The Australian Height Datum Turns 50: Past, Present & Future

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ABSTRACT

The Australian Height Datum (AHD) celebrates its Golden Jubilee (50th birthday) this year. This stalwart of Australian surveying remains our nation's first and only legal vertical datum. Recently, the ever-increasing use of Global Navigation Satellite System (GNSS) observations and airborne gravity measurements has led to the development of the Australian Vertical Working Surface (AVWS) as an alternative for advanced users and early adopters requiring higher-quality physical heights. This paper celebrates the achievements of AHD and its longevity, outlines its shortcomings and describes the datum maintenance and modernisation efforts undertaken by DCS Spatial Services to not only preserve but improve access to AHD, while also providing a solid foundation for AVWS across the State. It also looks ahead to a new era of vertical datum determination based on GNSS observations and gravity measurements. Acknowledging that there can be only one legal vertical datum, it remains to be seen what the future holds for legal heights in NSW and Australia.

KEYWORDS: *Australian Height Datum (AHD), Australian Vertical Working Surface (AVWS), AUSGeoid2020, AUSPOS, datum modernisation.*

1 INTRODUCTION

The Australian Height Datum (AHD) celebrates its 50th birthday this year and remains Australia's first and only legal vertical datum (Roelse et al., 1975). A vertical datum defines a reference for elevation comparisons and is essential for a wide range of applications relying on the flow of fluids, such as floodplain management, waterway navigation management, roadway and drainage design, agricultural management, and surveying in general. Vertical datums will also be essential and of interest to a wider audience as we move to 3-dimensional digital twins of the real world in which we work and play. Today's modern surveyor regularly works with two types of heights: ellipsoidal heights referred to the Geocentric Datum of Australia (GDA2020 – see ICSM, 2020a) and physical heights referred to AHD. In NSW, both are available through the Survey Control Information Management System (SCIMS), the State's database containing about 250,000 survey marks on public record across NSW, including coordinates, heights, accuracy classifications and other metadata, provided in GDA94, GDA2020 and AHD (Janssen et al., 2019).

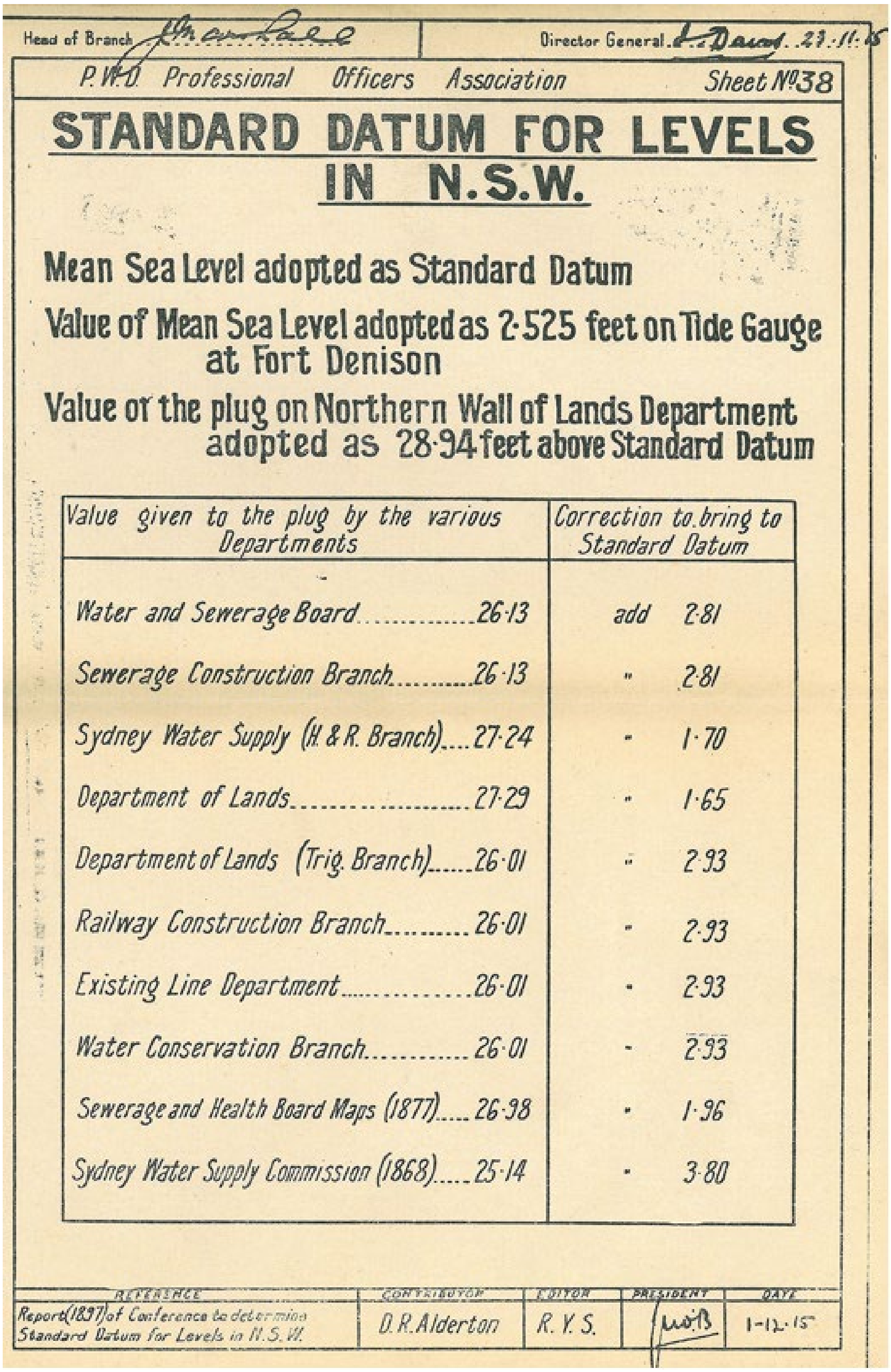
This paper focuses on physical heights in NSW and celebrates the achievements of AHD, outlines its shortcomings and looks ahead to a new era of vertical datum determination, based on Global Navigation Satellite System (GNSS) observations and gravity measurements, culminating in the Australian Vertical Working Surface (AVWS – see ICSM, 2020b). Recent developments in airborne gravity measurements are outlined and discussed in the Australian context to provide an indication of what may be on the horizon in the near future.

2 THE PAST

Celebrating its Golden Jubilee this year, AHD is Australia's first and only legal vertical datum. In NSW, it replaced the Standard Datum, which had been in use for some 80 years and was defined by the value of Mean Sea Level (MSL) at Fort Denison, accessible via a survey plug that was installed in 1882 (and still exists as PM50000) on the external northern wall of the former Department of Lands building in Bridge Street, Sydney (Figures 1 & 2). An interesting account of what transpired in the lead-up to the establishment of the Standard Datum and the introduction of AHD can be found in Blume (1975).

AHD (sometimes referred to as AHD71) was partly funded through a special 1961 Federal Government program to support the search for oil in Australia, via levelling within and connections between the various sedimentary basins (Granger, 1972; Roelse et al., 1975). In May 1971, it was adopted by the National Mapping Council as the datum to which all vertical control for mapping was to be referred. AHD was realised by setting MSL to zero at 30 tide gauges distributed around the coast of mainland Australia and adjusting 97,320 km of 'primary' 2-way spirit levelling across the country. The observations for MSL spanned 3 years (between 1 January 1966 and 31 December 1968) for all but one tide gauge, with earlier data over 4 years (between 1 January 1957 and 31 December 1960) being used at Karumba in the Gulf of Carpentaria. A subsequent adjustment also included about 80,000 km of 'supplementary' 1-way and 2-way spirit levelling, in addition to and dependent upon the 'primary' levelling (Roelse et al., 1975). For the first time, this provided a nationwide network of physical heights known as the Australian National Levelling Network (ANLN) – a stunning and quickly implemented achievement that required enormous effort. Prior to AHD, many disconnected local height datums were used in the states and territories.

Figure 1: Survey plug (now PM50000) on the external northern wall of the former Department of Lands building in Bridge Street, Sydney.



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STANDARD DATUM FOR LEVELS IN N.S.W.

Mean Sea Level adopted as Standard Datum

Value of Mean Sea Level adopted as 2·525 feet on Tide Gauge at Fort Denison

Value of the plug on Northern Wall of Lands Department adopted as 28·94 feet above Standard Datum

Value given to the plug by the various Departments	Correction to bring to Standard Datum
Water and Sewerage Board .... 26·13	add 2·81
Sewerage Construction Branch .... 26·13	" 2·81
Sydney Water Supply (H. & R. Branch) .... 27·24	" 1·70
Department of Lands .... 27·29	" 1·65
Department of Lands (Trig. Branch) ...... 26·01	" 2·93
Railway Construction Branch .... 26·01	" 2·93
Existing Line Department .... 26·01	" 2·93
Water Conservation Branch .... 26·01	" 2·93
Sewerage and Health Board Maps (1877) ..... 26·98	" 1·96
Sydney Water Supply Commission (1868) ..... 25·14	" 3·80

Reference	Contributor	Editor	President	Date
Report (1897) of Conference to determine Standard Datum for Levels in N.S.W.	D.R. Alderton	R.Y.S.	[signature]	1-12-15

Figure 2: Specifying corrections for various values used for the Department of Lands plug to refer its level to the Standard Datum for NSW in 1915.

The question is naturally asked why third-order levelling was used for the primary survey, and the short answer is that this practice was followed in order to produce the most useful outcome within the framework of funds and time available (e.g. Granger, 1972; Lambert and Leppert, 1976). From that point of view, third-order levelling certainly provided an adequate basis for the topographic mapping program, for general engineering purposes, and for the coordination of levelling surveys undertaken during gravity observations. According to Lambert and Leppert

(1976), anything more was reportedly considered as "striving against the forces of nature in order to achieve an impossible dream". The authors pointed out that an important time consideration was the fact that third-order levelling could be accomplished with readily available equipment and by available professional staff found in both the government and private sector. Considering the cost factor, as a rough rule of thumb, they determined that an increase in a survey operation by a factor n involves an increase in time and funds of n^2. On this basis, they estimated that the 160,000 km of the Australian survey, which cost approximately $7M if carried out say 25% to first order, 25% to second and 50% to third order, would have cost about $24M in those days (or $105M and $358M today, respectively). Furthermore, even if better leveling standards had been adopted, this accuracy would have been swamped in the warping of the level surface to hold MSL equal to zero at the tide gauges.

