, much improved Australian national datum that is based on a single, nationwide least squares network adjustment and rigorously propagates uncertainty (ICSM, 2018). GDA2020 is defined in the current state-of-the-art global International Terrestrial Reference Frame 2014 (ITRF2014 – see Altamimi et al., 2016) at epoch 2020.0. The coordinates are extrapolated into the future to 1 January 2020 in order to extend the lifespan of the datum. In October 2017, GDA2020 was realised by gazetting an expanded Australian Fiducial Network (AFN) consisting of 109 GNSS Continuously Operating Reference Stations (CORS) contributing to the Australian Regional GNSS Network (ARGN) and the AuScope network (NMI, 2017; ICSM, 2018). The move from GDA94 to GDA2020 causes the horizontal coordinates of a mark to shift by up to 1.8 m to the north-east (due to tectonic motion of the Australian plate from 1994 to 2020), while the ellipsoidal height decreases by about 0.09 m (due to improvements from ITRF92 to ITRF2014 to better define the shape of the Earth). GDA2020 is expected to replace GDA94 in practice by 1 January 2020.

Vertical coordinates continue to be referred to the Australian Height Datum (AHD) (Roelse et al., 1975). It is well known that shortcomings in the AHD realisation (AHD71 for mainland Australia and AHD83 for Tasmania) resulted in considerable distortions of up to about 1.5 m into AHD across Australia, which is therefore considered a third-order datum (e.g. Morgan, 1992; Featherstone and Filmer, 2012; Watkins et al., 2017). However, in the immediate future AHD continues to be a practical height datum or working surface that provides a sufficient approximation of the geoid for many surveying and engineering applications. In the longer term, the Intergovernmental Committee on Surveying and Mapping (ICSM) will consider updating AHD or replacing it potentially with a new national gravity-based vertical reference frame (Filmer and Featherstone, 2012). Geoscience Australia plans to lead the development of a new vertical working surface as an alternative to AHD (Brown et al., 2018).

In order to connect to AHD via GDA2020 ellipsoidal heights, a new quasigeoid model (AUSGeoid2020) has been produced (Featherstone et al., 2018; ICSM, 2018; Brown et al., in prep.). Due to the aforementioned 0.09 m difference in ellipsoidal heights between GDA94 and GDA2020, it is crucial for users to apply AUSGeoid2020 *only* to GDA2020 ellipsoidal heights, while its predecessor AUSGeoid09 *must* be used to convert GDA94 ellipsoidal heights.

In September 2017, Geoscience Australia finalised the release version of AUSGeoid2020. As NSW is preparing to enable GDA2020, this paper aims to quantify the expected improvement of using AUSGeoid2020 in conjunction with GDA2020 ellipsoidal heights over using the current AUSGeoid09 in conjunction with GDA94 ellipsoidal heights to access AHD in NSW. Three tests are performed in order to evaluate how well the two quasigeoid models fit known AHD heights across the State, based on (1) 138 CORSnet-NSW sites, (2) seven GNSS-based network adjustments of varying extent and size, and (3) numerous height control points from these adjustments.

2 RECENT QUASIGEOID MODELS IN 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 (e.g. Vaniček et al., 2012; Sjöberg, 2013). The Australian Height Datum can be thought of as a hybrid of these two vertical surfaces because normal gravity, referenced to a mean Earth ellipsoid, was used in the orthometric correction formulae instead of observed gravity (Roelse et al., 1975). 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).

Over many years, the use of quasigeoid models has helped GNSS users to compute AHD heights (H_{AHD}) from ellipsoidal heights (h) by applying the ellipsoid-to-AHD separation (N_{AHD}) (e.g. Featherstone and Kuhn, 2006; Janssen, 2009):

$$H_{AHD} = h - N_{AHD} \tag{1}$$

Figure 1 illustrates this relationship between GNSS-derived ellipsoidal heights and AHD heights.

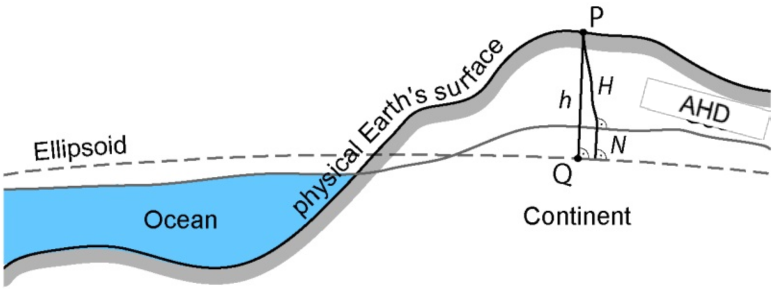

Figure 1: Relationship between ellipsoidal height (h), AHD height (H) and ellipsoid-to-AHD separation (N), courtesy of M. Kuhn, Curtin University of Technology.

The first version of AUSGeoid, AUSGeoid91, was released in 1991, followed by AUSGeoid93 and AUSGeoid98 (e.g. Kearsley, 1988; Kearsley and Steed, 1995; Featherstone et al., 2001). This section briefly describes the two most recent versions, AUSGeoid09 and AUSGeoid2020.

