THREE VIABLE OPTIONS FOR A NEW AUSTRALIAN VERTICAL DATUM

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ABSTRACT

While the Intergovernmental Committee on Surveying and Mapping (ICSM) has stated that the Australian Height Datum (AHD) will remain Australia's official vertical datum for the short to medium term, the AHD contains deficiencies that make it unsuitable in the longer term. We present and discuss three different options for defining a new Australian vertical datum (AVD), with a view to encouraging discussion into the development of a medium- to long-term replacement for the AHD. These options are a i) levelling-only, ii) combined, and iii) geoid-only vertical datum. All have advantages and disadvantages, but are dependent on availability of and improvements to the different data sets required. A levelling-only vertical datum is the traditional method, although we recommend the use of a sea surface topography (SSTop) model to allow the vertical datum to be constrained at multiple tide-gauges as an improvement over the AHD. This concept is extended in a combined vertical datum, where heights derived from GNSS ellipsoidal heights and a gravimetric quasi/geoid model (GNSS-geoid) at discrete points are also used to constrain the vertical datum over the continent, in addition to mean sea level and SSTop constraints at tide-gauges. However, both options are ultimately restricted by the requirement to upgrade the Australian National Levelling Network (ANLN). It is also desirable that the ANLN be kept in reasonable shape for the validation or testing of height products. On the other hand, a geoid-only vertical datum, where GNSS-geoid is used to continuously define the vertical datum, has advantages primarily because it avoids the requirement to level long distances to upgrade the levelling network. However, it is not routinely possible to realise a geoid of the desired 1-2 cm accuracy necessary to develop a geoid-only vertical datum, especially to a local precision that can match levelling, such that a geoid-only vertical datum is considered a long-term proposition. In the meantime, a combined vertical datum is a more suitable option for any new AVD in the next decade or so, although a geoid-based vertical datum which retains only the higher quality parts of the ANLN in Australia's densely settled areas, but connected by a geoid model rather than continent-wide levelling, may also have merit.

Keywords: vertical datum, AHD, geoid, levelling, SSTop.

INTRODUCTION

The Australian Height Datum (AHD) (Roelse *et al*. 1971; 1975; Granger 1972) has served Australia well since its inception in 1971, when the national levelling network (with Rapp [1961] normal-orthometric corrections applied) was fixed to mean sea level (MSL; adopted as the AHD zero-reference) at 30 mainland tide-gauges. However, it no longer meets the requirements for a modern vertical datum (e.g., Holloway 1988; Kearsley *et al*. 1988; 1993; Morgan 1992; Featherstone 1998; 2002; 2004; 2006; 2008; Featherstone and Dent 2002; Featherstone and Kuhn 2006; Featherstone and Sproule 2006; Featherstone and Filmer 2008). This is primarily because the sea surface topography (SSTop) induced north-south slope (Featherstone 2004; 2006; Filmer 2011, Chapter 5) and other distortions caused mostly by levelling errors (Morgan 1992; Filmer and Featherstone 2009) make AHD normal-orthometric heights (H) inconsistent (by up to ~1 m) with ellipsoidal heights from Global Navigation Satellite Systems (GNSS) (h) and gravimetric quasigeoid models (N; herein representating both *gravimetric* geoid and quasigeoid heights). Therefore, the expectation that $H = h - N$ is not met, noting that when N is a geoid height, H is an orthometric height and when N is a quasigeoid height, H is a normal height; normal-orthometric H *approximately* relates to quasigeoid heights (cf. Filmer *et al.* 2010). Indeed, the new gravimetric quasigeoid model over the Australian region, AGQG09 (Featherstone *et al*. 2011) needed to be distorted to 'fit' the AHD resulting in AUSGeoid09 (Featherstone *et al*. 2011; Brown *et al*. 2011) to enable GNSS users to transform directly to the AHD and vice versa.