2.1 Practical Realisation of AHD in NSW

On the ground in NSW, AHD was realised by networks of approved survey marks. Some states organised their own ground marking and benefited as a result, others left this to contract surveyors (Lambert and Leppert, 1976). Typically, AHD marks were placed at intervals of one mile in regional areas and two miles in remote areas (e.g. Western Division), usually following major roads. In towns and cities, the network was far denser. The separation was also varied to enable marks to be placed at easily identifiable locations (e.g. crossroads, property entrances, hill crests and bridges) in an era predating handheld GNSS positioning or even full mapping of the State. In many instances, ANLN marks were located close to existing road mile posts for easier retrieval.

Marking typically consisted of five SSMs (PSM Type 1 – Ground Level) followed by a PM (PSM Type 6 employing a stainless-steel rod), with this pattern being repeated for the entire level run. Sometimes, pairs of PMs on opposite sides of the road were placed to provide extra redundancy. Different level runs met and joined at Junction Points (labelled JP in SCIMS). Marks specifically placed for AHD are easily identifiable by their low consecutive number series, while existing marks were included in the level run along the way. Later, marking became more non-standard with entire runs sometimes consisting of only PMs or only SSMs and inter-station distances opting between miles or kilometres. Marks also varied with soil condition (PSM Type 8 – Department of Water Resources Type C) and/or when existing surveys were to be adopted or recycled (e.g. ACT's Rural Bench Mark [RBM] and the Snowy Mountains Hydro-Electric Authority's Permanent Bench Mark [PBM]).

Later, in the 1970s, NSW installed a series of Fundamental Bench Marks (FBMs) and Geodetic Bench Marks (GBMs). These were high-stability marks designed to physically hold and preserve AHD. Based on a European design, they were modified for Australian conditions, akin to trigonometrical (trig) stations for height. FBMs and GBMs consisted of 2-3 marks installed in clusters at each location, with the primary mark being located under a standard cover box. Marks consisted of stainless-steel rods driven to refusal in auger holes that were backfilled with sand to decouple the mark from any local soil movement (Figure 3).

FBMs and GBMs were placed in locations next to ANLN runs, including parks, schools, police stations and an interesting collection of golf course club houses. AHD was then transferred to these marks by separate first-order levelling runs. An extensive network of FBMs and GBMs was envisaged when construction began in 1973 and marks were placed and surveyed (Naylor, 1976), predominately in eastern NSW with a higher density in north-eastern NSW. Unfortunately, the program was abruptly terminated due to budget constraints and an interdepartmental disagreement as to who would pay for the repairs to a loaned Public Works Department (PWD) vehicle that mounted the drilling auger (!).

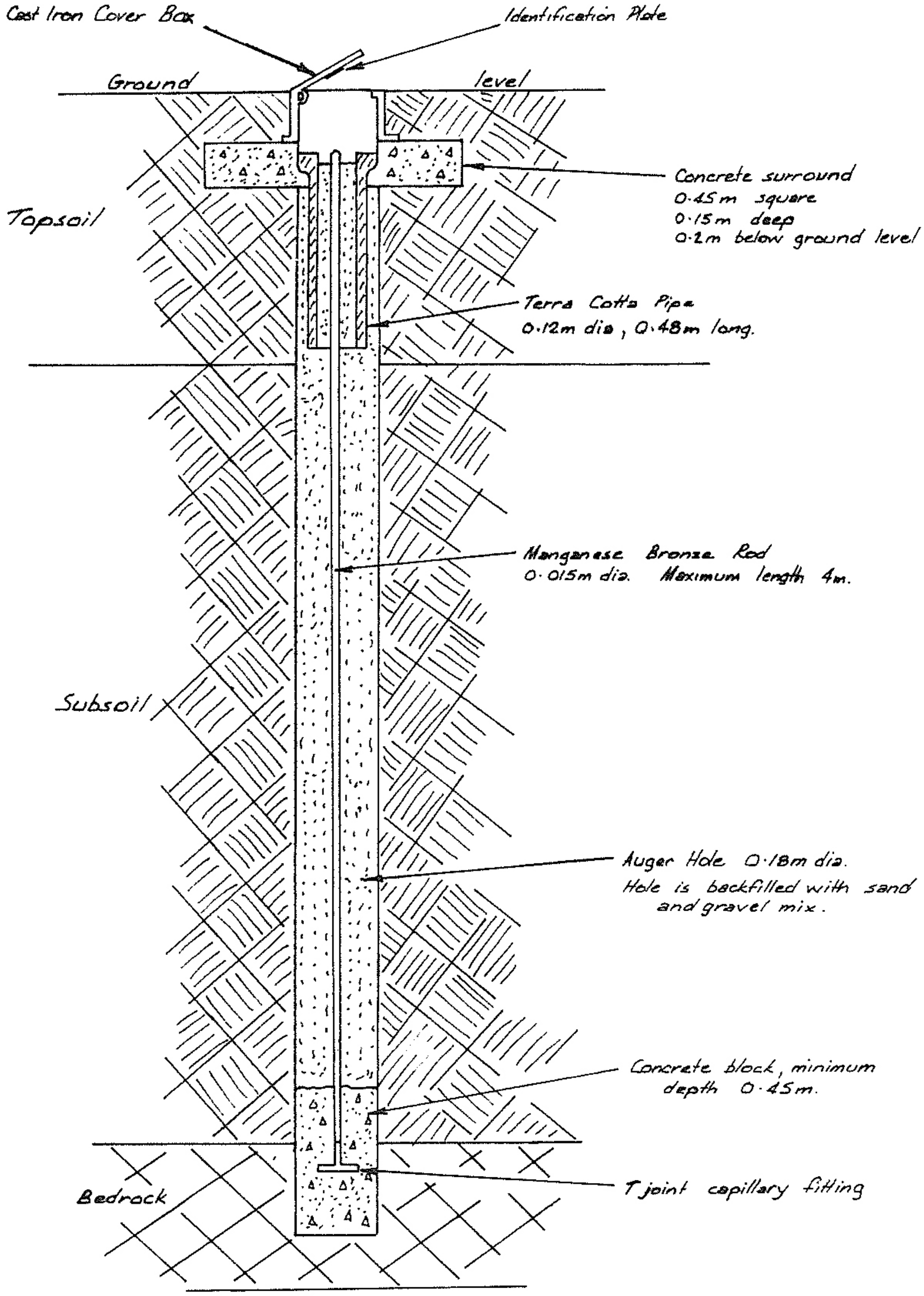

Figure 3: Fundamental Bench Mark (FBM) design (Naylor, 1976).

As stated earlier, AHD was designed as a third-order levelling network to produce the most efficient result within the framework of funds and time available (e.g. Granger, 1972; Lambert and Leppert, 1976). However, NSW set a far higher standard and supplemented, strengthened and improved AHD by observing the nation's most extensive and ambitious network of first-order levelling (Figure 4), which extended throughout the Eastern and Central Divisions of the

State. Whilst third-order levelling was performed by private sector contractors (whose participation was vital to the timely completion of AHD), first-order levelling was conducted by the Central Mapping Authority (CMA), now DCS Spatial Services, a business unit of the NSW Department of Customer Service (DCS). This first-order levelling network covered the length of the NSW seaboard, connecting tide gauges and extending as far west as Albury, Jerilderie, Wagga Wagga, Cootamundra, Cowra, Orange, Dubbo, Gilgandra, Coonabarabran, Narrabri, Bingara and Ashford (on the Queensland border). It also included existing first-order levelling, e.g. from the Snowy Mountains Hydro-Electric Authority (SMA).