2.1 AUSGeoid09

In March 2011, AUSGeoid98 was replaced by AUSGeoid09, the first combined gravimetric-geometric quasigeoid model for Australia (Brown et al., 2011; Featherstone et al., 2011). AUSGeoid09 has the same extent as its predecessor (between 108ºE and 160ºE longitude and 8ºS and 46ºS latitude) but is given on a 1’ by 1’ grid (about 1.8 by 1.8 km), making it four times denser.

Previous versions of AUSGeoid were predominantly gravimetric-only quasigeoids, and it was assumed that these were sufficiently close approximations of AHD – an assumption we now know to be incorrect. In contrast, AUSGeoid09 is a combined gravimetric-geometric quasigeoid, providing a direct connection to AHD and thereby allowing a more reliable determination of AHD heights from GNSS observations.

The gravimetric component of AUSGeoid09 is the Australian Gravimetric Quasigeoid 2009 (AGQG09) (Featherstone et al., 2011). It provides the gridded ellipsoid-quasigeoid separation and is a product far better than the one used in AUSGeoid98, mainly due to a larger amount of input data and improved modelling.

The geometric component of AUSGeoid09 delivers a grid of quasigeoid-AHD separation values, derived from an empirical dataset of collocated GNSS ellipsoidal heights and AHD heights. It accounts for the offset between AHD and the quasigeoid, ranging from about -0.5 m (AHD below quasigeoid) in the south-west of Australia to about +0.5 m (AHD above quasigeoid) in the north-east of Australia (-0.3 m to +0.2 m across NSW). This offset is predominantly caused by the AHD definition 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. By constraining each of the 30 tide gauges used in the definition of AHD to zero without considering the differences in mean sea level, these effects were propagated into the adjustment (Brown et al., 2011). The introduction of the geometric component takes care of most of this 1-metre trend across Australia (0.5-metre trend across NSW), thereby providing a better overall fit to AHD. Across NSW, the geometric component of AUSGeoid09 is based on 100 control points (Figure 2).

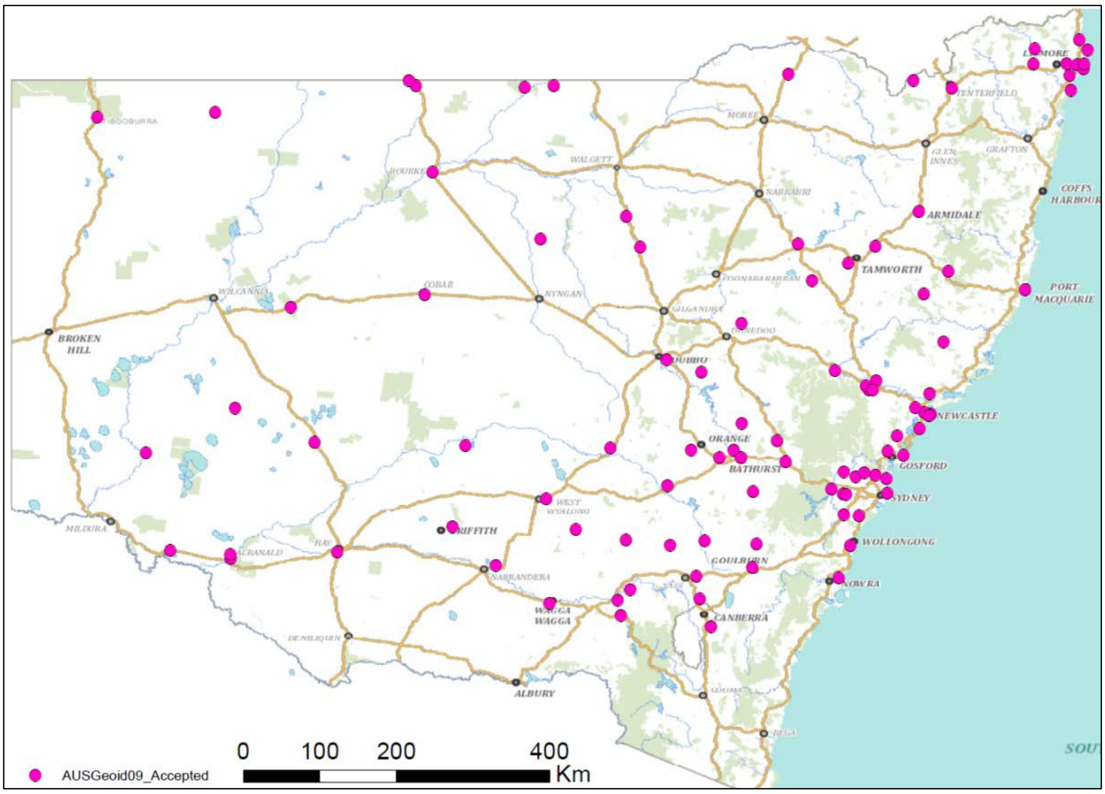

Figure 2: Levelled marks observed by GNSS and providing control for AUSGeoid09.

