AHD Turns 50:

The Story So Far

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The Australian Height Datum (AHD) celebrates its 50th anniversary this year and remains Australia's first and only legal vertical datum. Vertical datums define a reference for elevation comparisons and are of growing interest to a wider audience with an insatiable appetite for three-dimensional digital twins of the real world. For most surveyors, AHD has been ubiquitous for the entire duration of their professional careers, being the vertical datum of choice because it was the only one.

Surveyors typically work with two types of heights: ellipsoidal heights referred to the Geocentric Datum of Australia (GDA2020) and physical heights referred to AHD. Both are available through the NSW Survey Control Information Management System (SCIMS), the state's database containing approximately 250,000 survey marks on public record.

In this article, we focus on physical heights in NSW and explore the achievements of AHD in its golden jubilee year. We also outline the shortcomings of AHD and look ahead to a new era of vertical datum determination, based on Global Navigation Satellite System (GNSS) observations and airborne gravity measurements, culminating in the Australian Vertical Working Surface (AVWS).

AHD history

In NSW, AHD replaced the Standard Datum, which was in use for some 80 years and defined by the value of Mean Sea Level (MSL) at the Fort Denison tide gauge, located on an island in Sydney Harbour and 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.

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. 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 along the coast of mainland Australia and adjusting 97,320 km of primary two-way spirit levelling across the country. MSL observations spanned three years for all but one tide gauge, with earlier data over four years used at Karumba in the Gulf of Carpentaria. A subsequent adjustment also included about 80,000 km of supplementary one-way and two-way spirit levelling, in addition to and dependent upon the primary levelling.

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 Australian states and territories. In NSW, this included local datums for Water and Sewerage, Railway, Department of Lands, and Department of Lands – Trig Branch.

The question is naturally asked why third-order levelling was used for the primary survey. The short answer is that this practice was followed to produce the most useful outcome within the framework of funds and time available. 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. Anything more was reportedly considered as "striving against the forces of nature in order to achieve an impossible dream".

An important time consideration was that third-order levelling could be accomplished with readily available equipment and by available professional staff found in both the government and private sector. Of course, third-order levelling was also much cheaper than first-order and second-order levelling. Considering the cost factor, as a rough rule of thumb, it was determined that an increase in a survey operation by a factor n involves an increase in time and funds of n^2. Furthermore, even if better levelling 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 30 tide gauges.

Practical realisation of AHD in NSW

On the ground, 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. Typically, AHD marks were placed at intervals of one mile in regional areas and two miles in remote areas, usually following major roads. The network was far denser in towns and cities. The separation was also varied to enable marks to be placed at easily identifiable locations (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 State Survey Marks (SSMs, brass plaque in concrete) followed by a Permanent Mark (PM, usually employing a stainless-steel rod with concrete collar), 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. 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 and when existing surveys were adopted or recycled.