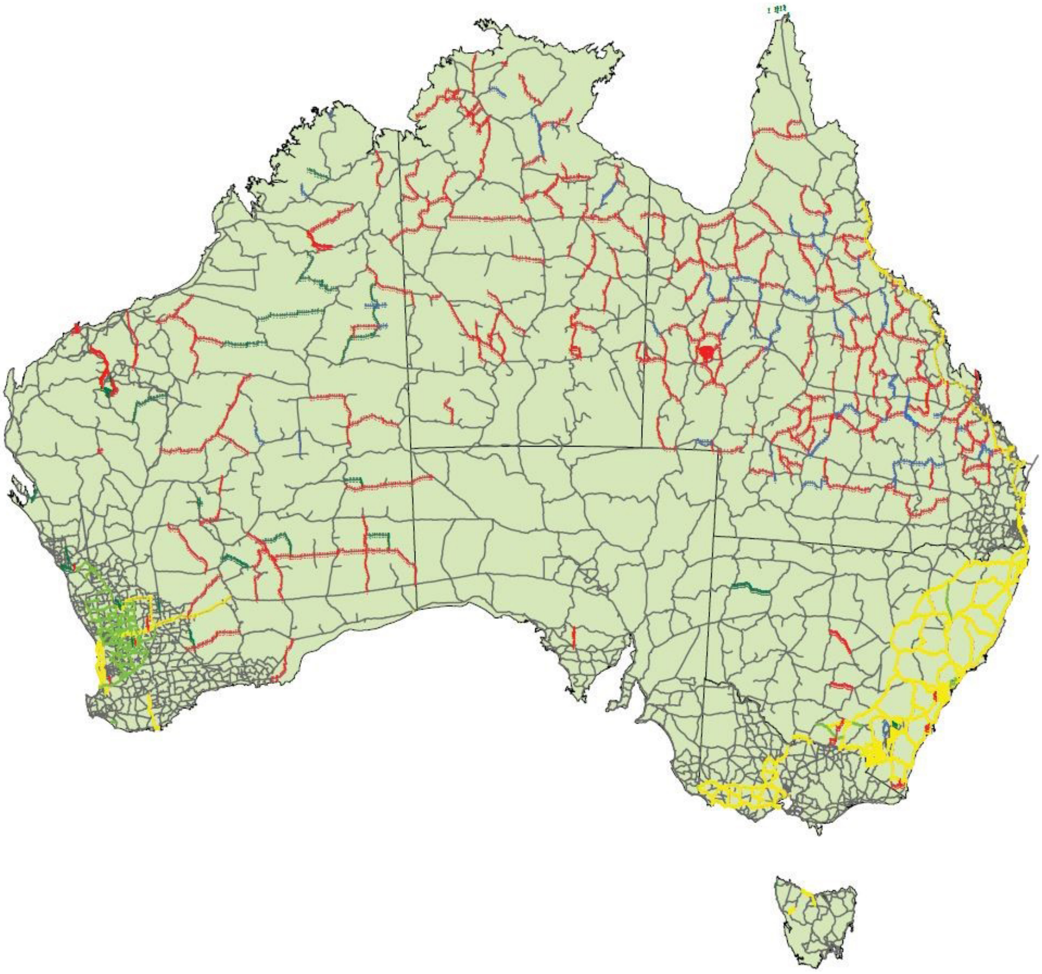

Figure 4: ANLN, showing first-order levelling sections (yellow), second-order sections (light green), third-order (fine grey), fourth-order (dark green), 1-way third-order (red) and 2-way levelling of undefined quality (blue) (Filmer et al., 2010).

Over the years, further level runs of various quality and including 1-way levelling were added to extend the network and/or investigate anomalies. An extensive capillary network of levelling to mountain-top trig stations was also established, typically 1-way only, connecting to the nearest ANLN mark (labelled T to T levelling, with T junction labels in SCIMS). To this day, discussions continue about the existence and nature of any systematic errors that may lay dormant in this then fit-for-purpose survey methodology. For DCS Spatial Services, the era of optically (or digitally) observing extensive levelling networks ended well before the start of the 21st century, and in-house geodetic levelling subject matter experts have since retired. Today, AHD is primarily derived from GNSS baseline networks (Class B), while digital levelling is only conducted for special projects, ad-hoc surveys or in some urban instances.

2.2 Adjustment of the ANLN

Prior to the adjustment, observed levelling data was corrected for the effect of non-parallelism of equipotential surfaces by applying the orthometric correction based on normal gravity (e.g. Granger, 1972; Roelse et al., 1975; Lambert and Leppert, 1976). Normal gravity is an approximation of true gravity generated from a mathematical model representing the Earth. Orthometric corrections can be as large as several centimetres in mountainous regions where the level surfaces exhibit steeper slopes than in lowlands, e.g. 309 mm correction for the 146 km level run from Adaminaby into the Snowy Mountains vs. 33 mm correction for the 155 km level run between Dubbo and Forbes. For the technically minded, AHD is thus considered a normal-orthometric height system because existing gravity observations were insufficient (e.g. Featherstone and Kuhn 2006; Filmer et al., 2010). Instead, a truncated normal-orthometric correction was applied to the spirit levelling observations, which only utilised normal gravity (i.e. referenced to an ellipsoid approximating the Earth, in this case GRS67). For a detailed treatment of height systems and vertical datums in the Australian context, the reader is referred to Featherstone and Kuhn (2006) and Filmer et al. (2010). A technical discussion of the difference between the geoid (the equipotential surface that best approximates MSL and is the basis for orthometric heights, measured along the curved plumbline based on Earth's gravity) and the quasigeoid (the non-equipotential surface that normal heights refer to, measured along the slightly curved ellipsoid normal based on normal gravity) can be found, e.g., in Vaniček et al. (2012) and Sjöberg (2013, 2018).

The interconnected network of level sections and junction points was constrained at 30 tide gauge sites, which were assigned an AHD height of zero. In NSW, this included the tide gauges at Coffs Harbour, Sydney's Camp Cove and Port Kembla, while Eden was excluded at the request of the Victorian and NSW Surveyors-General due to poor data (Roelse et al., 1975). The selection of Camp Cove (established in 1916) over Fort Denison, the second continuously recording tide gauge established in Australia in 1886 with records dating back even further and a long association with levelling datums, was attributed to the difficulty in making the cross-water connection (about 600 m between the island and Mrs Macquarie's Point) and the existence of a tidal gradient between the entrance to Sydney Harbour and Fort Denison (Blume, 1975; Lands, 1976). While it was noted that there were many interruptions to the national tide gauge network recordings due to theft, vandalism and faulty gauges, acceptable results were obtained from the 30 gauges eventually chosen (Granger, 1972).

The least squares adjustment propagated MSL heights, or AHD heights, across the levelling network. This adjustment occurred in two phases due to the computational limits of CSIRO's impressive CDC 3600 computer used at the time (Figure 5).

Figure 5: Control Data Corporation CDC 3600 computer used for the AHD adjustment.

In phase 1, five regional adjustments were made within boundaries approximating state limits (i.e. WA, SA and NT, QLD, NSW, VIC). In phase 2, these were combined to produce two solutions: (1) a minimally constrained solution with one station held fixed (Johnston Geodetic Station in central Australia) to assess the quality of the levelling, and (2) the final adjustment constrained to the 30 tide gauges, run on 5 May 1971 (Granger, 1972; Roelse et al., 1975; Lambert and Leppert, 1976). The minimally constrained solution indicated a standard deviation of about 0.3 m in the centre of Australia. Despite the best efforts of surveyors, gross, random and systematic errors crept into the level sections and were distributed across the network within the adjustment (ICSM, 2020a).

Lambert and Leppert (1976) noted the average loop closure was ± 6 mm/√km but the loop closures did not conform to a normal distribution. The average correction applied to the regional adjustments was ± 3 mm/√km. An assessment of the standard weight of the minimally constrained adjustment was ± 7 mm/√km for all states but NSW, which had an issue. Analysis indicated a degree of suspicion in respect to either the mathematical model or the processed data. Detailed analysis indicated that the data for the south-eastern corner of NSW was statistically inferior despite the existence of mostly first-order levelling. They reported that this would seem to indicate that, after a number of years, first-order surveys tend to deteriorate to much the same order of accuracy as third-order levelling.

It should be noted that Lord Howe Island and Norfolk Island are not covered by AHD and continue to use local historical height datums, the origins of which require more detailed investigation, documentation and public communication. As an aside, the Tasmanian AHD (often referred to as AHD-TAS83 or AHD83) was realised separately by setting MSL observations for only one entire year (1972) to zero at the tide gauges in Hobart and Burnie. It was propagated using mostly third-order levelling over 72 sections between 57 junction points and adjusted on 17 October 1983 (ICSM, 2020a).

2.3 Shortcomings of AHD

Over time, significant and well-documented shortcomings in the AHD realisation became apparent. In short, due to dynamic ocean effects (e.g. winds, currents, atmospheric pressure, temperature and salinity), tide gauge observations only spanning a period of 3 years and the omission of observed gravity, MSL was not coincident with the geoid at the tide gauge locations. The primary bias with respect to the geoid is due the AHD realisation ignoring the effect of the ocean's time-mean dynamic topography, resulting in AHD being about 0.5 m above the geoid in north-east Australia and about 0.5 m below the geoid in south-west Australia (Featherstone and Filmer, 2012). Together with uncorrected gross, random and systematic levelling errors, this introduced considerable distortions of up to about 1.5 m into AHD across Australia (e.g. Morgan, 1992; Featherstone and Filmer, 2012; Watkins et al., 2017). The interested reader is referred to the readily available literature for many more investigations into the shortcomings of AHD.

For example, observational blunders included those caused by observing in imperial units, where a whole foot was easily 'dropped' and/or 'picked up'. Random errors included those caused by metrification in Australia, having to use metres in calculations although the data was observed in feet. However, there were also downright fraudulent level runs, including the fable of the private contractor who supposedly adjusted out a misclose of more than 7 feet while enjoying a cold beer at a pub in Tibooburra. Lambert and Leppert (1976) also politely noted at the time that an unexpected effect appears to have been the independent approach of a few surveyors who did not fully conform to the prescribed specifications.

Despite all this, AHD has, overall, continued to be a practical height datum that is fit for purpose, providing a sufficient robustness for many surveying and engineering applications and even ‘mums and dads’, particularly over smaller areas (less than 10 km). For most surveyors, AHD has been ubiquitous for the entire duration of their professional careers, being the vertical datum of choice (when available) because it was the only one.

3 THE PRESENT

Over the last half century, surveyors have continued to extend and propagate AHD, primarily in urban regions, along transport corridors and within large infrastructure projects. However, large sections of the State, particularly rural and remote NSW, and even some suburbs of Sydney, do not have and have never had AHD established. When it does exist in these areas, it has been derived from GNSS.

A further issue affecting the availability of AHD is mark destruction. Despite the best efforts in the Preservation of Survey Infrastructure (POSI – see DCS Spatial Services, 2020a), entire sections of original ANLN spirit-levelled AHD have been destroyed. Ad-hoc audits indicate mark destruction is far higher in eastern NSW, with some level runs completely lost in city regions or along highways. In rural and remote areas, marks often still exist but can be difficult to find due the removal of all physical connections listed on locality sketch plans (e.g. road mile posts, telegraph lines and relocated fences or gates) and road realignments, which alter chainages or deviate far from the original road corridors. Pleasingly, with enough effort and skilled crews, many ANLN marks previously identified as ‘destroyed’ or ‘not found’ in SCIMS are being successfully recovered in good condition (and maintained and upgraded using Geoscience Australia’s free online GPS processing service, AUSPOS – see Janssen and McElroy, 2020; GA, 2021). On some level runs in the Central West, DCS Spatial Services field crews report a recovery rate of 20% or better for such lost marks. Finding marks that had reference blazes cut on trees is even more successful. As such, DCS Spatial Services now searches for all ANLN marks regardless of their historical status in SCIMS.