AUSGeoid09 was found to provide connection to AHD at the ±0.05 m uncertainty level (1 sigma) across most of Australia, although the uncertainty can exceed a decimetre in some areas due to errors in the ageing levelling network, land subsidence, geoid anomalies or data deficiency (e.g. Janssen and Watson, 2010, 2011; Brown et al., 2011; Sussanna et al., 2014, 2016; Allerton et al., 2015).

2.2 AUSGeoid2020

In September 2017, Geoscience Australia finalised the release version of AUSGeoid2020 (version 08/09/2017). AUSGeoid2020 is also a combined gravimetric-geometric quasigeoid model. The gravimetric component is a 1’ by 1’ grid of improved ellipsoid-quasigeoid separation values created using data from satellite gravity missions (e.g. GRACE and GOCE), re-tracked satellite altimetry, localised airborne gravity, land gravity data from the Australian national gravity database and a Digital Elevation Model to apply terrain corrections. This gravimetric component is known as the Australian Gravimetric Quasigeoid 2017 (AGQG2017 – see Featherstone et al., 2018 for details on its input data and computation).

The geometric component is basically a 1’ by 1’ grid of improved quasigeoid-AHD separation values, derived from a much larger dataset of collocated GNSS ellipsoidal heights and AHD heights across Australia, accounting for the offset between AHD and the quasigeoid. It should be noted that only a single grid of ellipsoid-AHD separation values is made available to users.

While AUSGeoid2020 has the same extent (albeit with a larger computation area during its generation) and density as its predecessor AUSGeoid09, it is based on a much larger and much more homogeneous dataset. For example, DFSI Spatial Services has collected over 2,500 extended GNSS datasets (at least 6 hours but generally 12-24 hours duration) on levelled benchmarks across NSW as part of its ‘Saving AHD’ project (Figure 3). These datasets inform the geometric component of AUSGeoid2020, thereby helping to provide a much improved connection to AHD for GDA2020 ellipsoidal heights across the State.

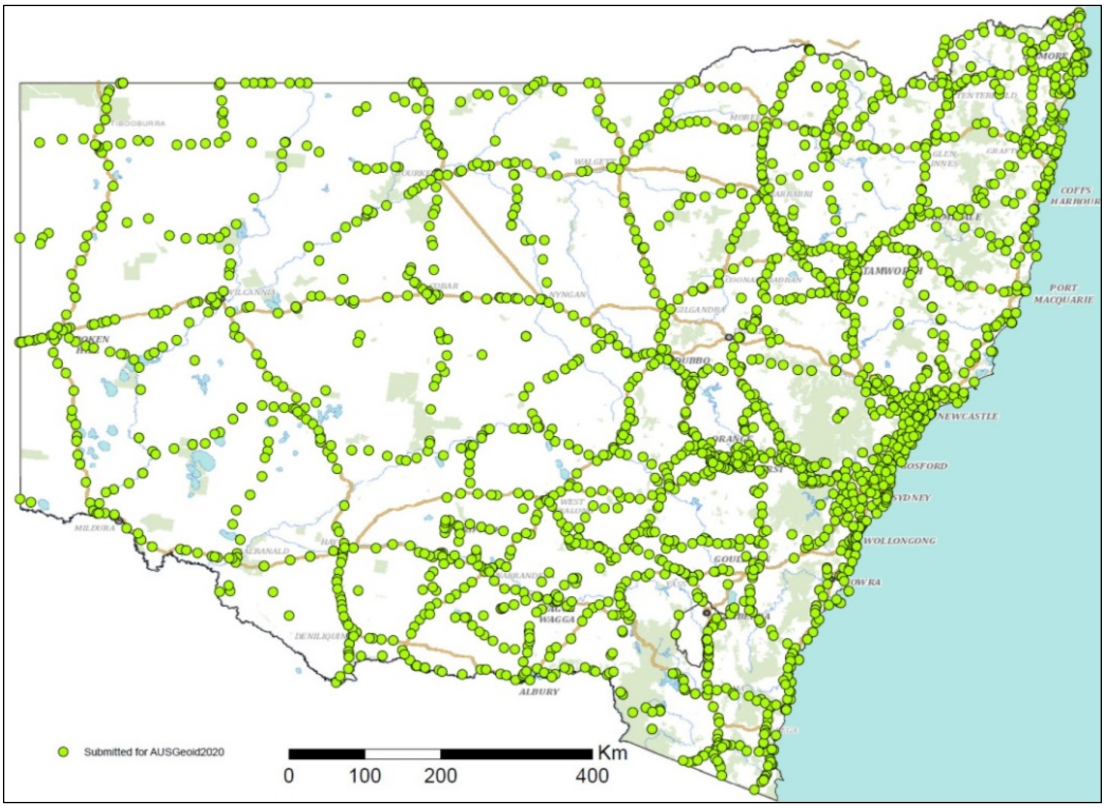

Figure 3: GNSS datasets (6+ hour duration) observed on levelled marks by DFSI Spatial Services, contributing to AUSGeoid2020.