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

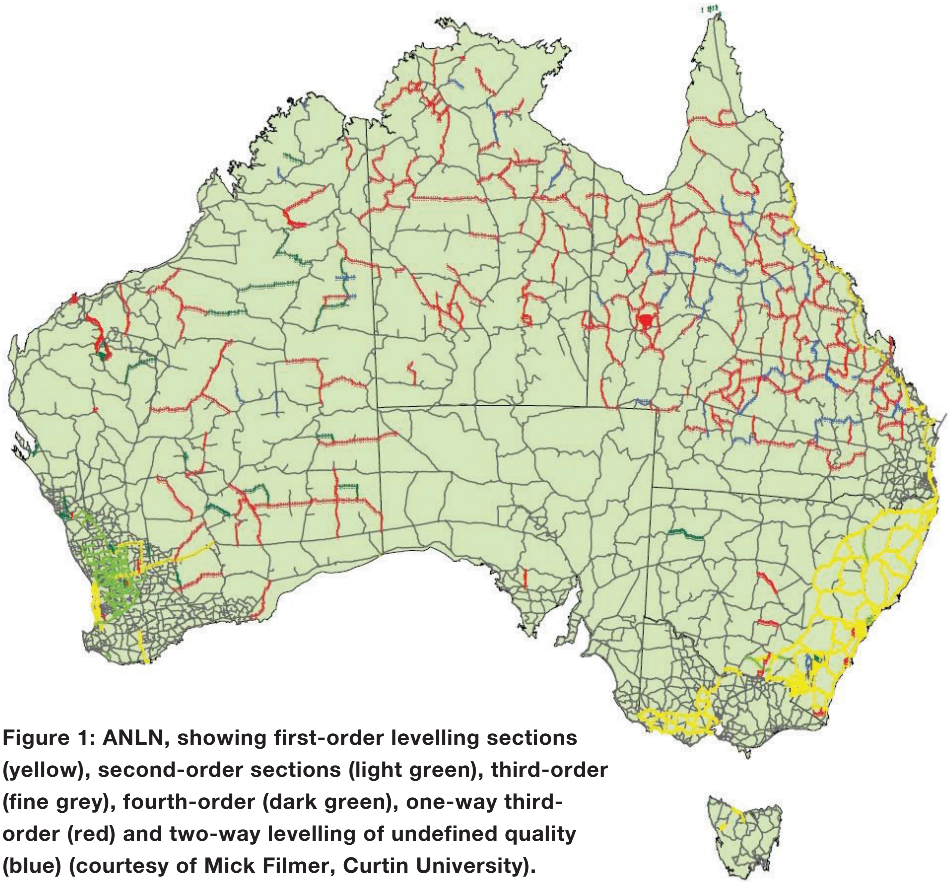

Figure 1: ANLN, showing first-order levelling sections (yellow), second-order sections (light green), third-order (fine grey), fourth-order (dark green), one-way third-order (red) and two-way levelling of undefined quality (blue) (courtesy of Mick Filmer, Curtin University).

modified for Australian conditions, akin to trigonometrical (trig) stations for height. FBMs and GBMs consisted of two to three marks installed in clusters, 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. An extensive network of FBMs and GBMs was envisaged when construction began in 1973, but the program was abruptly terminated due to budget constraints.

While AHD was designed as a third-order levelling network, NSW set a far higher standard. It supplemented, strengthened and improved AHD by observing the nation's most extensive and ambitious network of first-order levelling (Figure 1), which extended throughout the eastern part of the state. While 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).

Over the years, further level runs of various quality including one-way levelling were added to extend the network and investigate anomalies. An extensive capillary network of levelling to mountain-top trig stations was also established, typically one-way only, connecting to the nearest ANLN mark. 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, while digital levelling is only conducted for special projects, ad-hoc surveys or in some urban instances.

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 (modelled) gravity, which approximates true gravity. Orthometric corrections can be as large as several centimetres in mountainous regions where the level surfaces exhibit steeper slopes than in lowlands, for example 309 mm correction for the 146 km level run from Adaminaby into the Snowy Mountains versus 33 mm correction for the 155 km level run between Dubbo and Forbes.

AHD is thus considered a normal-orthometric height datum because existing gravity observations were insufficient. Instead, a truncated normal-orthometric correction was applied to the spirit levelling observations, which only utilised normal gravity (referenced to the GRS67 ellipsoid approximating the Earth).

The network of level sections and junction points was constrained at 30 tide gauges, 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. 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. While 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.

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 the impressive CDC 3600 computer used at the time. In phase 1, five regional adjustments were made within boundaries approximating state limits (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 to assess the quality of the levelling, and (2) the final adjustment constrained to the 30 tide gauges, run on 5 May 1971. 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.

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. Detailed analysis indicated that the data for the south-eastern corner of NSW was statistically inferior despite the existence of mostly first-order levelling. Reportedly, this indicated that, after several years, first-order surveys tend to deteriorate to much the same order of accuracy as third-order levelling.

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 whole 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.

Shortcomings of AHD

Over time, significant and well-documented shortcomings in the AHD realisation became apparent. In short, due to dynamic ocean effects (winds, currents, atmospheric pressure, temperature and salinity), tide gauge observations only spanning a period of three years and the omission of observed gravity, MSL was not coincident with the geoid at the tide gauge locations. The primary bias is due to 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. Together with uncorrected gross, random and systematic levelling errors, this introduced considerable distortions of up to about 1.5 m into AHD across Australia.