Another challenge affecting AHD is mark movement. How well has the mark been able to hold its initial AHD height over half a century? Fortunately, Australia enjoys rather stable tectonics, where vertical movements are generally infrequent and not substantial. However, there are exceptions, most notably in (usually very localised) subsidence areas caused by mining or major construction activities. Whilst we know that AHD has been lost in regions of reactive black soil and that any new value would soon be invalid following the next wet or drought season, what about other less obvious regions? For example, a recent investigation into a height anomaly of about 0.14 m at the NSW-Victoria border revealed that issues arise with constraining ANLN junction points when new levelling observations are taken between them. Allowing for apparent mark instability at one junction point and using the new levelling data resulted in the discrepancy to be reduced by more than 50% (Watkins et al., 2017). As previously noted, such mark movement supports the notion that, after several years, first-order levelling surveys tend to deteriorate to much the same order of accuracy as third-order levelling, which becomes apparent when runs are re-levelled (Lambert and Leppert, 1976).

3.1 Saving AHD

Whilst the role of the Survey Operations group within DCS Spatial Services is to maintain the State's survey control network, in the last 10 years it has taken on a more active role in both POSI and its effort to 'save' AHD. To this end, several projects have been undertaken.

3.1.1 Tide Gauge Monitoring

Over the years, DCS Spatial Services has continued to monitor the stability of tide gauges via precise optical levelling, then digital levelling and recently precise EDM height traversing. Generally conducted every 2-5 years, these surveys monitor the stability of the tide gauge compared to a near array of stable marks. Port Kembla tide gauge has been regularly monitored for over 20 years, while Fort Denison tide gauge has been resurveyed 'across the gap' from Mrs Macquarie's Point (and then back to the Department of Lands plug in Bridge Street). More recently, Eden tide gauge has been similarly connected.

Five GNSS Continuously Operating Reference Stations (CORS) were either specifically built or adopted to augment long-term tide gauges located along the NSW coast in order to support sea-level monitoring: Fort Denison, Port Botany, Newcastle East, Port Kembla and Eden (Janssen et al., 2013).

3.1.2 ANLN Level Run Sampling with AUSPOS

In a first dedicated effort, AHD marks were sampled across the entire State, as quickly as possible, for improvement of the national AUSGeoid model (e.g. Brown et al., 2018; Featherstone et al., 2019) to provide a better connection between GNSS-derived ellipsoidal heights and AHD heights. This was conducted in a series of 'Saving AHD' AUSPOS survey campaigns, commencing in 2015 and employing multiple crews from all DCS Spatial Services survey offices (see sections 3.1.5 & 3.3). In the first pass, each level run was investigated and sampled. A single field day was invested in each level run, while the longest runs out west (e.g. Broken Hill to Mildura) were allocated two days. Each crew typically had 5-6 GNSS receivers that were deployed over the length of the level run, predominately at PMs. Whilst harder to locate, PMs were believed to be more stable than SSMs. Each mark was maintained (i.e. cleared, painted and protected using generally 3 painted star pickets), photographed, observed by an overnight AUSPOS session, and SCIMS was updated with current metadata.

3.1.3 Observing FBMs and GBMs with AUSPOS

Similarly, a dedicated campaign is well underway to find, maintain and AUSPOS the FBMs and GBMs, recalling that these marks were specifically designed to maintain height, whether it be AHD, ellipsoidal or even AVWS height.

3.1.4 Recovering Lost Levelling

Noting the high quality and higher expense of good-quality spirit levelling, DCS Spatial Services has invested significant resources over the last few years in trying to recover lost levelling. A good example is the first-order levelling from SMA, which included some 1,000 marks over 1,000 km from Cooma to Tumut and on to the Victorian border, surveyed in the days of the Snowy Mountains Hydro-Electric Scheme (construction from 1949 to 1974). Unfortunately, none of these marks were ever entered into SCIMS, even though they were readjusted from the SMA datum to AHD as part of the initial AHD realisation. In fact, until recently, SCIMS did not include any ANLN levelling between Cooma and Jindabyne. To date, nearly 15% of these marks have been recovered, maintained and observed by DCS Spatial Services, which is a great result considering that SCIMS basically held no levelled heights at all in Kosciuszko National Park, and these marks are now 70 years old.

Over the past few years, DCS Spatial Services has conducted multiple survey campaigns to recover, maintain and AUSPOS as many surviving marks as possible. Through searching our archives, we have found fragments of records and used this data to search for what can be found in the field. Results have been very mixed, and only those marks that were found have been included in SCIMS for everyone’s benefit. Placed and surveyed as far back as the 1950s, these marks are again being used, now for the Snowy 2.0 project.

In a similar fashion, DCS Spatial Services continues to recover, on an ad-hoc basis, 1950s National Mapping Division levelling, observed to support ‘AeroDist’ surveys. As a bonus, this data is predominately located in remote regions of the State, with level runs reaching out to a graticule of 1° map corners, which are often located amongst a few scattered salt bushes in the middle of an outback paddock.

DCS Spatial Services was also planning a similar project to recover RBMs with accurate AHD heights, installed by the Australian Capital Territory (ACT) at the same time AHD was being observed. Whilst about 450 of the 1,200 RBMs installed are located in NSW, only a handful are included in SCIMS. A planned joint project with the ACT Office of the Surveyor-General to recover these RBMs was cancelled in 2020 due to travel restrictions during the COVID-19 pandemic. The project has now been pencilled in for the 2021/22 financial year.

3.1.5 High Fidelity (HiFi) Saving AHD

In the Central West, DCS Spatial Services is now nearing completion of its HiFi Saving AHD project. In this area, every rural ANLN mark has been searched for, then maintained and upgraded (including a 6+ hour AUSPOS session). To date, some 1,200 km of levelling has been audited and then surveyed, while another 400 km is planned in the next few months (Figure 6).

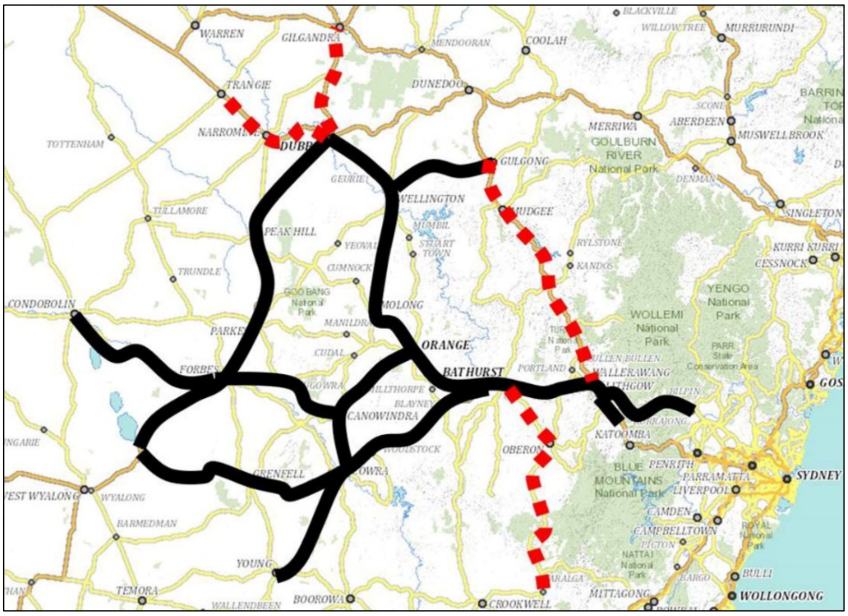

Figure 6: HiFi Saving AHD in the Central West, showing completed (solid black lines) and planned (broken red lines) level runs.

All work has been conducted via day trips, usually by a single crew, one week of every month or so. The number of ANLN marks that could be recovered is astonishing and exceeded expectations, with evidence that some have obviously been used by other surveyors. Whilst it is pleasing to find and recover such marks, it is disappointing that surveyors have not reported these finds (e.g. via the NSW Survey Marks Mobile App – see DCS Spatial Services, 2020b), so they can be shared for everyone's benefit in SCIMS. DCS Spatial Services is considering expanding this project to all its other survey offices including Lismore, Coffs Harbour, Newcastle, Sydney and Nowra.

As part of NSW's contribution to the development of AUSGeoid2020, DCS Spatial Services collected over 2,500 extended GNSS datasets (at least 6 hours but generally 12-24 hours duration for AUSPOS processing) on levelled benchmarks across NSW. These GNSS datasets informed the geometric ('sliver') component of AUSGeoid2020, thereby helping to provide a much better connection to AHD for GNSS-based height transfer, noting that its predecessor AUSGeoid09 was based on only 100 such control points in NSW (Janssen and Watson, 2018). Furthermore, for many of these old benchmarks, GNSS datasets improved their horizontal position, which was initially obtained by scaling off a map, often resulting in positioning errors of several hundred metres. This not only improved user access to these benchmarks, but also allowed preservation efforts to be undertaken (you can only protect a mark if you know where it is).

DCS Spatial Services continues these datum modernisation efforts through its ongoing 'Saving AHD' campaigns, which commenced in 2015 and have to date yielded almost 900 additional extended GNSS datasets on levelled benchmarks since the computation of AUSGeoid2020 on 1 February 2018 (Figure 7). While the Intergovernmental Committee on Surveying and Mapping (ICSM) currently does not plan to update AUSGeoid2020 into the future, these datasets will be very valuable for the continuing improvement of AVWS (see section 3.5).

