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NSW Surveyor General International Fellowship 2018: Investigation into Vertical Datums Defined by Gravimetric Geoid Models

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ABSTRACT

The NSW Surveyor General International Fellowship in Surveying and Spatial Information is offered annually to spatial professionals to facilitate personal and professional development in emerging areas, to promote the broader opportunities for spatial professionals, and to gain knowledge of international best practice through overseas travel and work experience. The successful application for 2017 proposed to investigate the developing trend towards vertical datums based on gravimetric geoid models in the broader context of Australian datum modernisation. During the travels undertaken in 2018, geodetic experts at Land Information New Zealand, the US National Geodetic Survey and the Canadian Geodetic Survey were interviewed regarding their new vertical datums and what they considered were successes and lessons learned. This study suggests that significant improvements in accuracy and productivity could be gained with the adoption of a vertical datum defined by a gravimetric geoid model, although airborne gravity across Australia would be required for best results and levelling would still be required for local-scale, height-critical projects. Additionally, new vertical datums are noted to be most readily accepted by the user community where the case for change is well understood and a full suite of user tools is available upon release.

KEYWORDS: *NSW Surveyor General International Fellowship, vertical datum modernisation, Australian Height Datum, physical geodesy*.

1 INTRODUCTION

The 2018 Surveyor General International Fellowship in Surveying and Spatial Information (SGF2018) sought to evaluate the suitability of vertical datums defined by gravimetric geoid models, rather than levelling measurements, for application in NSW and Australia. This was carried out by visiting the geodetic agencies of countries which have already made this change, i.e. New Zealand, the US and Canada, as well as meeting with relevant experts at Ohio State University (OSU) and the Canadian Geophysical Union (CGU) 2018 annual meeting.

1.1 SGF2018 Proposal

In submission, this proposal sought to:

- Gain knowledge, experience and practical insight into next-generation vertical gravimetric datums, both in a technical sense and regarding implementation and lessons learned.
- Contribute significantly to the author's PhD studies by exposure to international organisations and universities.

- Influence discussions on, and the direction of, Australia’s next generation vertical datum based on international progress in this topic area.
- Evaluate the benefit of a next-generation vertical datum to NSW’s surveying and spatial information industry and flag potential stumbling blocks for user uptake.

It was expected that such a proposal would deliver benefits in terms of increased in-house expertise in vertical datums, maintenance of DFSI Spatial Services’ capability and reputation as a leader in Australian geodesy, and obtaining advanced warning of any stumbling blocks for industry uptake. Additionally, it was expected the proposal would benefit the PhD studies of the author through international networking and face-to-face collaboration with world experts in physical geodesy.

1.2 Concept of Heights

Vertical datums provide a common reference point or surface by which heights of points and features on the Earth can be meaningfully related. Traditionally, vertical datums have been established through a network of levelled height differences based on one or more benchmarks which are usually related to mean sea level (e.g. Australian Height Datum, AHD – Roelse et al., 1971). These vertical datums, in almost all cases, describe physical heights, i.e. those which intend to represent the flow of fluids.

Heights observed using Global Navigation Satellite System (GNSS) technology, however, provide a height above the surface of the reference ellipsoid, and these heights do not describe the flow of fluids. Therefore, a geoid (or quasigeoid, herein called geoid when dealing in general terms) model is used to convert from ellipsoidal heights to physical heights. Height determination from levelling and GNSS is compared in Figure 1. Recently, improvements in geoid modelling have seen a handful of countries adopt the geoid model as the basis of their national vertical datums, rather than renewing their levelling networks.