Although the (fitted) gravimetric quasigeoid is a pragmatic solution to the discrepancies between H from traditional vertical datums and $h - N$ (cf. Smith and Milbert 1999; Smith and Roman 2001; Iliffe *et al*. 2003), we consider this only to be an interim solution (Featherstone *et al*. 2011). Acknowledging that the Inter-governmental Committee on Surveying and Mapping (ICSM) has stated that the AHD will remain Australia's 'official' vertical datum for the foreseeable future, the development of a new vertical datum that is correct with respect to the geoid or quasigeoid, thus satisfying public, industry and scientific needs is - in the authors' view - the appropriate long term solution. This is because a new, improved Australian vertical datum (AVD) would be:

1) directly compatible with $h - N$ without the necessity to fit the quasi/geoid model to a sub-standard vertical datum;
2) compatible with (non-AUSGeoid) global and regional gravimetric quasi/geoid models (e.g., EGM2008; Pavlis *et al*. 2008), MSL plus SSTop models ($SSTop = MSL - N$; herein, SSTop and N are both mean local values) e.g., CSIRO Atlas of Regional Seas 2006 (CARS2006) (Ridgway *et al*. 2002), and other Earth observation programs;
3) suitable for scientific testing and validating of height based data sets (benefiting public and industry users) – the AHD is not satisfactory for this task (e.g., Claessens *et al*. 2009; Hirt *et al*. 2010; Featherstone *et al*. 2011);
4) suitable for integration into any future physical global vertical datum (GVD; based on gravity potential) – the AHD is not adequate for this purpose due to its spatially variable offset to a level surface (Featherstone 2000).

Any discussion about the future of heights in Australia will be influenced by a number of factors, including the requirement for improvements in the available data, unification of mainland and Tasmanian AHDs, compatibility within any future GVD, and the concept of time-dependent heights, leading to a dynamic vertical datum (cf. Tregoning and Jackson 1999). The idea of changing vertical datums and the possible upheaval that can accompany the change will naturally cause concern among users.

However, from international experience, it is clear that national vertical datums have finite life-spans and are routinely replaced or upgraded every few decades (e.g. Zilkoski *et al*. 1992; Marti and Schlatter 2002; Yang *et al*. 2003; Véronneau *et al*. 2006; NGS 2008; Rangelova *et al*. 2009; Amos and Featherstone 2009). This is beneficial when technological and data advances can result in large improvements from the upgraded/renewed vertical datum. In addition, time-dependent variations in the surface of the Earth (i.e. subsidence/uplift) may cause inconsistencies within vertical datums (e.g., Carrera 1984). Australia has been relatively fortunate in regard to tectonic deformation (cf. Dentith and Featherstone 2003; Dawson *et al*. 2008), as it does not contain major active fault lines where significant vertical crustal motion occurs (cf. Vaníček *et al*. 1985). However, subsidence/uplift does occur in Australia (e.g., Wellman and Tracey 1987; Belperio 1993; Dawson 2008) and needs to be addressed when considering the development of any new AVD.

The quality and completeness of different data sets (e.g., the Australian National Levelling Network [ANLN], tide-gauge records, terrestrial and satellite/airborne gravity, SSTop models and GNSS) will affect decisions regarding the exact form of any new AVD (see later). In addition, the concept of connecting the ~100 local vertical datums (LVDs) (Ihde and Sánchez 2005) around the world to form what has variously been referred to as a world vertical network (Colombo 1980), global vertical datum (Balasubramania 1994) or world height system (Rapp and Balasubramania 1992; Ihde and Sánchez 2005) has been developed over several decades (cf. Rummel and Teunissen 1988), but has not yet been realised.

While there have been notable improvements in global geopotential models in recent years (e.g., EGM2008), and the potential of the European Space Agency's Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite mission (e.g., Johannessen *et al*. 2003; Drinkwater *et al*. 2003) with respect to the realisation of a GVD (e.g., Arabelos and Tscherning 2001), the low quality of some of the existing LVDs around the world continues to be an impediment. The AHD in its current form will not be fully compatible with any future GVD. The north-south slope and regional distortions mean that any vertical offset to the GVD will be a function of its horizontal position (cf. Featherstone 2000). Unification of mainland Australia and Tasmania into one vertical datum is also an issue that will need to be addressed (Rizos *et al*. 1991; Rapp 1994; Featherstone 2000), although Filmer and Featherstone (2011b) suggest that the SSTop-induced offset may only amount to a few cm, and that SSTop models and/or $h - N$ may be used to remove this offset.