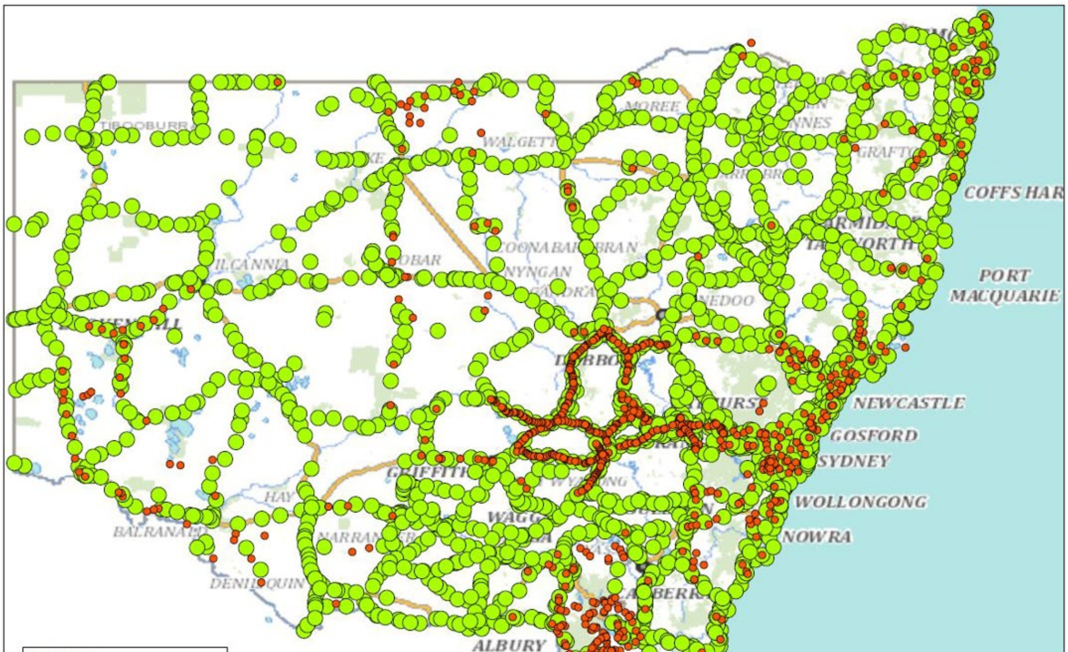

Figure 7: GNSS datasets of at least 6 hours duration on levelled marks observed by DCS Spatial Services, including those contributing to AUSGeoid2020.

3.1.6 Digitising Historical Levelling Records

In NSW, AHD is simply a set of numbers printed on some 3,600 cardboard sheets, which are now safely stored in State Archives after nearly 50 years of living in a filing cabinet in Bathurst. These levelling cards summarise each level run, including the height differences, orthometric corrections and distances between adjacent survey marks, and are abstracts of the original field notes, also stored in Bathurst archives and rarely accessed. At some stage, these AHD values were manually typed into SCIMS (naturally including unknown typos associated with all manual data entries), and an electronic master version does not exist. In fact, despite the efforts by academics and federal agencies over the years, the original AHD values cannot be reproduced. The value on the card is AHD, warts and all.

Noting the importance of these 3,590 historical levelling cards, detailing the measured and adjusted height differences between benchmarks and junction points, these cards are progressively being preserved and digitised. The first and now completed step was to scan all cards into TIF and PDF versions (Figure 8), safely archived in a digital environment. The intent was to convert these files to smart digital files, but unfortunately Optical Character Recognition (OCR) failed. Therefore, each card was manually converted to Excel files (one per level run), which was an enormous and time-consuming task but well worth the effort. Quality assurance of this manual data entry process is currently underway, using a dozen different manual and automated checks.

1/1

PROGRAM AMENDED 01/04/74
COMPUTED 19/06/74

NATIONAL LEVELLING ADJUSTMENT OF AUSTRALIA
PREPARED FOR THE NATIONAL MAPPING COUNCIL BY
THE DIVISION OF NATIONAL MAPPING

LINEAR ADJUSTMENT BETWEEN PREVIOUSLY ADJUSTED JUNCTION POINTS 359 AND 358

SECTION 358- 359
FIRST ORDER LEVELLING
PRIMARY SECTION

AUSTRALIAN HEIGHT DATUM 1971
NEW SOUTH WALES

BENCHMARKS FROM A	TO B	DISTANCE KMS	HEIGHT DIFFERENCES OBSERVED	ORTHOMETRIC METRES	ADJUSTED	CORR	LATITUDE OF B	LONGITUDE OF B	LOCATION OF B	ADJUSTED HT IN METRES OF B
	PM39						32 15	148 36	DUBBO 359	263.999
PM39	PM830	.2	.3487	.3487	.3487	-.0000	32 15	148 36		264.348
PM830	PM839	.3	2.4451	2.4451	2.4451	-.0000	32 15	148 36		266.793
PM839	PM2295	.5	8.0891	8.0891	8.0890	-.0001	32 15	148 36		274.882
PM2295	SSM969	1.6	18.5459	18.5456	18.5454	-.0002	32 16	148 38		293.427
SSM969	SSM970	1.6	8.7472	8.7472	8.7470	-.0002	32 16	148 39		302.174
SSM970	SSM971	1.6	11.4721	11.4721	11.4719	-.0002	32 16	148 40		313.646
SSM971	(I)PM2296	1.6	8.5792	8.5789	8.5787	-.0002	32 17	148 41		322.225
PM2296	SSM972	1.6	23.8622	23.8622	23.8620	-.0002	32 17	148 41		346.087
SSM972	SSM973	1.6	-11.5178	-11.5184	-11.5186	-.0002	32 18	148 42		334.568
SSM973	SSM974	1.6	27.3476	27.3476	27.3474	-.0002	32 18	148 43		361.916
SSM974	PM2297	1.6	-7.3768	-7.3774	-7.3776	-.0002	32 19	148 44		354.538
PM2297	SSM975	1.6	21.1665	21.1665	21.1663	-.0002	32 19	148 44		375.705
SSM975	SSM976	1.6	8.7724	8.7718	8.7716	-.0002	32 20	148 45	WONGARBON	384.476
SSM976	SSM977	1.6	2.9194	2.9188	2.9186	-.0002	32 21	148 46		387.395
SSM977	PM2298	1.6	5.7440	5.7440	5.7438	-.0002	32 21	148 47		393.139
PM2298	SSM978	1.6	-5.3879	-5.3885	-5.3887	-.0002	32 22	148 47		387.750
SSM978	SSM979	1.6	-33.4997	-33.4997	-33.4999	-.0002	32 22	148 48		354.250
SSM979	SSM980	1.6	-15.5201	-15.5207	-15.5209	-.0002	32 23	148 49		338.729
SSM980	PM2299	1.6	-17.1499	-17.1505	-17.1507	-.0002	32 24	148 49	GEURIE	321.579
PM2299	SSM981	1.6	-9.6530	-9.6530	-9.6532	-.0002	32 24	148 50		311.925
SSM981	SSM982	1.6	21.6573	21.6570	21.6568	-.0002	32 25	148 50		333.582
SSM982	SSM983	1.6	1.6490	1.6490	1.6488	-.0002	32 25	148 51		335.231
SSM983	PM2300	1.6	22.2324	22.2318	22.2316	-.0002	32 26	148 52		357.463
PM2300	SSM984	1.6	23.4504	23.4504	23.4502	-.0002	32 26	148 53		380.913
SSM984	SSM985	1.6	-16.3946	-16.3952	-16.3954	-.0002	32 27	148 53		364.518
SSM985	SSM986	1.6	-35.3144	-35.3150	-35.3152	-.0002	32 28	148 54		329.202
SSM986	PM2301	1.4	-21.7831	-21.7831	-21.7832	-.0001	32 28	148 54		307.419
PM2301	SSM987	1.8	9.3369	9.3366	9.3364	-.0002	32 29	148 55		316.756
SSM987	SSM988	1.8	-8.2793	-8.2796	-8.2798	-.0002	32 30	148 55		308.476
SSM988	SSM989	1.4	-14.9053	-14.9056	-14.9057	-.0001	32 31	148 56		293.570
SSM989	PM2302	1.6	4.1520	4.1520	4.1518	-.0002	32 31	148 56		297.722
PM2302	SSM990	1.8	3.8356	3.8353	3.8351	-.0002	32 32	148 57	WELLINGTON	301.557
SUMMATION		47.6	37.5711	37.5630	37.5580	-.0050				

Figure 8: Scanned levelling card for ‘primary’ first-order level run between Dubbo (JP 359) and Wellington (JP 358).

Once complete, the values in SCIMS can themselves be checked to remove any typos that have lain dormant for decades. Using all original ANLN levelling, supplemented with all digital levelling archived from internal and external organisations, combined with 3D GNSS observations and a much improved AUSGeoid2020 (e.g. Brown et al., 2018; Janssen and Watson, 2018; Featherstone et al., 2019), we can then, in the future, detect and correct AHD blunders and issues. All data will be combined into the 'all-in-one' state adjustment and complement each other. The enormity of this task and its outcomes should not be underestimated. While Victoria has already completed a state-wide levelling adjustment, other jurisdictions are now also commencing similar projects.

It should be emphasised that there are no plans to readjust (or re-realise) AHD. Under the original rules, jurisdictions cannot modify the height of junction points without federal approval (e.g. Lands, 1974, 1976; NMC, 1979). The height of intermediate marks can be updated if a blunder or mark movement is detected and proven, which is part of the day-to-day maintenance.

3.1.7 Building the NSW Levelling Adjustment

Together with the results of data-mining existing levelling files in the DCS Spatial Services archive, the digitised historical levelling data is being used to generate a single, state-wide levelling adjustment for NSW. Whilst this work is still ongoing, it is clear that it will provide huge benefits to surveying and spatial professionals in regard to accessing height information across the State. As of March 2021, the NSW levelling adjustment comprises about 132,000 measurements and 98,000 stations (Figure 9).