Observational blunders included those caused by observing in imperial units, where a whole foot was easily dropped 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 contractor who supposedly adjusted out a misclose of more than seven feet while enjoying a cold beer at a pub in Tibooburra. The independent approach of a few surveyors who did not fully conform to the prescribed specifications also caused issues.

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, particularly over smaller areas (less than 10 km).

A new era of vertical datum determination

The era of GNSS technology ushered in the development of geoid or quasigeoid models to convert GNSS-derived ellipsoidal heights to physical heights, including the AUSGeoid models for Australia. This conversion is often needed because positions obtained by GNSS include heights referred to a reference ellipsoid. These heights are based purely on the geometry of the ellipsoid and therefore have no physical meaning, so 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, for example in drainage and pipeline design.

Addressing 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. This culminated in the development of the Australian Vertical Working Surface (AVWS) as an alternative for users requiring higher-quality physical heights than those AHD can provide. AVWS allows early adopters to realise the full potential of modern technology, making height determination

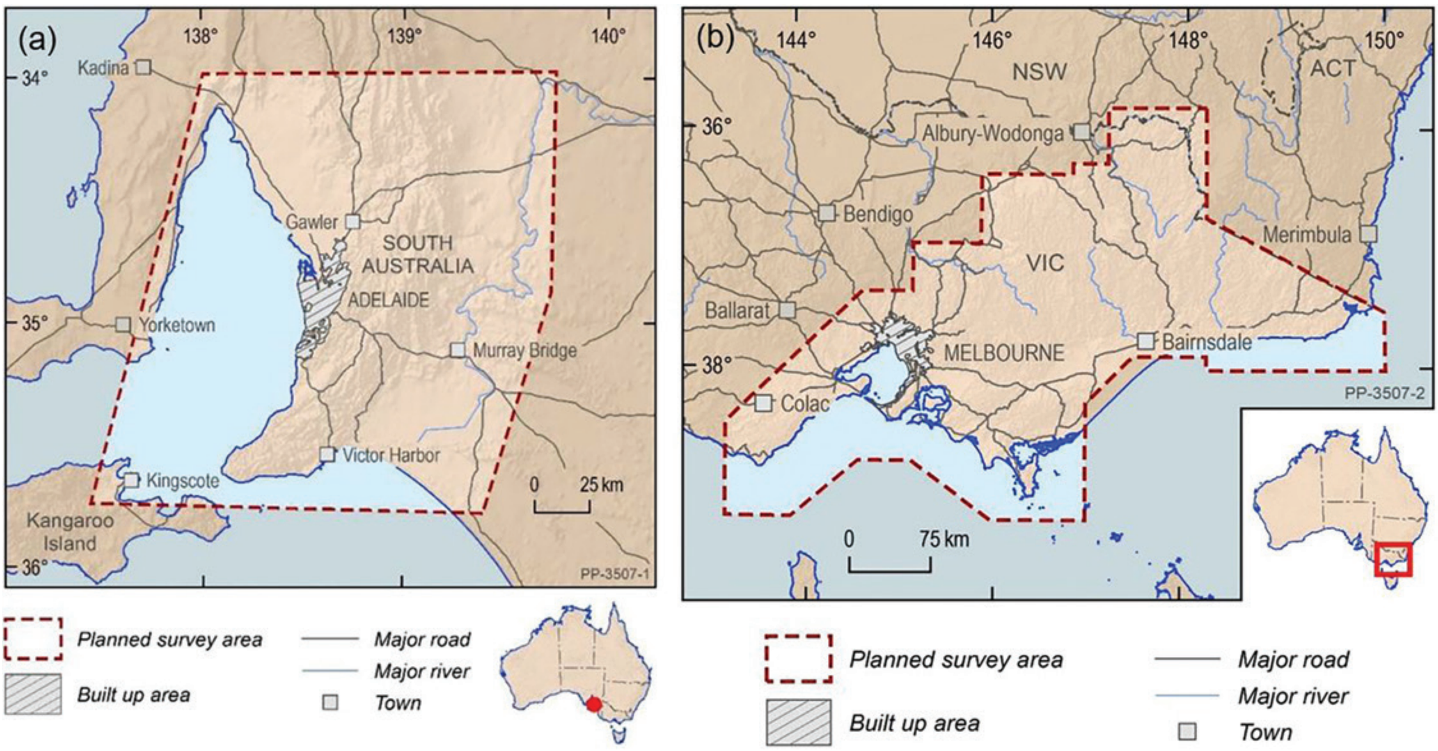

Figure 2: Targeted airborne gravity survey areas in (a) South Australia and (b) Victoria (courtesy of SA Government and VIC Government).

and transfer more efficient than with the traditional techniques employed in the 1970s and 1980s.