Therefore, it is appropriate to begin discussion and research into if and how a new AVD may be implemented, particularly as progress towards new vertical datums is relatively advanced in some other countries, such as the US (NGS 2007; 2008; Smith and Edwards 2010), Canada (Véronneau *et al*. 2006; Rangelova *et al*. 2009), and some European countries (Ihde *et al*. 2002). It is partly in response to the progress described in these papers, that we look to firstly discuss international continent-wide vertical datum development, and then present three options that could be used to develop a new AVD.

INTERNATIONAL CONTINENT-WIDE VERTICAL DATUMS

The AHD is unique in that it is realised from a single levelling network traversing an entire continent. The US and Canada exhibit the most comparable experiences to Australia with respect to national vertical datums, primarily because of their continental extent bounded by oceans. The US's first national vertical datum was the Mean Sea Level Datum of 1929 (MSLD1929) but referred to since 1973 as the National Geodetic Vertical Datum of 1929 (NGVD29) (Lachapelle and Gareau 1980). This resulted from a least-squares adjustment (LSA) of the US and Canadian levelling networks, adopting MSL (tide-gauge observation epoch unknown) as its zero-reference at 26 tide-gauges (21 US; five Canadian) (Zilkoski *et al*. 1992). Canada did not adopt the MSLD1929, instead retaining the previously published heights from the Canadian Geodetic Vertical Datum of 1928 (CGVD1928), which adopted MSL as the zero-reference at five tide-gauges (Lachapelle and Gareau, 1980). Note that the MSLD1929 and the CGVD1928, like the AHD (more than 60 years later), adopted MSL observed at multiple tide gauges (thus neglecting the effects of SSTop) for defining its zero-reference.

In a massive task, new levelling and gravity surveys, plus readjustment programs began in the US and Canada in 1977 (Whalen 1980; Boal *et al*. 1985), resulting in the North American Vertical Datum 1988 (NAVD88) (Zilkoski *et al*., 1992), which was the US's second national vertical datum. However, Canada chose not to adopt NAVD88 due to unexplained discrepancies between the east and west coasts (e.g. Carrera 1984; Vaníček *et al*. 1985), with the CGVD1928 still its 'official' vertical datum. NAVD88 uses the Helmert orthometric height system (Helmert 1890) and is referenced to MSL at a single tide-gauge located at Father Point/Rimouski (Canada), at the mouth of the St. Lawrence River (Zilkoski *et al*. 1992).

The most significant issue in the establishment of continent-wide vertical datums is the accumulation of systematic errors in the levelling network over the vast distances to be covered (e.g., Entin 1959; Angus-Leppan 1975; Vaníček *et al*. 1980; Balazs and Young 1982; Morgan 1992; Craymer *et al*. 1995; Rüeger 1997), and the possibility of gross errors in low-redundancy regions of the network (e.g., Filmer and Featherstone 2009). This is highlighted by discrepancies between NGVD29 and NAVD88 of between −0.40 m and +1.50 m (Zilkoski *et al*. 1992), to which uplift or subsidence could also contribute (e.g., Carrera 1984; Chi and Reilinger 1984).

Incompatibility between $h - N$ and NAVD88 Helmert orthometric H ranging between $\pm$1.50 m led to a pragmatic solution (Milbert 1995; Smith and Milbert 1999; Smith and Roman 2001), where a gravimetric geoid model was 'fitted' to the NAVD88 at 2951 GNSS/levelling points to provide a 'product' (cf. Vermeer 1998) that would enable users to directly realise NAVD88 from GNSS h, a strategy recently adopted in Australia (Featherstone *et al*. 2011; Brown *et al*. 2011). Both the US and Canada have begun development towards a new vertical datum that is based on a geoid model (Véronneau *et al*. 2006; NGS 2007; 2008; Rangelova *et al*. 2009; Smith and Edwards 2010) rather than a levelling network constrained to MSL, termed a geoid-only vertical datum (see later for a definition and discussion).