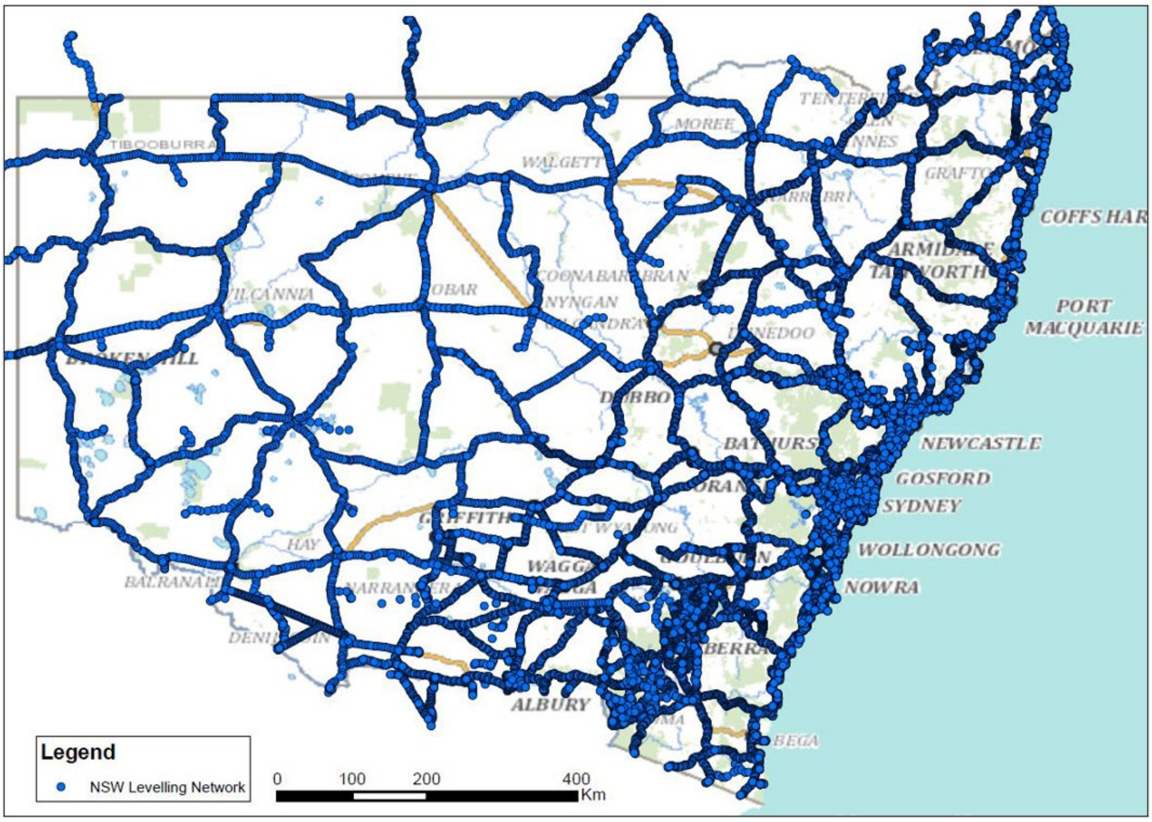

Figure 9: Location of benchmarks included in the NSW levelling adjustment.

3.2 GNSS Technology

The next challenge for AHD is technology itself, i.e. is AHD still fit for purpose? The era of GNSS technology ushered in the development of geoid or quasigeoid models to convert GNSS-derived ellipsoidal heights to physical heights. This conversion is often needed because positions obtained by GNSS (e.g. GPS, GLONASS, BeiDou, QZSS and Galileo) include heights referred to a reference ellipsoid. These heights are based purely on the geometry of the ellipsoid and therefore have no physical meaning, i.e. they cannot be used to predict the direction of fluid flow because they do not consider changes in gravitational potential. In practice, however, heights are generally required that correctly reflect the flow of fluids, e.g. for drainage and pipeline design.

Following national datum modernisation efforts, these AUSGeoid models have improved over time. The first, AUSGeoid91, was released in 1991, soon followed by AUSGeoid93 and then AUSGeoid98. These predominantly gravimetric-only quasigeoids were incorrectly assumed to be sufficiently close approximations of AHD. Correcting this oversight and delivering a more user-driven product, AUSGeoid09 was the first combined gravimetric-geometric quasigeoid, providing a more direct connection to AHD and thereby allowing a more reliable determination of AHD heights from GNSS observations (Brown et al., 2011). The geometric component (or 'sliver') basically constitutes a grid of quasigeoid-AHD separation values, empirically derived from collocated GNSS ellipsoidal heights and levelled AHD heights (see Figure 7). In effect, the gravimetric quasigeoid model is warped and distorted to fit the AHD using GNSS-levelling data, accounting for the offset between the quasigeoid and AHD (about -0.3 m to +0.2 m across NSW).

The most recent model is AUSGeoid2020 (e.g. Brown et al., 2018; Janssen and Watson, 2018; Featherstone et al., 2019), to be used only in conjunction with GDA2020 ellipsoidal heights. Due to the biases and distortions inherent in AHD, AUSGeoid2020 is only capable of providing GNSS-derived AHD heights with an official accuracy of 6-13 cm across Australia (ICSM, 2020b), although it has been shown that AUSPOS-derived AHD heights in NSW can be much better than reported (Janssen and McElroy, 2020). In layman's terms, we have now reached a stage where whilst we can measure with unprecedented accuracy, what we are measuring from (ground zero, or our origin) is a magnitude less accurate. Our flat playing field is in fact a crumpled-out piece of paper that has been ironed flat, with some evidence of crinkles remaining.

In order to address the shortcomings of AHD in an era of ever-increasing usage and availability of GNSS observations and airborne gravity measurements, work commenced to investigate options for a potential new vertical datum (e.g. Featherstone, 2008; Filmer and Featherstone, 2012). This culminated in the development of the Australian Vertical Working Surface (AVWS) as an alternative for advanced users and early adopters requiring higher-quality physical heights than those AHD can provide (see section 3.5). AVWS allows users to realise the full potential of modern technology in order to make height determination and transfer more efficient than with the traditional techniques used in the 1970s and 1980s.

3.3 Recent Datum Modernisation Efforts in NSW

DCS Spatial Services is responsible for the maintenance of the State's survey control network. Datum modernisation and further improvement of survey infrastructure is required to accommodate the increasing accuracy and improved spatial and temporal resolution available from modern positioning technologies such as GNSS to an ever-broadening user base.

This has led to the establishment of CORSnet-NSW, Australia's largest state-owned and operated GNSS CORS network (e.g. Janssen et al., 2016; DCS Spatial Services, 2021). CORSnet-NSW is not only the backbone of GDA2020 across the State but also provides fundamental positioning infrastructure that is authoritative, accurate, reliable and easy-to-use for a wide range of applications. Furthermore, with all sites contributing to AUSPOS, it comprises a fundamental, high-density and long-term component of AUSPOS infrastructure within the State (Janssen and McElroy, 2020).

Consequently, the use of AUSPOS campaigns has developed into a capable and reliable alternative to conducting traditional static GNSS baseline surveys, simplifying field work logistics and reducing processing times. This has substantially accelerated the process of including additional survey marks into the GDA2020 state adjustment in order to improve user access to GDA2020 coordinates and uncertainties on public record through SCIMS (e.g. Gowans et al., 2015; Janssen and McElroy, 2020). As discussed in section 3.1, AUSPOS has become the primary survey technique used by DCS Spatial Services to 'save' AHD.

In support of these datum modernisation efforts, DCS Spatial Services is currently building an updated 'passive' survey control network (in the Eastern and Central Divisions) with a minimum of one fundamental survey mark observed by 6+ hour AUSPOS every 10 km. Its vision is to ensure that any future user is no further than 5 km (and often much less) from such a fundamental mark providing direct connection to datum. Similarly, levelled AHD marks are observed by 6+ hour AUSPOS every 10 km, often at a far greater density up to every mile (see section 3.1.5). This will allow users to achieve DCS Spatial Services' vision of a Positional Uncertainty (PU) of 20 mm in the horizontal and 50 mm in the vertical (ellipsoidal height) component anywhere in the State and easily apply transformation tools to move between current, future and various historical datums and local working surfaces (e.g. Standard Datum or Railway Datum).

3.4 Gravity Matters!

3.4.1 Australian Vertical Datum Modernisation Efforts

Several countries have used, or are about to use, (nationwide) airborne gravity measurements to develop high-quality gravimetric quasigeoid models in order to modernise their national vertical datums. For example, this includes:

- Canadian Geodetic Vertical Datum 2013 (CGVD2013 – Véronneau and Huang, 2016).
- New Zealand Vertical Datum 2016 (NZVD2016 – McCubbine et al., 2018).
- North American-Pacific Geopotential Datum 2022 (NAPGD2022 – NGS, 2007, 2017).

Gowans (2019) summarised the reasons for moving to vertical datums based on gravimetric quasigeoids as follows: The maintenance of national levelling networks is no longer viable because they are too costly, too time consuming, and the results are too short-lived in countries subject to significant surface displacement. Gravimetric quasigeoid models are far more cost effective to maintain and less susceptible to surface movements. Their complete spatial coverage provides significant efficiency gains for industry when accessing the datum because propagating the datum from the nearest levelled benchmark(s) is no longer required. Basically, the datum is available everywhere, so there are no more 'black holes' as in AHD. However, digital levelling is still considered the most accurate technique for height transfer across short distances and will retain relevance in surveying for height-critical, local-scale projects. Since a model can only ever be as good as the data that informs it, the systematic acquisition of nationwide airborne gravity has proven to significantly benefit these quasigeoid models.

In Australia, efforts are underway to collect airborne gravity data over targeted regions in, for example, South Australia and Victoria (Figure 10) to improve the Australian gravimetric quasigeoid model. The objective is to collect consistent and evenly distributed gravity measurements with minimal disturbance to land users and the environment, using specialised gravity-sensing instrumentation to measure extremely small variations in the Earth's natural gravitational pull. In Victoria, such airborne gravity surveys have already been successfully completed across coastal Gippsland (2011), south-west Victoria (2019) and near Bendigo (2004 and 2019) (VIC Government, 2020). DCS Spatial Services is currently preparing a business case for the modernisation of the Foundation Spatial Data Framework (FSDF), which includes an option to secure funding for airborne gravity surveys across the entire State.