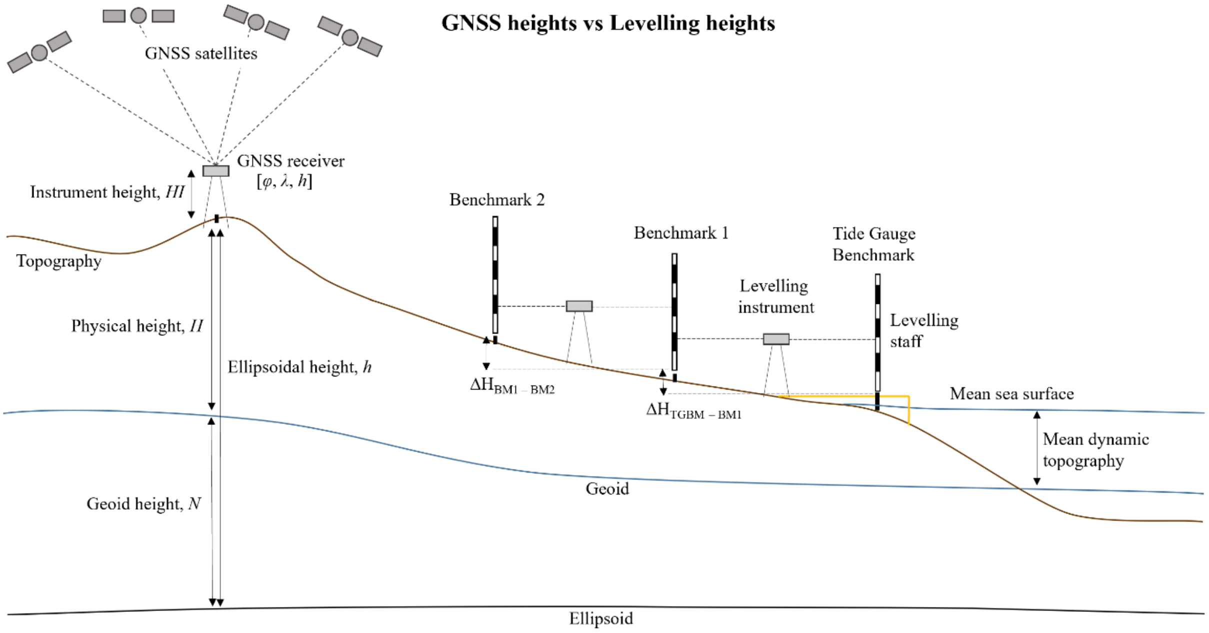

Figure 1: Height determination by GNSS (left) versus levelling (right).

1.3 Australian Height Datum

The Australian Height Datum (AHD) has been Australia's national vertical datum since 1971, as adopted by the National Mapping Council of Australia (Roelse et al., 1971). It was based on a least squares adjustment of almost 100,000 km of primary levelling, fixed to mean sea level at 30 tide gauges around mainland Australia. An additional ~80,000 km of supplementary levelling was then adjusted to fit the heights established in the primary adjustment. In Tasmania, AHD was established in 1983 in a separate levelling adjustment fixed to two tide gauges. While strictly they are different datums, often they are collectively referred to as 'AHD'.

Since 1971, many analyses of AHD have been undertaken (e.g. Coleman et al., 1979; Kearsley et al., 1988; Morgan, 1992; Featherstone and Stewart, 1998; Featherstone, 2004, 2006; Featherstone and Filmer, 2008, 2012; Filmer and Featherstone, 2009; Filmer, 2010). These found that generally, while AHD meets the requirements of a third-order levelling datum, it has regional biases, and contains a ~1 m north-south tilt due to the effect of neglecting oceanic mean dynamic topography (MDT – depicted in Figure 1) at tide gauges.

In the last decade, Australian geoid models have attained such an accuracy that they now must be retro-fitted, or warped, in order to deliver AHD with its distortions. While this might benefit a surveyor, who is required to work on AHD over short distances, this 'temporary fix' has significant, real-world problems across larger areas. For example, since 2012, Geoscience Australia has required that all Light Detection and Ranging (LiDAR) surveys are transformed from GNSS heights to physical heights using the Australian Gravimetric Quasigeoid 2009/2017 (AGQG – Featherstone et al., 2011, 2018), rather than AUSGeoid09/2020 (Brown et al., 2018a, 2018b) models. This requirement is borne out of necessity to accurately model flooding events, e.g. across the Murray Darling Basin.