AUSGeoid2020 provides a rigorous uncertainty value associated with the separation between the ellipsoid and AHD, varying as a function of location (Featherstone et al., 2018; ICSM, 2018; Brown et al., in prep.). In contrast, AUSGeoid09 only provides a constant uncertainty estimate (Brown et al., 2011). Consequently, AUSGeoid2020 users are expected to benefit from more realistic uncertainty information, particularly in the coastal zone where offshore data is included in the model computation and mountainous regions or other areas exhibiting sparser input datasets.

3 PERFORMANCE OF AUSGeoid2020 IN NSW

NSW is currently preparing to enable GDA2020. The move from GDA94 to GDA2020 causes the horizontal coordinates of a mark to shift by up to 1.8 m to the north-east and the ellipsoidal height to decrease by about 0.09 m. Consequently, a comparison between AUSGeoid09 and AUSGeoid2020 necessitates the availability of both GDA94 and GDA2020 coordinates for the test points utilised in order to quantify the expected improvement in the connection to AHD, as realised by known AHD heights of sufficient quality (class and order) on public record in the Survey Control Information Management System (SCIMS).

SCIMS is the State's database containing about 250,000 survey marks across NSW, including coordinates, heights and metadata (Kinlyside, 2013). For a discussion of the terms class and order, the reader is referred to ICSM (2007) and Dickson (2012). While it is acknowledged that ICSM (2007) has recently been superseded by ICSM (2014b), this update does not affect the outcome of the analysis presented in this paper.

Since it is necessary to consider coordinate differences of opposite signs, the Root Mean Square (RMS) is deemed appropriate to quantify the average agreement to AHD. The following sections describe the three tests performed and outline the results obtained.

3.1 Test 1: Analysis Based on CORSnet-NSW Sites

CORSnet-NSW is Australia's largest state-owned and operated network of permanent GNSS reference stations. It is built, owned and operated by Spatial Services, a unit of the NSW Department of Finance, Services and Innovation (DFSI) (e.g. Janssen et al., 2016; DFSI Spatial Services, 2018). As of March 2018, the network consists of 200 reference stations, providing fundamental positioning infrastructure that is authorative, accurate, reliable and easy-to-use for a wide range of applications across NSW (Figure 4). Upon completion, CORSnet-NSW is planned to include 220 CORS.

138 of these CORSnet-NSW sites, i.e. those that had both Regulation 13 certified GDA94 coordinates (GA, 2018) and a locally 'established' SCIMS AHD height (albeit obtained by DFSI Spatial Services through an A1 class/order GNSS-based local tie survey – see Gowans and Grinter, 2013), were selected for comparable test calculations. The GDA2020 coordinates of these sites were obtained directly from the national GDA2020 adjustment.