New airborne gravity data will significantly improve the gravity (and gravimetric quasigeoid) model and thus the accuracy of GNSS-derived physical heights. The gravity data will also be used by geoscientists to further their understanding of Australia's geological 'architecture' and how it has evolved over time, as well as advance the geoscience that assists management of earth resources, infrastructure and natural hazards.

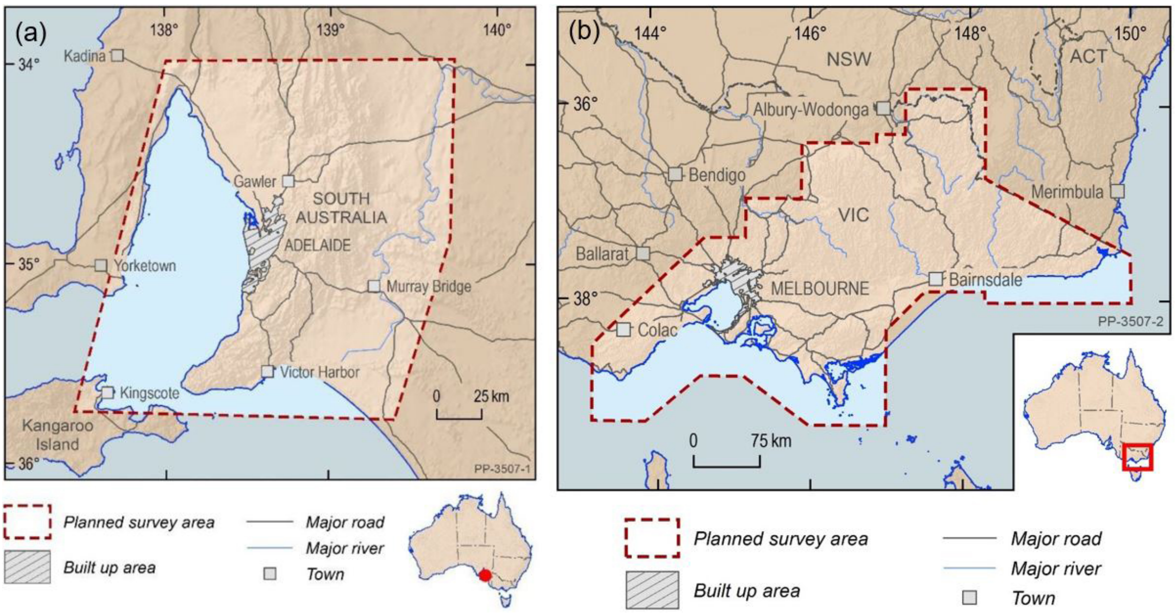

Figure 10: Targeted airborne gravity survey areas in (a) South Australia and (b) Victoria (SA Government, 2020; VIC Government, 2020).

3.4.2 Airborne Gravimetry: Theory and Data Acquisition

Gravity is a rather complex topic that most surveyors will not have embraced since their university days. This section provides some technical background information for those who wish to learn a little more about airborne gravimetry and reacquaint themselves with the fascinating world of physical geodesy.

Gravity is the force acting on a body on or near the Earth's surface, which is a combination of the gravitational force (the force of attraction between two masses) and the centrifugal force (the apparent force caused by the uniform circular motion of a body about a fixed point) of the Earth's rotation. In the absence of friction and other forces, it is the rate at which objects will accelerate towards each other. At the surface of the Earth, gravity (acceleration) is approximately 9.8 m/s^2, with absolute gravitational acceleration varying across Australia between 9.780 m/s^2 in northern Australia and 9.805 m/s^2 in southernmost Tasmania (Kennett et al., 2018).

In principle, gravity is measured using an accelerometer (although, technically, the accelerometer only senses action forces and not gravitational forces), which houses a proof mass that is restricted to movement along a sensitive axis and a restraining device (e.g. a spring). The mass is supported by the restraining device and displaces with respect to an equilibrium position when subject to acceleration. Knowing the relationship between the displacement and the restoring force applied to the mass, the accelerometer provides a measure of the force required to counter the force due to accelerations acting on the mass. Gravity is generally measured in units of Gal (1 cm/s^2 or 0.01 m/s^2) or mGal (0.001 cm/s^2).

An absolute gravity meter (or gravimeter) measures gravity at a single location, which is currently restricted to ground-based acquisition. It determines the actual value of the gravitational acceleration, generally by measuring the speed of a falling mass in vacuum using a laser beam and optical interferometry. A relative gravimeter is much more common and measures the difference in gravity between two locations via ground-based, shipborne, airborne or satellite-based acquisition, generally using a spring supporting a proof mass. In order to be truly effective, surveys carried out with relative gravimeters must include acquisition at one or more sites where absolute gravity is known (e.g. at the airport and in the area of interest for airborne gravimetry). Today's airborne gravimetry systems can be separated into traditional airborne gravity systems and gradiometer systems.

Airborne gravity systems measure a combination of aircraft accelerations and the Earth's gravitational field. Consequently, most of the design and processing is aimed at maintaining the gravity sensing unit in a vertical orientation and accurately measuring the aircraft's corresponding vertical movement using differential GNSS velocities. Commercial gravimeters utilise gyro-stabilised platforms to maintain the vertical orientation. In simple terms, subtracting the GNSS-derived vertical accelerations of the aircraft from the total vertical gravity measured by the instrument will provide residual gravity. In practice, additional corrections are required, e.g. to account for platform misalignment (tilt), lever arm (spatial relationship between the GNSS antenna, airborne gravimeter and any other equipment used within the aircraft), horizontal accelerations, drift, Eötvös effect (change of the centrifugal force of the Earth's rotation due to being on a moving platform) and minor temperature and pressure variations (Wooldridge, 2010).

The reduction of airborne gravity data requires the use of low-pass filters because the long- to medium-wavelength signal is of interest, while most noise has a short wavelength (i.e. high frequency). The effective resolution of the system is generally equated to the half-wavelength of the filter multiplied by the speed of the aircraft (consequently, half-wavelength filter lengths are often quoted rather than the full-wavelength filter). By shortening the filter length, the system resolution is improved at the expense of accuracy (Wooldridge, 2010). Factors influencing resolution and accuracy include aircraft speed, altitude and the spacing of flight lines. While precision from airborne data can be assessed well (using repeat tracks, adjacent tracks, crossovers or grid comparisons), accuracy is much harder to determine (using models, satellite data or ground data) because the true value is not really known, although good global models are available (Preaux, 2016).

Airborne gravity gradiometer systems measure, in principle, the gradient of the Earth's gravitational field independent of aircraft accelerations. The two current commercial airborne gravity gradiometer systems providing high-resolution gravity gradiometer data are the Airborne Gravity Gradiometer (AGG), known as the 'Falcon' system, and the Full Tensor Gradiometer (FTG). Both utilise spinning discs equipped with multiple accelerometers, which measure two or more components of the gravity gradient tensor depending on the number of discs present and their orientation. The gradients measured at different locations are transformed to vertical gravity. Gravity gradients are measured in units of Eötvös (Eö), where 1 Eö = $10^{-9}/s^2$ = 0.1 mGal/km, i.e. a variation of 1 mGal/km is 10 Eö (Fairhead et al., 2017).

Airborne gravity gradiometer systems are generally more accurate (higher resolution) and more robust than traditional airborne gravimetry, but also much more expensive. They must detect very small differential gravitation signals over a short baseline. This requires accounting for errors such as scale factor errors (accelerometers are not perfectly matched), alignment errors (sensitive axes of the accelerometers are not parallel), asymmetry of the configuration (measurement point is not the centre of mass of the accelerometer pair) and self-gradients (the gradient field is changed due to the rotation of the aircraft about the stabilised platform hosting the instrument), which is mostly achieved through calibration and filtering (Jekeli, 2003).

3.5 AVWS

The Australian Vertical Working Surface (AVWS) is a new reference surface for physical heights in Australia, released on 1 January 2020 to provide a height reference surface that works seamlessly onshore and offshore, is directly compatible with GNSS, continuously improved over time and more accurate than AHD because it does not suffer from the biases and distortions present in AHD. In practical terms, AVWS provides an alternative for users requiring higher-quality physical heights (current accuracy about 4-8 cm) than those AHD can provide (accuracy about 6-13 cm) (ICSM, 2020b).

GNSS users can access AVWS by applying the Australian Gravimetric Quasigeoid (AGQG) model to their GDA2020 ellipsoidal heights, just like AUSGeoid2020 is used to obtain AHD heights. In practice, this means simply picking model 'B' instead of the usual model 'A' in your GNSS processing software or the GNSS rover during real-time (RTK/NRTK) surveys. The initial version, AGQG_2017 (Featherstone et al., 2018), is the gravimetric component of AUSGeoid2020, providing the offset between the ellipsoid and the quasigeoid without being contaminated by the distortions inherent in AHD.

The current version of AGQG (AGQG_20201120) differs from AUSGeoid2020 by between -1.8 m and +0.7 m across Australia, resulting in AVWS (normal) heights differing from AHD (normal-orthometric) heights by the same amount when determined via GNSS and the respective models (J. McCubbine, pers. comm.). In NSW, users can expect differences of between -0.5 m and +0.1 m (Figure 11). Geoscience Australia is working with all jurisdictions to continuously improve AGQG as new gravity data (particularly airborne gravity) is included and modelling techniques are refined.