Furthermore, soon Geoscience Australia will enable centimetre-accurate, real-time positioning through the AU$260 million National Positioning Infrastructure Capability (NPIC – Australian Government, 2018). This will see everyday users achieving better accuracies than AHD can support. In this context, the SGF2018 travels were completed in order to assess the potential benefit for Australia from the implementation of a vertical datum defined by a gravimetric geoid model.

2 STUDY DESTINATIONS

The SGF2018 travels spanned five main organisations, three countries, four weeks, and approximately 40,000 km in distance travelled (Table 1 & Figure 2).

Table 1: Itinerary of SGF2018 travels.

Dates	Destination	Primary Contact
7-11 May 2018	Land Information New Zealand (LINZ) Wellington, New Zealand	Dr Matt Amos
17 May 2018	Ohio State University (OSU) Columbus, Ohio, USA	Prof Chris Jekeli
21-23 May 2018	National Geodetic Survey (NGS) Silver Spring, Maryland, USA	Dr Dan Roman
4-8 Jun 2018	Canadian Geodetic Survey (CGS) Ottawa, Ontario, Canada	Marc Véronneau
11-14 Jun 2018	Canadian Geophysical Union (CGU) 2018 Annual Meeting Niagara Falls, Ontario, Canada	N/A

Figure 2: SGF2018 study destinations.

2.1 Land Information New Zealand, Wellington, New Zealand

Land Information New Zealand (LINZ) is the geodetic agency for New Zealand, which was the first country to adopt a geoid model as its vertical datum. The New Zealand Vertical Datum 2009 (NZVD2009) is defined by the New Zealand Quasigeoid 2009 (NZGeoid2009) and was introduced as a way to unify 13 disparate local vertical datums (LVDs – Figure 3a) across the country. NZGeoid2009 was later replaced by NZGeoid2016 (Figure 3b), which incorporated new aerial gravity over the country, providing a more consistently performing geoid model.