Several countries have used, or are about to use, (nationwide) airborne gravity measurements to develop high-quality gravimetric quasigeoid models to modernise their national vertical datums. For example, this includes the Canadian Geodetic Vertical Datum 2013 (CGVD2013), the New Zealand Vertical Datum 2016 (NZVD2016) and the North American-Pacific Geopotential Datum 2022 (NAPGD2022).

The reasons for moving to vertical datums based on gravimetric quasigeoids can be summarised as follows: The maintenance of national levelling networks is no longer viable (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 height 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 2) to improve the Australian gravimetric quasigeoid model. 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). 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. It 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.

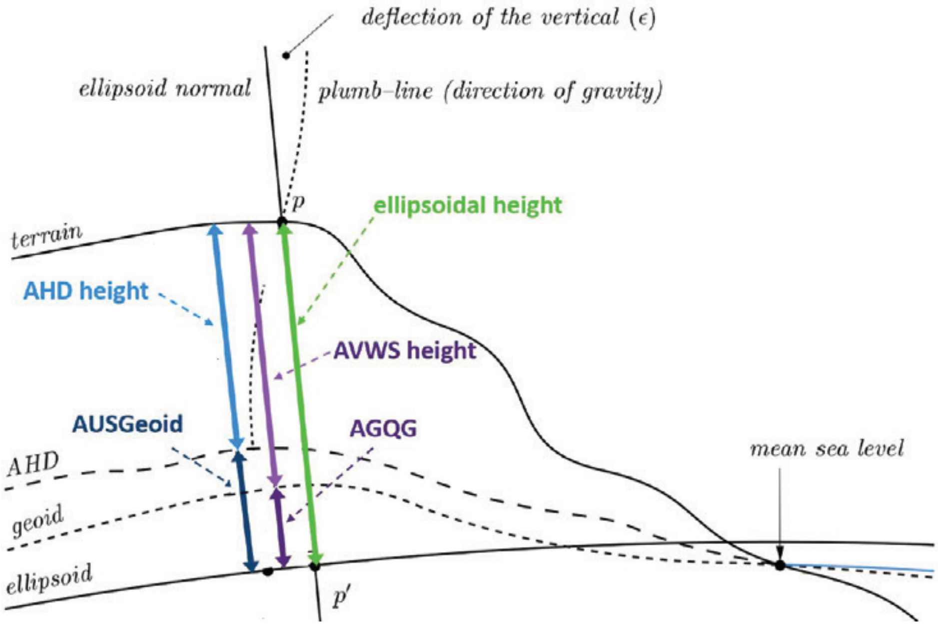

Figure 3: Converting ellipsoidal heights (green) to AHD heights (light blue) by subtracting the AUSGeoid model (dark blue) and to AVWS heights (light purple) by subtracting the AGQG model (dark purple), taken from ICSM's AVWS technical implementation plan.

AVWS

The Australian Vertical Working Surface (AVWS) is a new reference surface for physical heights in Australia, released on 1 January 2020. It 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). GNSS users can access AVWS by applying the Australian Gravimetric Quasigeoid (AGQG) to their GDA2020 ellipsoidal heights, just like AUSGeoid2020 is used to obtain AHD heights (Figure 3). In practice, this means simply picking AGQG rather than AUSGeoid2020 as the geoid model in your GNSS rover or post-processing software.

The initial version, AGQG_2017, 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. In NSW, users can expect differences of between -0.5 m and +0.1 m (Figure 4). 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.