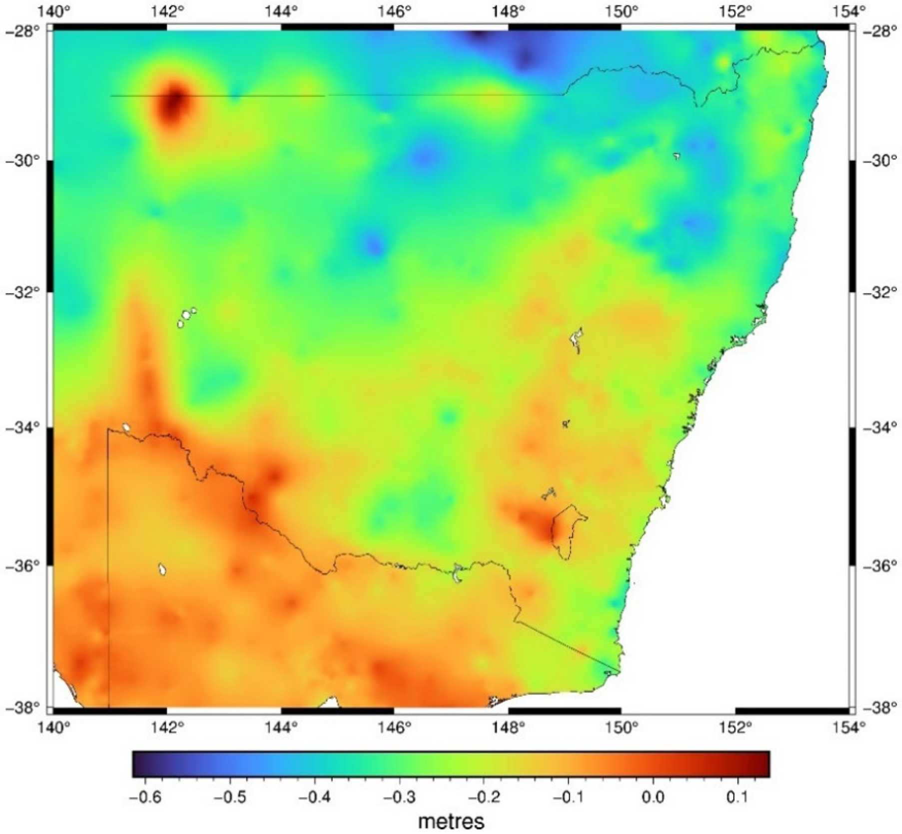

Figure 11: Differences in N values between AGQG_20201120 and AUSGeoid2020 across NSW, which is equivalent to the differences between AVWS heights and AHD heights.

Recently, a FrontierSI project investigated current and future user requirements for physical height determination and transfer in Australia (Brown et al. 2019a, 2019b; McCubbine et al., 2019). It was found that AHD is still deemed fit for purpose over short distances (less than about 10 km) for applications such as cadastral surveying, civil engineering, construction and mining. However, users working over larger areas wanted access to higher-quality heights to reap the full benefits of modern technology for environmental studies (e.g. flood or storm modelling), Light Detection and Ranging (LiDAR) surveys, geodesy or hydrography projects. The study concluded by recommending a two-frame approach for heights, with AHD remaining as Australia's legal datum and AVWS being provided as an alternative, analogous with the two-frame approach taken with GDA2020 (ICSM, 2020a) and ATRF2014 (ICSM, 2020c). In practice, the surveyor and client would choose which one to use for a particular job, considering relevant legislation that may apply.

From a user perspective, AVWS provides improved access to physical heights, higher accuracy, increased efficiency, a surface without the known gross, random and systematic errors of the levelling network, better alignment with GNSS, and national consistency including a seamless onshore-offshore transition. GNSS-derived ellipsoidal heights are converted to AVWS heights by applying the AGQG model (i.e. option 'B' from above), in the same way that they are converted to AHD heights using the AUSGeoid model (Figure 12). Given that AVWS heights are not (currently) provided for benchmarks on public record, these AVWS heights can then be used as reference heights or starting points for spirit levelling surveys. While normal corrections should theoretically be applied to levelled height differences, this can generally be neglected in practice at the cost of introducing a small amount (sub-mm) of error (ICSM, 2020b).

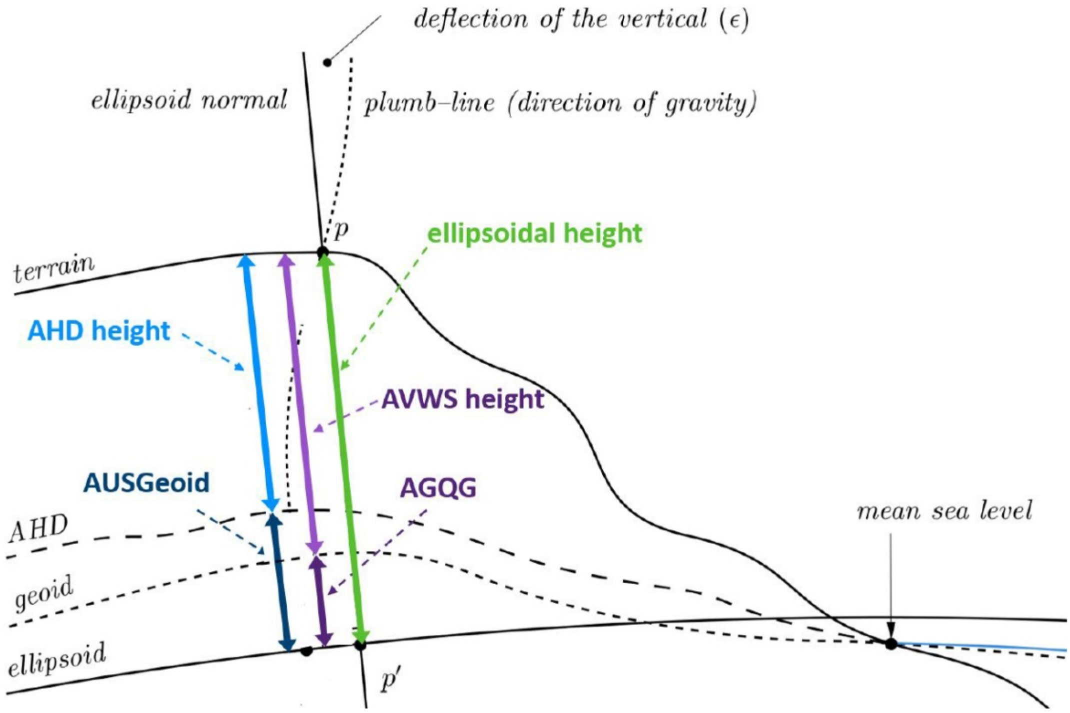

Figure 12: Converting ellipsoidal heights (green) to AHD heights (light blue) by subtracting the AUSGeoid model (dark blue) and to AVWS heights (light purple) by subtracting the AGQG model (dark purple) (ICSM, 2020b).

It should be noted that other vertical working surfaces or local vertical datums exist, e.g. the Lowest Astronomical Tide (LAT) used for hydrographic applications. Whilst these are out of scope for this paper, it is important to note that multiple height reference surfaces have been used in Australia for a long time to cater for certain applications. The introduction of AVWS simply adds to the spatial professional's toolbox but also highlights the importance of metadata clearly specifying which datum or reference surface you are working in.

4 THE FUTURE

Whilst written nearly half a century ago, Blume (1975) noted "*With the adoption in New South Wales of the Australian Height Datum (AHD) 1971 as a new levelling datum, the previously used Standard Datum has been superseded. The small difference between the two datums has resulted in many surveyors being vocally critical of the new datum and the opinion has been expressed that the introduction of AHD was an unwarranted alteration to a long established and acceptable system*." He continued: "*Further investigation in connection with AHD is certain to continue and as a result of such research into tides, levelling, mathematical adjustments and revision, new values and possibly datums will arise. Because of the ever-changing level of the sea, any new datum would not necessarily agree with AHD, just as AHD did not agree with Standard Datum, which in turn did not agree with former datums based on sea levels. However, the need to replace AHD will doubtless require deep consideration in order to produce very strong and compelling reasons*."

These sentiments are just as true today, and his crystal-ball wisdom about the debate the profession will soon begin in regard to AHD and AVWS is visionary. A testimony to its true quality and immense expense, AHD has long outlasted its horizontal datum counterparts (i.e. AGD66, AGD84, GDA94), and it is unlikely that GDA2020 will still be operating in another

50 years. Acknowledging that there can be only one *legal* vertical datum, it remains to be seen what the future holds for legal heights in NSW and Australia.

While DCS Spatial Services does not expressly advocate or legislate adoption of AVWS at this time (currently it is neither implemented nor supported in SCIMS), we are collecting and maintaining new ellipsoidal height datasets with the aim to investigate and contribute to future applications of AVWS. Meanwhile, AHD remains the only legal height datum for Australia, and is still deemed fit for purpose for cadastral, civil engineering, construction and mining applications as well as ‘mums and dads’.

5 CONCLUDING REMARKS

This paper has celebrated the 50th anniversary and Golden Jubilee of AHD along with its achievements and longevity, outlined its shortcomings and described the datum maintenance and modernisation efforts undertaken by DCS Spatial Services to not only preserve but improve access to AHD, while also providing a solid foundation for AVWS across the State. It has also looked ahead to a new era of vertical datum determination, based on GNSS observations and gravity measurements.

AHD has been a stalwart of Australian surveying, replacing a collection of various local vertical datums and the then 80-year old Standard Datum, and successfully satisfied users ranging from ‘mums and dads’ to engineers and geodesists for 50 years. It has been the only vertical datum for most surveyors for the entire duration of their professional careers. That some should raise an eyebrow at even the thought of changing it, is quite understandable. But it is, like some of us, showing its age and is deteriorating, despite the best efforts to maintain it. As the sun has set on the age of long level runs across towns, cities, shires, states and the nation, users want physical heights delivered at the push of a button, anywhere and anytime. As positioning tools and sensors collect data over larger and larger swaths, at increased precisions, local distortions or warts in the fundamental datum can no longer be tolerated.

There can be only one *legal* vertical datum, and currently there is no planned push to replace AHD. Therefore, it remains to be seen what the future holds for legal heights in NSW and Australia. DCS Spatial Services has yet to implement AVWS but continues to investigate and contribute towards it. The successful uptake of any alternative height surface(s), such as AVWS, will in reality be decided by its users and their clients. You all will soon play a key role in deciding the future of AHD and whether it will be able to celebrate its 75th or maybe even its 100th anniversary.

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