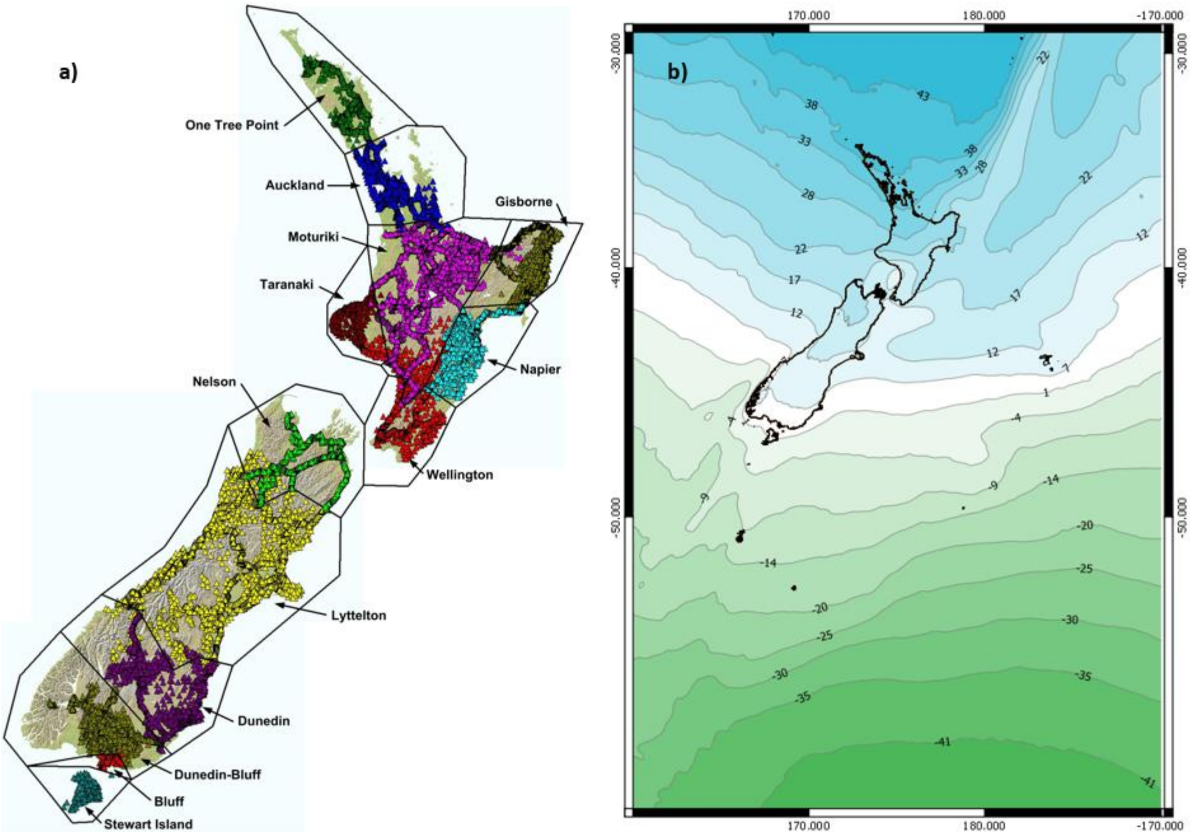

Figure 3: (a) New Zealand local vertical datums, and (b) New Zealand Quasigeoid 2016 (LINZ, 2019a, 2019b).

2.1.1 Lessons Learned from NZVD2009

New Zealand's first geoid-defined vertical datum, New Zealand Vertical Datum 2009 (Amos, 2010), was never fully implemented. For example, NZVD2009 heights were not published by LINZ, and there was a very low user uptake.

While there were many factors contributing to this, the most significant are:
- It only had a nominal 1-sigma accuracy of ±0.06 m (when users wanted ±0.03 m).
- At the time of product delivery, there were no implementation tools or products available to aid industry uptake.
- LINZ quickly had the business case approved to fly gravity over the country, and so in the knowledge that a new geoid model was on the horizon, the rollout and implementation of NZVD2009 stalled.

Further, recovery efforts following the Canterbury earthquake of 2011 showed that NZVD2009 was not suitable to restore the water/sewer infrastructure in an efficient manner. Levelling was required across the entire affected area.

2.1.2 Successes of NZVD2016

The New Zealand Vertical Datum 2016 (NZVD2016 – McCubbine et al., 2018) was released with a three-pronged strategy:
1) *It is a superior technical product, meeting a minimum accuracy standard*. Airborne gravity covering the entire country was incorporated into the geoid model, and this was combined with surface gravity, ship-track gravity and a more recent gravity reference-field model (EIGEN-6C4 EGM). This resulted in a nominal accuracy figure of ±0.03 m, which was more in line with the user community's requirements.
2) *The local vertical datum offsets are better quantified*. An increase in co-located GNSS-levelling sites meant more sophisticated modelling of the relationship between the local vertical datums and NZVD2016 was possible. These trended surfaces are provided to industry as a 2-arc-minute grid, whereas only a simple, constant offset (i.e. block shift) quantified the relationship between NZVD2009 and each of the local vertical datums.
3) *A suite of tools was available at the time of product release and industry was briefed throughout the process*. LINZ dedicated significant effort towards enabling industry to adopt NZVD2016 which encompassed efforts to streamline the user interface, availability of heights through the LINZ survey database and a number of online and offline tools to transform between the New Zealand Geodetic Datum 2000 (NZGD2000) and NZVD2016 as well as between NZVD2016 and the LVDs. In the lead-up to release, a range of industry briefings and workshops were held to update the relevant stakeholders.