By contrast to the continent-wide vertical datums of Australia, the US and Canada, European vertical datums have been characterised by separate (usually national) levelling networks using different height systems and tide-gauges to define MSL (e.g., Marti and Schlatter 2002; Christie 1994), so the collective European vertical datums cannot really be considered a continent-wide vertical datum. Moves to unify the European vertical datums through a combination of levelling networks, tide-gauge records, gravity measurements and GNSS observed h are described in Ihde and Sánchez (2005), but this unification is not yet complete. The European approach using levelling networks referenced to MSL at a single tide-gauge (Normaal Amsterdams Peil [NAP]), but underpinned by a GNSS-derived network of h and a gravimetric quasigeoid model (Ihde *et al*. 2002), differs from the geoid-only approach of the US and Canada to vertical datum re-definition (cf. Véronneau *et al*. 2006).

South American (e.g., Sánchez 2002; Luz *et al*. 2002; de Freitas *et al*. 2002) and African (e.g., Merry 2003) vertical datums are, like Europe, a collection of different national vertical datums established as separate levelling networks using local MSL as their zero-reference, and as such are also not considered continent-wide vertical datums comparable with the AHD, NAVD88 or CGVD28. Ihde and Sánchez (2005) propose that the European approach be adopted to connect separate national vertical datums in South America, in contrast to the geoid-only approach of the US and Canada. However, this European approach appears to be hindered by the generally lower quality levelling networks in many South American and African countries. Merry (2003) discusses proposals for the unification of African vertical datums, but at this stage GNSS/levelling points are only publicly available in Algeria, Egypt and South Africa.

OPTION 1: A LEVELLING-ONLY NEW AVD

A levelling-only vertical datum is defined here as a national levelling network constrained at one or more tide-gauges, with the zero reference defined by local MSL only or local MSL that has been corrected by a SSTop model to yield a better estimate of the quasi/geoid. The most common type of national vertical datum is where the levelling network is fixed to MSL at one tide-gauge in a national adjustment (e.g., Vaníček 1991; Zilkoski *et al*. 1992; Christie 1994; Ihde *et al*. 2002; Yang *et al*. 2003; Ses and Mohamed 2009; Abeyratne *et al*. 2010). The AHD and CGVD28 are possibly the only current large national vertical datums where the levelling network is fixed (with the exception of one tide-gauge in the CGVD) (Lachapelle and Gareau 1980) to MSL at multiple tide-gauges. To the authors' knowledge, there are no 'official' national vertical datums where the levelling network has been constrained to MSL plus SSTop at tide-gauges (cf. Filmer *et al*. 2011).

It should be noted that both the levelling-only and combined vertical datum (see later) can be approximately, but indirectly realised in areas where BMs are sparse or non-existent through $h - N$, as is currently the case in most countries. N, or its 'fitted' geometric approximation can be interpolated from the available grid (e.g., 1 arc-minute by 1 arc-minute for AUSGeoid09) provided the horizontal position of the required point is available (GNSS can provide this). However, the accuracy to which the vertical datum can be accessed through this method is variable, due to the quasi/geoid and vertical datum zero-reference not being coincident. This problem should be reduced considerably, but not eliminated by upgrading/renewing the vertical datum, as stated in point 1 of the Introduction. The advantages of a levelling-only vertical datum compared to combined and geoid-only vertical datums (herein described under options 2 and 3, respectively) are:

1) The vertical datum is independent of $h - N$, so it can be used to validate global and regional quasi/geoid models, or other height datasets (and *vice versa*) (e.g., Featherstone and Guo 2001; Claessens *et al*. 2009; Hirt *et al*. 2010), in combination with alternative methods such as deflections of the vertical from digital zenith cameras (e.g., Hirt and Flury 2008; Voight *et al*. 2009) or airborne gravimetry (e.g., Schwarz and Li 1996);
2) Benchmarks (BMs) with heights directly related to the vertical datum are available for users; users can access the heights without the need for access to carrier-phase GNSS technology;
3) High local precision from levelling, whereas GNSS is less accurate in the height component, especially over short distances. Out to a few tens of kilometres, levelling provides the more accurate approach to relative height determination.

However, levelling-only vertical datums have a number of disadvantages (cf. Véronneau *et al*. 2006; NGS 2008), particularly relating to the quality of the levelling networks used:

1) Long-wavelength systematic and gross levelling errors (particularly in low-quality vertical datums such as the AHD) introduce distortions (cf. Featherstone and Filmer 2008), making it difficult to accurately realise the vertical datum from $h - N$ (h and N errors notwithstanding);
2) A levelling network needs periodic upgrades, plus ongoing maintenance (observations and BMs), which is costly. In addition, as a levelling-only vertical datum ages, it suffers degradation in integrity from subsidence and uplift (briefly discussed earlier) and the deliberate or accidental removal of BMs.