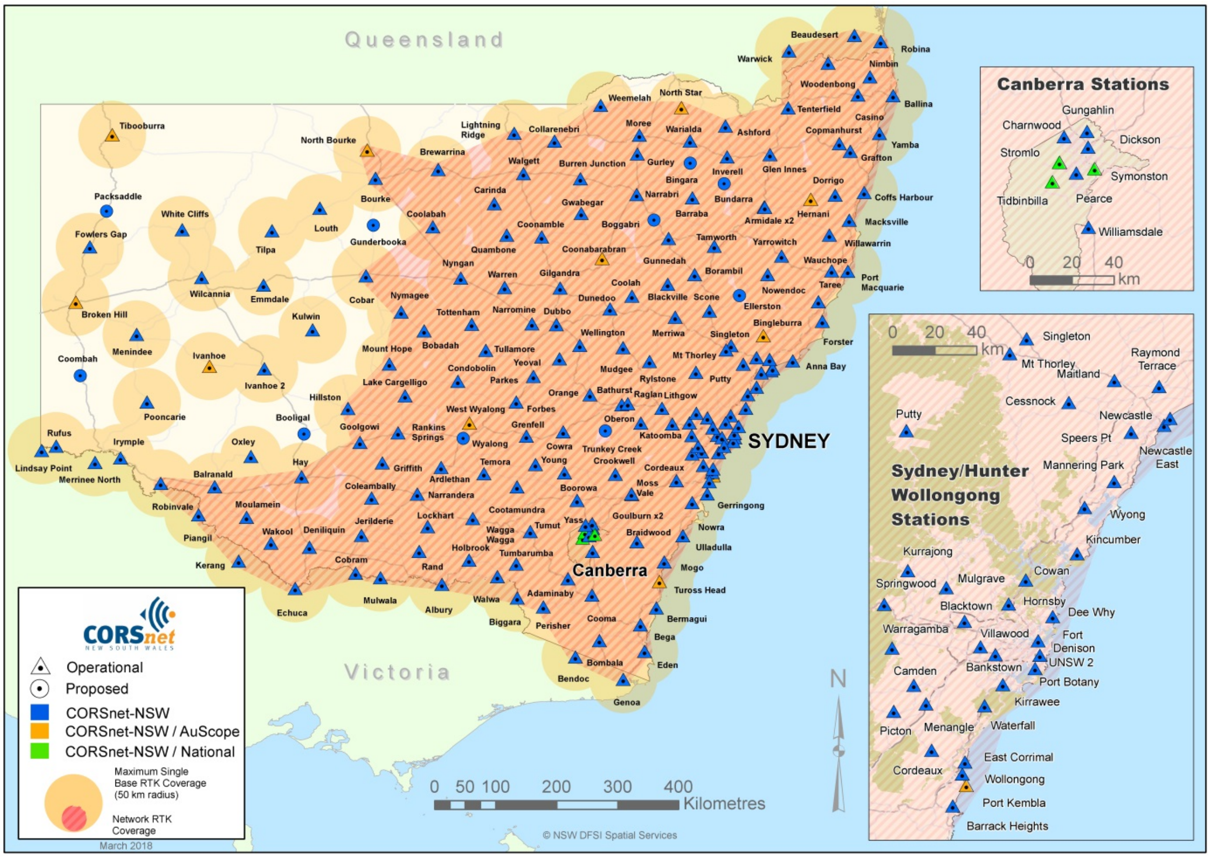

Figure 4: CORSnet-NSW network map as of March 2018 (DFSI Spatial Services, 2018).

Applying AUSGeoid2020 to GDA2020 national-adjustment derived ellipsoidal heights as opposed to applying AUSGeoid09 to Regulation 13 GDA94 ellipsoidal heights revealed an improvement by a factor of 2.3 in the agreement to AHD with the RMS dropping from 0.056 m to 0.024 m. The range of residuals for this dataset decreased from 0.33 m (-0.185 m to +0.142 m) to 0.22 m (-0.158 m to +0.063 m), improving by a factor of 1.5. It is also interesting to note that the number of absolute differences from AHD greater than 0.1 m decreased from 12 to 1. The only remaining misfit in excess of 0.1 m occurs at GURL CORS (-0.158 m).

GURL CORS is located in 'black soil' country, which is well known for reactive soils that cause significant ground movement. These problems were clearly evident when processing both the CORS tie survey for GURL, which connected the CORS to the surrounding ground control network, and from DFSI Spatial Services' continuous daily station monitoring using the Bernese software (Haasdyk et al., 2010) – see Figure 5. Consequently, in SCIMS, GURL CORS was assigned class/order E5 for its AHD height, so the larger difference was expected. It should be noted that the height difference to SCIMS is even larger when using AUSGeoid09 (-0.185 m).

If GURL CORS is excluded from the analysis, the improvement achieved is even more pronounced. Using AUSGeoid2020 provides an improvement by a factor of 2.7 in the agreement to AHD with the RMS dropping from 0.054 m to 0.020 m. The range of residuals decreases from 0.25 m (-0.107 m to +0.142 m) to 0.12 m (-0.053 m to +0.063 m), improving by a factor of 2.2.

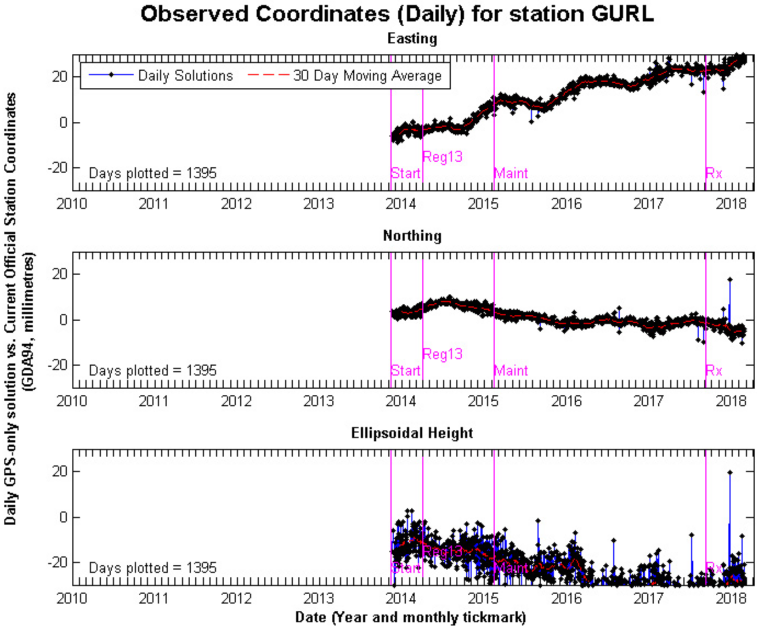

Figure 5: Coordinate time series for GURL CORS, based on daily Bernese processing (DFSI Spatial Services, 2018).

In summary, it is evident from the 138 CORSnet-NSW sites analysed that AUSGeoid2020 provides a considerably better fit to AHD across NSW than its predecessor AUSGeoid09.

3.2 Test 2: Constrained 3D Network Adjustment (Overall Fit)

In order to get an indication of the performance of the new quasigeoid model in practice with regards to GNSS-based adjustments in NSW, seven 3-dimensional GeoLab (BitWise Ideas, 2018) network adjustments were run using AUSGeoid09 in conjunction with GDA94 and AUSGeoid2020 in conjunction with GDA2020. The original quasigeoid files were converted to GeoLab geoid files using software developed in-house, which has been tested and validated over 20 years.

Height control points used for these adjustments had accurate (i.e. LCL3 or B2, or better), predominantly levelled AHD height values that were converted to ellipsoidal values before the adjustment using the selected quasigeoid 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 AHD across NSW.