LINZ now encourages adoption through open data, and a cost-sharing data-acquisition model. For example, LiDAR data is jointly funded by LINZ, councils and other government organisations with the understanding that the data will be open and published with reference to the national horizontal and vertical geodetic datums.

2.1.3 Airborne Gravity

From a value-for-money perspective, LINZ considers the acquisition of airborne gravity across the country a worthwhile investment. The largest improvements were gained across the littoral (coastal) zone where satellite altimetry is problematic and terrain modelling is usually void, and in other areas with no gravity data. For the Australian application, it follows that airborne gravity flown over the coastline, and across void areas, would provide the most significant improvements.

2.2 Institution of Surveyors New Zealand

A meeting was hosted by the Institution of Surveyors New Zealand where a representative of Wellington City Council was present. The rollout of NZVD2016 was discussed along with if/when the council was likely to adopt. The representative acknowledged that NZVD2016 had proved its worth in highlighting local gross errors and distortions within the Wellington LVD, yet all but ruled out the possibility of its adoption by Council. Some concerns were raised regarding where the cost of implementation would fall, but by far the biggest obstacle was the attitude of “I don’t want to change, it’s not the right time”. When queried what circumstances would indicate the right time, the answer was “Maybe when I retire”.

2.3 Ohio State University, Columbus, OH, USA

Prof Chris Jekeli, Ohio State University (OSU), was interviewed based upon his expertise in height systems and physical geodesy (e.g. Jekeli, 2000). His current research investigates gravity gradiometry, which can provide far higher resolution than traditional relative airborne gravity techniques, although this technology is currently very expensive.

Perhaps the most insightful comment came while he was lamenting the US’s failure to adopt the metric system. He remarked there was probably a point where it was possible to adopt the system, but delays in making that decision caused the costs of adoption to increase until it was no longer viable. In many ways, this could parallel Australia and its reluctance to improve AHD. Changing the vertical datum is already considered very difficult. It is suggested that very difficult is easier to achieve than impossible.

2.4 National Geodetic Survey, Washington, DC, USA

The US National Geodetic Survey (NGS) has resolved to replace the North American Vertical Datum 1988 (NAVD88 – Zilkoski et al., 1992) with the North-American-Pacific Geopotential Datum 2022 (NAPGD2022 – NGS, 2007, 2017). This comes at the expense of US$40 million to fly gravity over the whole of the continental United States (see section 2.4.2).

NGS’s justification for moving away from levelling is as follows:

- To re-level the country would cost between US$200 million and US$2 billion (NGS, 2017).
- Due to the effect of glacial isostatic adjustment (GIA) and other surface movements, the results would be outdated before the fieldwork is finished.

In the Australian context, a superficial estimate suggests the cost to re-level the ~200,000 km in the original primary and supplementary AHD networks to be a minimum of about AU$150 million. This does not include the estimated tens to hundreds of thousands of kilometres of levelling carried out since that time. There is a reasonable question to ask if airborne gravity would deliver better value for money.

NGS’s public message for vertical datum modernisation justification is summarised as (1) vertical positioning is now accurate at the centimetre-level but the vertical datum is only accurate at the decimetre-level, and (2) levelling is not sustainable long term.

2.4.1 Role of Levelling within a Gravimetric Geoid-Based Vertical Datum

NGS does accept, however, that levelling still has a role to play in surveying. Once NAPGD2022 is implemented, NGS will recommend that any levelling carried out is controlled by GNSS+geoid derived heights at distances no further than 30 km. This demonstrates that, at the local scale, levelling is still superior and is likely to remain the tool of choice by surveyors for height-critical projects.

In the Australian context, AUSGeoid2020 provides superior performance to that of third-order (cf. ICSM, 2007) levelling at distances greater than 3 km (Brown et al., 2018a). While this figure is more like ~15 km for second-order and ~50+ km for first-order levelling, the notion that levelling can be controlled by GNSS is supported by Australian research.