Fixing a levelling-only vertical datum to MSL (with or without SSTop corrections) at one tide-gauge could be effective with a high quality levelling network of limited extent e.g., Taiwan (Yang *et al*. 2003) or Malaysia (Ses and Mohamed 2009). However, for large levelling networks covering entire continents such as Australia, systematic levelling errors accumulating over long distances and/or gross errors in poorly-checked sections degrade the resulting heights (e.g., Morgan 1992; Filmer and Featherstone 2009). Where errors in levelling networks that connect tide-gauges become larger than MSL and SSTop errors at those tide-gauges (e.g., Filmer 2011, Chapter 5), fixing the levelling network at only one tide-gauge becomes a less attractive option (cf. Zilkoski *et al*. 1992).

On the other hand, adopting local MSL (with no SSTop corrections) at multiple tide-gauges (e.g., Roelse *et al*. 1971; Zilkoski *et al*. 1992) remains an option. However, this is the same strategy as used to realise the current AHD. Because the vertical offset between tide-gauge-observed MSL and the quasi/geoid (i.e., the mean local SSTop) is different at each tide-gauge, changing principally in the north-south direction in Australian coastal regions (by ~0.7 m), the problem with the north-south slope is likely to be present in any new AVD that adopts uncorrected MSL as its zero-reference. As such, this option is not considered appropriate for any new AVD.

We consider the best solution is to constrain (not fix) (e.g., Filmer *et al*. 2011) the levelling network to multiple tide-gauges, but with modelled mean local SSTop removed from MSL at each tide-gauge as a more accurate approximation of the quasi/geoid (e.g., Merry and Vaníček 1983). The respective errors from the levelling, MSL and SSTop can then be appropriately weighted in the LSA to account for discrepancies between the multiple tide-gauge observations. This approach is also suggested by Vaníček (1991), but is dependent on the accuracy of MSL and SSTop at each tide-gauge (see later section on data issues). MSL observations are generally of high precision, but modelling SSTop in coastal regions is problematic (e.g., Hipkin 2000), so that the accuracy of modelled SSTop is likely to be a limiting factor for this approach. Testing with oceanographic, geodetic, and combined oceanographic-geodetic modelled SSTop in Australian coastal regions by Filmer (2011, Chapter 5) suggest that oceanographic SSTop models are now of sufficient accuracy that using multiple tide-gauges with an SSTop model is now a realistic option if a levelling-only vertical datum constrained at multiple tide gauges becomes the preferred choice for Australia.

Although there are advantages for using a levelling-only vertical datum, these are often overshadowed by the high costs of upgrading and maintaining the levelling network (Véronneau *et al*. 2006), particularly if the network has been neglected for a period of time. However, it is desirable that the levelling network be kept in reasonable condition, as it is of considerable importance for testing height-related data, which indirectly contribute to the quality of height data sets/products developed for industry users. Consequently, historical levelling data should not be simply 'thrown away' as they will remain a valuable resource.

OPTION 2: A COMBINED NEW AVD

A combined vertical datum is defined here as one that combines SSTop-corrected MSL observed at multiple tide-gauges and $h - N$ at appropriately chosen points across the continent to define the zero-reference, but also relies on the levelling network (constrained to $h - N$ and SSTop-corrected MSL) to propagate the heights throughout the network that are connected to BMs. Here, h come from high-precision GNSS surveys and N come from a gravimetric quasi/geoid. Basically, all available height-related data are used to define the vertical datum, while also maintaining the past and current expectations that there are BMs to transfer heights for local projects.