Recently, a FrontierSI project (Next Generation Height Reference Frame) investigated current and future user requirements for physical height determination and transfer in Australia. It 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 (including flood or storm modelling), Light Detection and Ranging (LiDAR) surveys, geodesy or hydrography projects. The study recommended 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 and ATRF2014. 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 errors of the levelling network, better alignment with GNSS, and national consistency including a seamless onshore-offshore transition. Given that AVWS heights are not (currently) provided for

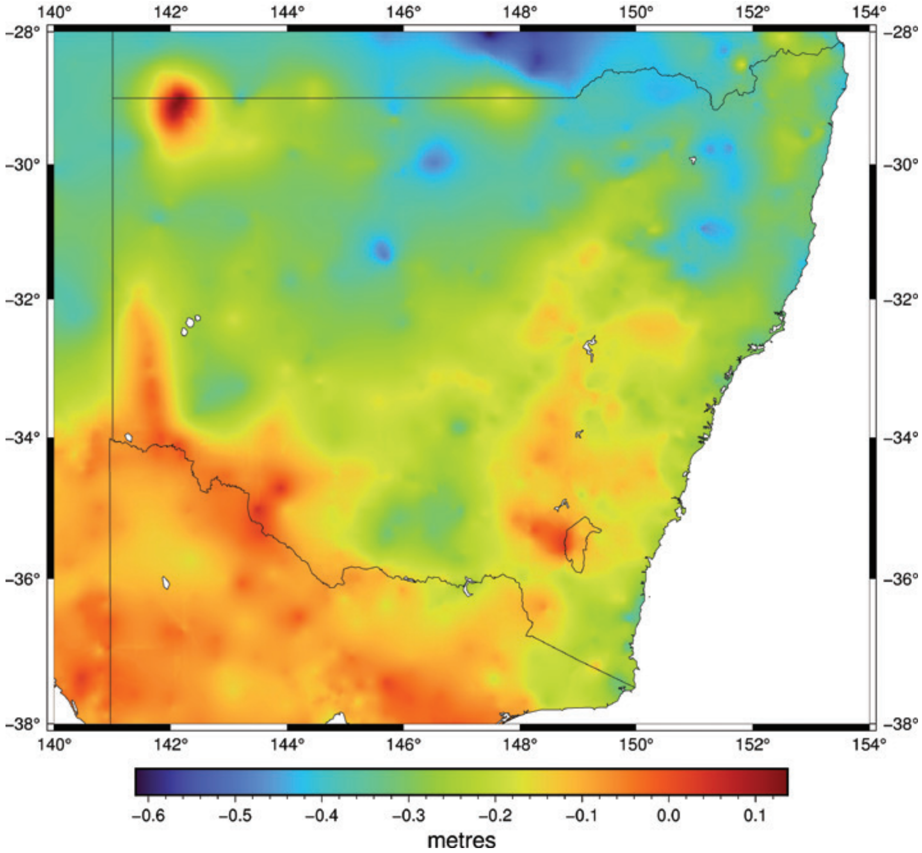

Figure 4: Differences in N values between AGQG_20201120 and AUSGeoid2020 across NSW, which is equivalent to the differences between GNSS-derived AVWS heights and AHD heights.

benchmarks on public record in SCIMS, 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.

Importantly, multiple height reference surfaces have been used in Australia for a long time to cater for certain applications, for example the Lowest Astronomical Tide (LAT) used for hydrographic 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.

The future

P.H. Blume, a surveyor with the NSW Maritime Services Board, noted nearly half a century ago: "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 from 1975 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 (AGD66, AGD84, GDA94), and it is unlikely that GDA2020 will still be operating in another 50 years. There can be only one legal vertical datum, so 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), it is 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 most applications.

Conclusion

AHD, in its golden jubilee year, should be celebrated for its achievements and longevity and noted for some of its shortcomings as a new era of vertical datum determination based on GNSS observations and gravity measurements dawns. 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 during 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. Positioning tools and sensors now collect data over larger and larger swaths, at increased precisions, and 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. 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 be decided by its users and their clients. You 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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