2.4.2 GRAV-D

GRAV-D stands for the Gravity for the Redefinition of the American Vertical Datum project (NGS, 2007). This project aims to capture airborne gravity at high elevation and link the terrestrial with the space-borne gravity datasets.

In summary, GRAV-D includes:
- Project cost: US$40 million.
- Two phases: Initial capture, and long-term monitoring at selected areas.
- Coverage: Entire US landmass, and as far out to sea as the continental shelf break.
- Flight lines: 10,000 ft elevation, 10 km spacing.
- Processing software: NEWTON, developed in-house.
- Aircraft: Several fixed-wing aircraft utilised, each highly individual in terms of calibration requirements.
- Positioning: GPS, initially by Real-Time Kinematic (RTK), but ultimately by Precise Point Positioning (PPP).
- Gravity calibration: Before and after the flight at the airport.

2.4.3 Time-Dependent Geoid Model

After completion of the initial GRAV-D project and the computation of the first geoid model, NGS intend to incorporate a time-dependent geoid component into their model. This time-dependent model will represent divergence from the initial geoid model and can be thought of as a vertical velocity model. Upon completion of the initial coverage of GRAV-D, key areas with known geophysical variations will be targeted, and re-observed. In the US, various terrestrial gravity surveys have observed changes from 5-10 mGal, which represents changes of up to 0.15-0.2 m in geoid height.

2.4.4 Communications with Industry

NGS is recognised and trusted as an expert in geodesy, therefore the agenda it sets will be followed by the spatial community. From industry’s perspective, they simply desire to know what is going to happen, and when. In this regard, NGS has a very good communication strategy. It provides updates to the spatial community through ‘industry days’, webinars and other conferences. The major software providers, e.g. ESRI, are contacted and encouraged to attend. The end-users in the spatial community are not worried about the coming changes to the geodetic datums, so long as the changes are supported by their software.

2.4.5 Financial Benefits of the Improved Vertical Datum

NGS reports that the accuracy improvements of the new vertical reference system will save US$240 million through improved floodplain management, and the overall vertical datum modernisation campaign will yield an estimated US$522 million in annual economic benefits to the United States.

2.5 National Society of Professional Surveyors

The US National Society of Professional Surveyors (NSPS) was contacted to represent the industry's opinion on the coming vertical datum. NSPS reports that industry is not overly worried about the change. It believes that NGS is doing a good job engaging with industry through workshops and webinars, so that surveyors are well aware of the case for change and any ramifications to their work.

NSPS also works with NGS to identify relevant legislation requiring updates in order to move from NAVD88 to the new vertical datum, which shows a good level of support and rapport between government and professional industry bodies.

2.6 Canadian Geodetic Survey, Ottawa, Canada

The Canadian Geodetic Survey (CGS) maintains Canada's geodetic reference frames and geodetic services. Canada recently adopted the Canadian Geodetic Vertical Datum 2013 (CGVD2013), based on the Canadian Gravimetric Geoid 2013 (CGG2013 – Véronneau and Huang, 2016), to replace the levelling-based Canadian Geodetic Vertical Datum 1928 (CGVD28).

2.6.1 Motivation for Change

Canada's decision to adopt a vertical datum defined by a geoid model was driven by having no other viable option. Knowing this, CGS still consulted with industry regarding the upcoming change and produced the required consultant reports and industry analysis. In this instance, the report simply provided the formal justification required to make such a change.

Levelling was considered unviable for several reasons:
- Skills and staff shortages.
- High ongoing costs.
- The dynamic nature of the Canadian landmass, due to effects such as GIA.

Furthermore, some repeat sections of levelling diverge in excess of the effect of GIA, so CGS believes there is some unaccounted systematic error in the levelling data.