Kearsley *et al*. (1993), Ahmad *et al*. (1993) and Hwang (1997) have all discussed the concept of a combined vertical datum (cf. Milbert 1988), while Filmer *et al*. (2011) present a numerical validation that this type of vertical datum is potentially viable for Australia. Australia is relatively well placed to consider this option, given access to over 100 tide-gauges along its entire coastline, the availability of AGQG09 and its successors, and the increasing number of GNSS observations across the continent (cf. Brown *et al*. 2011). The advantages in adopting this combined approach are:

1) BMs with heights directly related to the vertical datum are available for users, so that they can access the heights without having access to carrier-phase GNSS technology;

2) High localised (over a few tens of kilometres) precision from levelling;
3) Long-wavelength systematic and gross levelling errors, plus the 'noisy' nature of ANLN third-order levelling can be controlled by $h - N$ and MSL plus SSTop constraints to improve the accuracy of the transformation to the vertical datum from GNSS h using gravimetric N. Therefore, there may be less need to update the levelling network than for a levelling-only vertical datum. Moreover, the use of the additional constraints can be used to locate problematic levelling sections, which would otherwise not be detected by the poor redundancy of a levelling-only adjustment (Filmer and Featherstone 2009).

Despite the above-argued advantages over levelling- and geoid-only vertical datums, the combined vertical datum does have disadvantages:

1) The vertical datum will not be independent of $h - N$ as these observations are used as constraints, so a combined vertical datum cannot be used to validate global and regional quasi/geoid models (and *vice versa*), although "unofficial" adjustments of the levelling network without $h - N$ constraints could be used for quasi/geoid validation purposes (e.g., Featherstone *et al*. 2011);
2) The combined vertical datum can be more accurately realised from $h - N$ observations (compared to the levelling-only vertical datum). However, unresolved residuals between H and $h - N$ will remain, due to levelling, MSL plus SSTop and $h - N$ errors, although these may be only a few cm if the data sets are improved (see later);
3) The levelling network still needs to be upgraded and maintained, particularly through the provision of BMs, although there may be less need for new levelling than for the levelling-only datum because of the improved redundancy.

The major advantage of a combined vertical datum compared to a levelling-only vertical datum is the $h - N$ constraints that allow the long-wavelength levelling errors to be reduced (assuming that there are smaller long-wavelength errors in the quasi/geoid model). However, they are not completely removed (depending on error estimates for each data set), although improvements to data quality (discussed later) may decrease discrepancies between $h - N$ and H from a combined vertical datum to a few cm (cf. Filmer *et al*. 2011).

OPTION 3: A GEOID-ONLY NEW AVD

A geoid-only vertical datum (could also be quasigeoid-only, but the term geoid-only herein refers to both) is defined here as being determined solely by a specified gravimetric quasi/geoid model and ellipsoidal heights referred discretely to a specific geodetic datum, or reference frame (e.g., GDA or ITRF) at the stations of the regional GNSS network. Longer term, it is plausible that such a vertical datum would not necessarily contain BMs, or any levelling component, but that datum 'infill' would consist of continuously operating GNSS reference stations (CORS). The improvement (and further anticipated improvement) in accuracy of gravimetric quasi/geoid models through dedicated satellite gravimetry missions (e.g., Arabelos and Tscherning 2001) has prompted discussion and development in the area of geoid-only vertical datums (e.g., Véronneau *et al*. 2006; NGS 2008; Rangelova *et al*. 2009).

Geoid-only vertical datums are particularly attractive because:

1) They can avoid the expense and associated problems of maintaining and upgrading levelling networks (e.g., Christie 1994; Véronneau *et al*. 2006; NGS 2008; Smith and Edwards 2010);
2) Users can directly access the vertical datum using GNSS technology at any location of their choice as opposed to having to transfer control from BMs (cf. Featherstone and Dent 2002), or accept the approximate value of the levelling-based H from $h - N$ in areas with sparse or no BMs;
3) Time-dependent gravity causes only small variations in the quasi/geoid model (Véronneau *et al*. 2006; Rangelova *et al*. 2009; Smith and Edwards 2010), so geoid-only vertical datums appear to have an advantage in longevity compared to vertical datums that incorporate levelling, and are susceptible to large changes in the topographic surface (e.g., earthquake ruptures or other subsidence/uplift). However, these events are relatively rare in Australia (cf. Wellman and Tracey 1987; Dentith and Featherstone 2003; Dawson *et al*. 2008).