The following seven GNSS-based adjustment datasets were examined, increasing in size, extent and height variation from small to a state-wide network:

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 covering a quarter of the State 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, 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 6 illustrates their location and extent in NSW. It should be noted that each baseline component is represented as a separate observation.

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

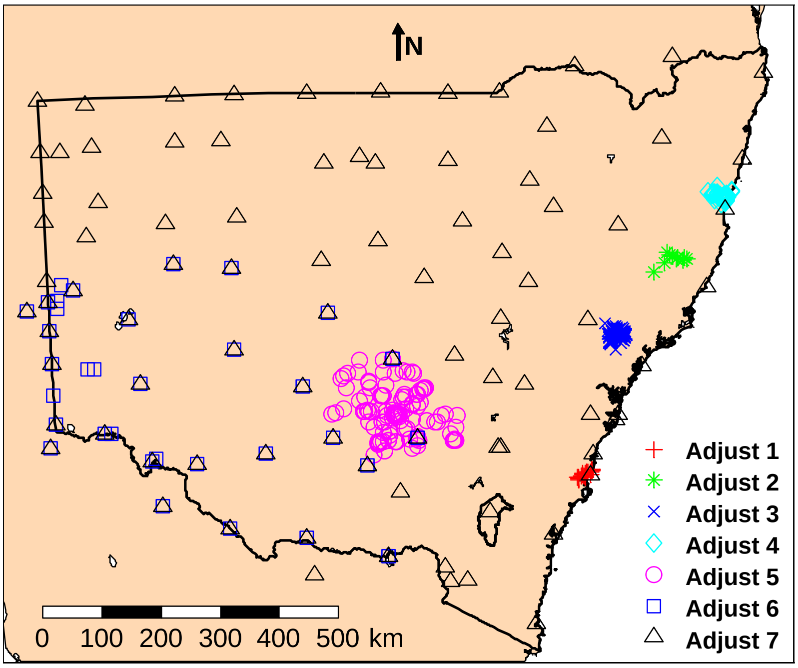

Figure 6: Location and extent of the GNSS-based adjustment datasets investigated.

In general, the utilisation of AUSGeoid2020 improved the variance factor (Table 2) and resulted in a comparable number of flagged residuals (Table 3), indicating a better adjustment result in comparison to using AUSGeoid09. The largest improvement was gained in adjustment 5, with the variance factor improving by a factor of 2.3, while the number of flagged residuals was reduced from 1 to 0. This adjustment covers a moderately sized area and exhibits a moderate variation in height, illustrating the positive effect AUSGeoid2020 can have on GNSS-based height transfer in NSW.

In one case, adjustment 2 (a small adjustment exhibiting a large variation in height), the variance factor increased slightly, bringing it a little closer to unity, while the number of flagged residuals increased from 0 to 2. However, this does not necessarily mean that AUSGeoid2020 performs worse than AUSGeoid09 in this case, but simply that previously hidden outliers are now detectable.

In this context, it should be noted that generally a variance factor of unity is desired to ensure that the uncertainties correctly represent the quality of the observations. However, in practice, DFSI Spatial Services does generally not modify uncertainties if the resulting variance factor is smaller than unity (i.e. the uncertainties could be tightened because the observation quality is actually better than that stated by the a-priori values). Consequently, for the purpose of this comparison, a lower variance factor is interpreted as a better result.

Table 2: Variance factors obtained for the adjustments investigated.

Adjustment	AUSGeoid09	AUSGeoid2020	Improvement Factor
1: South Coast	1.19	1.16	1.0
2: Oxley Hwy	0.54	0.71	0.8
3: Singleton	1.05	0.59	1.8
4: Bellingen	1.12	0.93	1.2
5: Bland	1.00	0.43	2.3
6: SW NSW	0.24	0.22	1.1
7: NSW	0.63	0.60	1.1

Table 3: Number of flagged residuals obtained for the adjustments investigated.

Adjustment	AUSGeoid09	AUSGeoid2020	Change
1: South Coast	2	2	0
2: Oxley Hwy	0	2	+2
3: Singleton	0	0	0
4: Bellingen	1	1	0
5: Bland	1	0	-1
6: SW NSW	0	0	0
7: NSW	1	2	+1

Adjustments 3 and 4 cover equally small areas and contain rather short baseline lengths. However, the improvement gained by using AUSGeoid2020 is much more pronounced for adjustment 3, which exhibits a moderate variation in height (variance factor improving by a factor of 1.8). For adjustment 4, which incorporates a large variation in height, the variance factor improves by a factor of 1.2, suggesting that most improvement is gained in areas exhibiting moderate height variations. Intuitively, this makes sense as input data density for AUSGeoid modelling is routinely lower at higher elevations.

The overall fit of the large adjustments (6 and 7) also improved but only slightly. 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 AUSGeoid2020 to some degree.

While 76% of the marks included in adjustment 6 are tightly constrained to their known AHD 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 AHD heights included in the adjustment and the improvement gained by utilising AUSGeoid2020.

In summary, based on these seven adjustments, further evidence is given that AUSGeoid2020 considerably improves access to AHD compared to AUSGeoid09 across NSW.