2.6.2 Lessons Learned from the Implementation of CGVD2013

Discussions with CGS indicate that the biggest barriers to change are people's attitudes. In CGS's experience, surveyors have a level of comfort with physical benchmarks, and they do not want their heights to change, despite the reality that they do in fact move. A lesson for Australia is that any new system should produce physical heights on the fly, from the best available model, rather than simply storing the result as is done with AHD. In practice, this could work by storing the GNSS-derived ellipsoidal heights, and then on delivery computing the physical height based on the latest available geoid model.

CGS believes that wide-scale adoption and acceptance will follow as part of generational change, similar to the way in which GNSS was resisted as ‘black box’ technology before seeing widespread adoption in the surveying industry. Even now, some 5 years after the release of CGVD2013, it has not been adopted by all Canadian provinces, although there is agreement to adopt over a transition period spanning years.

During SGF2018 discussions, CGS staff offered the following suggestions to Australia in regards to vertical datum modernisation:

- Before releasing a geoid model, ensure you can live with it for many years because people do not like change!
- But on the other hand, deliver to clients what they want now. However, in your own work be ahead of them by at least one step in order to anticipate the needs of industry.

In this context, CGS is working towards a time-dependent geoid model – one with a velocity model to account for changes of up to ~1.5 mm/yr observed in the geoid due to GIA, which is similar to that outlined in section 2.4.3.

2.7 Canadian Geophysical Union Annual Meeting, Niagara Falls, Canada

The Canadian Geophysical Union (CGU) encompasses five disciplines: Biogeosciences, Earth Surface Processes, Geodesy, Hydrology, and Solid Earth. This conference was of particular interest due to the North-American geoid workshop held. The geoid workshop illustrated how, for North Americans at least, political borders are no obstacle to science. Around the table were discussions on sharing the datasets of CGS (Canada), NGS (United States) and Inego (Mexico) for each to independently compute the geoid model and compare the results of their preferred technique. This meeting specifically clarified which data holdings would be used for the experimental geoid computations.

3 RECURRING THEMES AND LESSONS LEARNED

A recurring theme throughout the SGF2018 travels is that maintenance of national levelling networks is no longer viable. It is widely considered too costly, too time consuming, and in countries subject to significant surface displacement, the results are too short-lived. In this respect, gravimetric geoid models offer advantages because they are far more cost effective to maintain and less susceptible to surface movements. Furthermore, their complete spatial coverage provides significant efficiency gains for industry when accessing the datum – propagating datum from the nearest levelled benchmark(s) is no longer required. In this context, vertical datums have been upgraded via gravimetric geoid models to effectively and efficiently resolve a modern positioning paradox whereby users can readily obtain positions more accurate than the underlying datum.

However, 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. This often prompts the question “What is a short distance?” While AUSGeoid2020 can provide superior performance to third-order levelling at distances greater than ~3 km (see section 2.4.1), it is dependent on the accuracy of the underlying GNSS data, which is highly variable depending on observation and reduction techniques. The better strategy to answer this question is to review the individual requirements of the project and select the observing technique accordingly.

With regard to the utilisation of Australia's levelling data holdings in any future Australian vertical datum, it is currently unclear whether a readjustment of the Australian National Levelling Network (ANLN) based on modern techniques would provide a more accurate solution than adopting the stand-alone Australian Gravimetric Quasigeoid 2017 (AGQG2017 – Featherstone et al., 2018), *or* if some combination of the two (cf. Filmer and Featherstone, 2012) is the best strategy. A hybrid-style vertical datum, with the levelling network adjusted to GNSS control linked via AGQG2017 (or another geoid model) may provide a best-of-both-worlds solution.

A second recurring theme is the system acquisition of nationwide airborne gravity. This proved to significantly benefit the geoid models of the US and New Zealand. A model can only ever be as good as the data that informs it. It is therefore expected that the acquisition of airborne gravity would significantly improve the performance of Australia's geoid models.

Finally, the change-management aspect of vertical datum modernisation is often the most difficult. From the experience of the countries visited, it is apparent that a vertical datum is best implemented when:

- The technical product meets the user-required accuracy.
- The full suite of implementation products is available at launch (e.g. geoid models, interpolation and transformation tools, manuals, documentation and industry education).
- The stakeholders understand and support the case for change.
- The appropriate legislation to facilitate such a change is in place.