However, although a geoid-only vertical datum may seem like an 'easy fix', there are a number of issues that would need resolving. The disadvantages of a geoid-only vertical datum are:

1) BMs with published heights related to the geoid-only vertical datum will not be available for users unless the BMs have a previously observed GNSS h. Thus, users without ready access to carrier phase GNSS technology may not be able to fully access the vertical datum, unless BMs with GNSS h are specifically added by the responsible geodetic agency. For h to be measured with a GNSS receiver to an accuracy such that the geoid-only vertical datum can be realised at the cm level (in the absence of BMs), a carrier phase GNSS receiver would have to be placed continuously for a long period of time, which may be inconvenient (and uneconomic);
2) Although considered inexpensive to maintain, to achieve adequate local precision, the terrestrial gravity database will need to be improved. This will be at considerable expense, even if provided/supplemented by airborne gravimetry (e.g., NGS 2007), though the latter is likely to be less than the cost of re-levelling an entire continent (NGS 2008);
3) Local relative precision (subject to h and N errors) is not likely to be as high as that provided by levelling, because levelling is more precise than $h - N$ over short distances (say, tens of kilometres). It is not yet known fully if airborne and satellite gravimetry will provide the required level of accuracy for a vertical datum that is equivalent to third-order standard (or better), particularly in mountainous and coastal regions (cf. Serpas and Jekeli 2005; Hwang *et al*. 2007; NGS 2008);
4) Though a lesser point geoid-only vertical datums cannot (unlike high quality levelling-only vertical datums) independently validate new global and regional quasi/geoid models.

While development of geoid-only vertical datums is progressing, there are no geoid-only vertical datums (as defined here) in operation yet. The New Zealand Vertical Datum 2009 (NZVD2009) uses the New Zealand Quasigeoid 2009 (NZGeoid2009) (Claessens *et al*. 2011) as its zero-reference. However, NZVD2009 is used in conjunction with levelling-based LVDs using the normal-orthometric height system (Amos and Featherstone 2009) and therefore cannot be considered a geoid-only vertical datum under the definition used here, but rather as a geoid-*based* vertical datum, where minor levelling networks are connected through a quasigeoid model.

An alternative to pursuing a 'pure' geoid-only vertical datum for Australia, is to consider a geoid-based vertical datum, where the relatively higher-quality levelling surrounding Australia's major cities and settled areas could be considered as localised (but isolated) levelling networks. These localised levelling networks could be connected into a homogenous national vertical datum through a quasi/geoid model (cf. Amos and Featherstone 2009), thus retaining the localised precision of levelling, but avoiding the need for continent-wide levelling (and the associated problems) to form a new AVD. However, a problem with this approach is that it will cause fragmentation to Australia's vertical spatial data infrastructure.

It is likely that some of the disadvantages listed here for geoid-only vertical datums will be overcome sometime in the future (cf. Véronneau *et al*. 2006; NGS 2008; Rangelova *et al*. 2009), and although Australia could develop a geoid-only datum using currently available data, it is questionable whether its accuracy would be considered satisfactory just at this time. Importantly, this is not a complete exclusion of this option, where the concepts of geoid-*only* versus geoid-*based* vertical datums can also be considered. Over time, quasi/geoid models are likely to refine, especially with new data sources from dedicated satellite gravimetry and the increased coverage of terrestrial and airborne data, the latter being driven principally in Australia by resource exploration. However, dense and accurate gravity coverage in less prospective areas would have to be publicly funded.

DATA-DRIVEN ISSUES FOR NEW AUSTRALIAN HEIGHTS

The relative merits of the three proposed vertical datum options are highly dependent on the quality and availability of the necessary data. Indeed, the major impediment in developing a new AVD (of any type) at the current time is the low-quality and incomplete data available. A brief discussion on the different datasets available and the additional measures required to bring them up to an acceptable standard follows.

The ANLN

The ANLN has numerous problems that will need some attention if it is to be used as the basis for a levelling-only or combined vertical datum and also be kept in reasonable shape for scientific purposes. The ANLN database is not a complete record of levelling completed in Australia, because hard-copy records of levelling completed since the AHD was established are held at State and Territory geodetic agencies, but are not included in the ANLN database. The extent of such levelling data is currently unknown. However, the authors are aware of levelling in hard-copy format (in Western and South Australia) that is not in the current version of the ANLN (although Landgate continues to update the ANLN with Western Australian data, and some levelling has been obtained from South Australia), and it is likely that this situation exists at other States/Territories. The inclusion of this extra data would greatly improve the strength and veracity of the ANLN.