3.3 Test 3: Minimally Constrained 3D Network Adjustment (Height Observation Residuals)

In a further attempt to evaluate the performance of AUSGeoid2020 in practice, a third test was performed, based on the seven adjustments mentioned above. In this analysis, only one observed AHD 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 AHD heights, the adjusted heights (obtained by applying AUSGeoid09 to GDA94 ellipsoidal heights or AUSGeoid2020 to GDA2020 ellipsoidal heights) were compared against their known AHD values by analysing the residuals of the height observations after the adjustment. The values of these residuals indicate how well the quasigeoid model fits the AHD heights.

For each of the adjustment datasets described above, the height observation residuals for each quasigeoid model are summarised in Table 4. It is evident that the use of AUSGeoid2020 considerably improves the residuals in most cases with improvement factors generally around 1.4. By far the largest improvement is achieved for adjustment 5 with improvement factors of 1.8 for the RMS and 2.4 for the range of the residuals.

Table 4: Results of the height observation residual analysis.

Adjustment	Parameter	AUSGeoid09	AUSGeoid2020	Improvement Factor
1: South Coast (11 marks)	**RMS (m)**	0.024	0.022	1.1
	Range (m)	0.070	0.059	1.2
2: Oxley Hwy (5 marks)	**RMS (m)**	0.034	0.038	0.9
	Range (m)	0.050	0.076	0.7
3: Singleton (53 marks)	**RMS (m)**	0.029	0.021	1.4
	Range (m)	0.104	0.076	1.4
4: Bellingen (60 marks)	**RMS (m)**	0.053	0.044	1.2
	Range (m)	0.340	0.246	1.4
5: Bland (68 marks)	**RMS (m)**	0.049	0.027	1.8
	Range (m)	0.281	0.115	2.4
6: SW NSW (24 marks)	**RMS (m)**	0.087	0.061	1.4
	Range (m)	0.408	0.234	1.7
7: NSW (9 marks)	**RMS (m)**	0.144	0.071	2.0
	Range (m)	0.411	0.231	1.8

In most cases, the RMS values of the AUSGeoid2020 results show significant improvement and fall well within ±0.05 m, i.e. the accuracy estimate stated by Brown et al. (2011) and verified by Janssen and Watson (2010, 2011) for AUSGeoid09, although the range of residuals remains rather large in some cases. 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. On the positive side, the range of residuals is significantly reduced in these two cases (by factors of 1.7 and 1.8 respectively).

Only adjustment 2 shows no improvement over AUSGeoid09, with both the RMS and range of residuals increasing slightly. Considering that the sample size is very small and this adjustment exhibits a large variation in height, this result needs to be taken with caution as it is not representative of the general trend seen in the other adjustments. It should also be remembered that errors in the AHD and GNSS heights at the analysed points contribute cumulatively to the overall error in the residual comparison of these adjustments.

In summary, all three tests have shown that AUSGeoid2020 substantially improves access to AHD for GNSS-based height transfer in NSW. Furthermore, our results agree with absolute testing performed nationally. Brown et al. (in prep.) report standard deviations (1 sigma) of 0.038 m for about 7,600 GPS-levelling test points across Australia using the cross validation method and 0.027 m for about 8,400 independent GPS-levelling points across NSW, Victoria and Western Australia.

3.4 Rigorous Propagation of AUSGeoid2020 Uncertainty

As mentioned in section 2.2, AUSGeoid2020 provides a rigorous uncertainty value associated with the separation between the ellipsoid and AHD, varying as a function of location. AUSGeoid2020 users are therefore expected to benefit from more realistic uncertainty information, particularly in the coastal zone where offshore data is included in the model computation and mountainous regions or other areas exhibiting sparser input datasets. Unfortunately, at the time of writing, detailed information about the calculation of the AUSGeoid2020 uncertainty grid and the processing philosophy followed was not available to the authors. Consequently, this section can only provide a general examination of the AUSGeoid2020 uncertainty grid.

In order to briefly investigate the practical usefulness of the new uncertainty component of the AUSGeoid product, absolute uncertainty values were calculated for each survey mark in this study (approx. 610 in total). About 70% of the AHD heights used are independent of the data used to compute AUSGeoid2020. The resulting absolute (1 sigma) uncertainty values were determined via bi-cubic interpolation and ranged from about 0.07 m to 0.11 m, with a mean of 0.086 m. Figure 7 illustrates the distribution of AUSGeoid2020 uncertainty across the State, as obtained from the official AUSGeoid product. The location of levelled benchmarks along major roads, observed via GNSS by DFSI Spatial Services in preparation for the AUSGeoid2020 product, is clearly visible (cf. Figure 3).