Furthermore, industry champions hold a significant role in encouraging and facilitating adoption for everyday users. These might be organisations from whom industry source spatial data, such as state government organisations and local councils.

4 CONCLUDING REMARKS AND RECOMMENDATIONS

These studies suggest that the spatial industry in NSW and Australia could gain significant productivity benefits in the utilisation of a vertical datum defined by a gravimetric geoid model. Such productivity benefits are delivered through a significant decrease in time to establish vertical control (via GNSS), widespread coverage (rather than confined to levelling runs) and improved accuracy over the current AHD. Further, geodetic agencies would benefit from reduced maintenance costs associated with vertical datums defined by levelling. However, for the most accurate applications, such as critical water infrastructure, levelling is still required at the local scale.

Before implementation, any future Australian vertical datum modernisation effort must first educate users why change is necessary and provide convincing, compelling arguments. Once accomplished, implementation may begin. Industry must be supported with a suite of documentation, tools and transformation products.

As a result of the SGF2018 travels, the following recommendations are made to the NSW Surveyor General:

1. DFSI Spatial Services produces and maintains a dense network of high-quality ellipsoidal heights across NSW.
A gravimetric-geoid-model defined vertical datum is accessed by ellipsoidal height minus geoid separation. A dense, readily available network of precise ellipsoidal heights will support the NSW industry in accessing any new vertical datum. DFSI Spatial Services projects such as CORSnet-NSW (e.g. Janssen et al., 2016; DFSI Spatial Services, 2019), Saving AHD, Trig Maintenance and Upgrade (Gowans et al., 2015), Positioning Rural NSW, and AUSPOS at GBMs are invaluable in this respect and should be continued to maintain and improve the state control survey within the meaning of the Surveying and Spatial Information Act 2002.

2. DFSI Spatial Services maintains the technical skill and capability to carry out geodetic levelling.
Even if a new Australian vertical datum were defined solely by a geoid model, levelling would still be required for critical, local-scale water management projects. In order to set best-practice guidelines and directions, and to maintain relevance amongst industry, DFSI Spatial Services needs to have this capability.

3. DFSI Spatial Services digitises its levelling network and combines it into a single adjustment, to be merged with the GDA2020 network.
This is ongoing as part of the author's formal studies, and will provide significant benefit to NSW spatial stakeholders and Australian geodesy.

4. DFSI Spatial Services prepares to enable 4D geodesy.
One of the suggestions from CGS was for geodetic agencies to be at least one step ahead of the needs of industry, with work towards a time-dependent geoid model given as an example. For DFSI Spatial Services, keeping one step ahead becomes increasingly relevant as Australia prepares for the second stage of its datum modernisation agenda, i.e. the time-dependent Australian Terrestrial Reference Frame (ATRF – e.g. Janssen, 2017; GA, 2019). This theme will invariably transfer to any new vertical datum proposed for Australia.

5. ICSM reviews the case for nationwide airborne gravity.
In New Zealand and the US, the addition of airborne gravity has significantly improved their geoid modelling capability. For New Zealand, this difference was critical for successful implementation. As such, the potential benefit of airborne gravity to Australia's geoid modelling capability should be assessed.

6. ICSM continues investigations into an alternative to and/or successor for AHD.
An alternative to and/or successor for AHD is required for users to fully exploit modern, high-precision positioning technologies, such as the NPIC. As it stands, there are significant accuracy and productivity benefits to be gained from improving Australia's datum for physical heights. A real-world case study, which demonstrates and quantifies such benefits, could be a first step towards industry education and change management.

In closing, the following quote is offered: "Get it as right as possible the first time. People don't like change!" – Dan Roman, NGS Chief Geodesist, CGU Annual Meeting, June 2018.

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