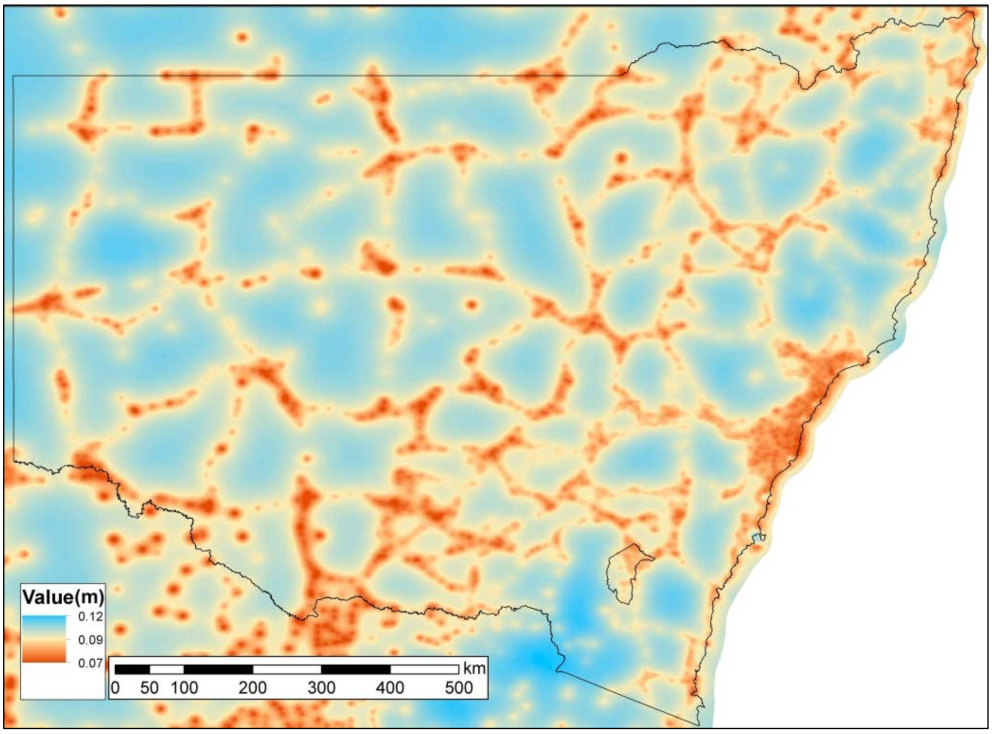

Figure 7: Distribution of absolute AUSGeoid2020 uncertainty across NSW.

Judging from the results presented in this paper, and those reported by Brown et al. (in prep.), it is apparent that these uncertainty values are overly conservative. Furthermore, the smallest rigorously propagated uncertainty value (0.07 m) is larger than the (constant) ±0.05 m accuracy estimate stated (and verified) for the previous product (AUSGeoid09), although the new product is based on much improved input datasets and modelling. Consequently, the AUSGeoid2020 uncertainty grid currently has only limited practical value. It should be noted that the relative uncertainties of the AUSGeoid2020 uncertainty grid (between marks) were not investigated as part of this study.

It is important to emphasise that the comparison of uncertainty values presented here can only provide a general assessment of the rigorously calculated AUSGeoid2020 uncertainties. Once more information about the generation of the AUSGeoid2020 uncertainty grid becomes available, a more thorough investigation will be possible.

4 CONCLUDING REMARKS

In September 2017, Geoscience Australia finalised the release version of AUSGeoid2020 (version 08/09/2017), which is to be used in conjunction with Australia's new national datum, GDA2020 (gazetted in October 2017), in order to connect GNSS-derived ellipsoidal heights to the Australian Height Datum. As NSW is preparing to enable GDA2020, this paper has shown that the AUSGeoid2020 product provides a considerably improved fit to AHD across NSW when compared to its predecessor.

Analysis based on 138 CORSnet-NSW sites showed that AUSGeoid2020 substantially enhances the quality of GNSS-based determination of AHD heights in NSW. The RMS of residuals improved by a factor of 2.3, while the range of the height residuals improved by a factor of 1.5 (2.7 and 2.2 respectively, if GURL CORS is excluded).

An investigation of several GNSS-based adjustments, incorporating various ranges in elevation and adjustment area sizes, revealed that the utilisation of AUSGeoid2020 generally improved the overall adjustment fit. This was evidenced by improved variance factors and comparable 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 AUSGeoid2020 improved the residuals, generally by a factor of about 1.4, reaching maximum values of 2.0 for the RMS and 2.4 for the range of the residuals.

In most cases the AUSGeoid2020 results fall well within ±0.05 m of the known AHD heights on public record, considering the existence of errors in both AHD and GNSS heights at the analysed points. However, the rigorous, location-based uncertainty values provided with the AUSGeoid2020 product appear to be overly conservative (ranging from 0.07 m to 0.11 m, with a mean of 0.086 m) and are therefore of limited practical use, apart from blunder detection. Once more information about the generation of the AUSGeoid2020 uncertainty grid becomes available, a more thorough investigation will be necessary.

The improvement achieved with AUSGeoid2020 can be explained mainly by the larger, denser and higher-quality input dataset and improved modelling. Users who derive their initial ellipsoidal heights using AHD and a quasigeoid model can expect that AUSGeoid2020 will serve them very well and the elevation products will represent local AHD much better than in the past. However, it must be remembered that AUSGeoid2020 can *only* be used in conjunction with GDA2020 ellipsoidal heights, while AUSGeoid09 *must* be used to convert GDA94 ellipsoidal heights to AHD.

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