A more critical deficiency is that only the average of the observed (mostly) (see Filmer and Featherstone 2009) two-way levelled height differences are held in the ANLN. This is a considerable problem when attempting to identify systematic and other levelling errors in the ANLN. For instance, combinations and permutations of forward and reverse traverses cannot be used to locate problematic sections, even with the inclusion of $h - N$ as quasi observations (cf. Filmer and Featherstone 2009). The omission of additional information such as time and date of observation and weather conditions (if ever recorded) would also be required for retrospective atmospheric refraction corrections to be applied to the levelling (cf. Holdahl 1981; Filmer 2011, Chapters 3 and 4). Furthermore, most ANLN BM positions (ϕ, λ) are only accurate to the nearest one arc-minute, which becomes an issue when attempting to interpolate observed gravity to the BMs to apply gravimetric height corrections to the levelling, introducing errors into the resulting heights (cf. Filmer and Featherstone 2011a)

It is likely that additional levelling may be required to correct identified errors, although it is highly recommended that field books containing suspect sections are first checked for typographic/transcription error, thus reducing cost. However, many State and Territory geodetic agencies are currently suffering staffing deficiencies, so this is improbable. The use of GNSS and

AGQG09 could be used to identify erroneous ANLN sub-sections in the field, thus avoiding the requirement to re-level entire ANLN sections to find a single gross error (e.g., Kearsley *et al*. 1993; Poutanen 1999; Filmer and Featherstone 2009). Faster levelling methods such as motorised and/or total station levelling (as distinct from trigonometrical heighting) may have a role to play where additional re-levelling is needed.

Basically, a cost-benefit analysis would be needed. The risk of degrading any new AVD by including levelling data of suspect quality will need to be balanced by the risk of removing too much of the levelling network such that the redundancy of the network is compromised, and BM coverage is significantly reduced in some regions.

Tide-gauge records and SSTop models

The availability of uninterrupted tide-gauge records of MSL (with levelling connections to the ANLN) for a period of 18.6 years to reduce the effect of the lunar nodal tide and other long period tides (cf. Vaníček 1978; Amin 1993; Shaw and Tsimplis 2010) is uncertain (cf. Dando and Mitchell 2010). While MSL from the 32 tide-gauges used in the AHD (30 mainland and two in Tasmania) and their levelling connections to the ANLN are available, they predominately relate to a three year mean, which is likely to be contaminated by a combination of errors in the mechanical tide-gauges (Mitchell 1973), local coastal variations due to the shape of the seabed and ocean currents (cf. Merry and Vaníček 1983), and their placement in harbours located on or near rivers (e.g., Mitchell 1973; Merry and Vaníček 1983; Morgan 1992). Vertical instability of the tide-gauges due to the structure on which the tide-gauge is mounted (cf. Mitchell 1973), coastal land subsidence (e.g., Belperio 1993), crustal movement and glacial isostatic adjustment (GIA) (e.g., Bouin and Wöppelmann 2010) contribute to further uncertainty in the MSL value.

Additional observations beyond the three year period used for the AHD are available from the 32 AHD tide-gauges, plus other mechanical tide-gauges, but the temporal compatibility of these data must then be considered because secular sea-level changes may approach 20 mm per decade (Church and White 2006). Moreover, many of these additional tide-gauges do not have levelling connections to the ANLN that are readily available, while their geodetic position (ϕ, λ) is often only accurate to the nearest arc-minute (needed for interpolating SSTop and/or geoid models to the tide-gauge position). The Australian SEAFRAME tide-gauges provide accurate sea-level observations over nearly 20 years, but are sparsely distributed around the coastline, and do not all have levelling connections to the current version of the ANLN.

Gravity data

Terrestrial gravity data in Australia (e.g., Murray 1997) have a number of deficiencies (e.g., Bellamy and Lodwick 1968; Fraser *et al*. 1976; Barlow 1977), whether being used in new gravimetric quasi/geoid models (e.g., Featherstone *et al*. 2011) that could be developed into geoid-only vertical datums, or to compute height corrections for the ANLN (e.g., Filmer *et al*. 2010; Filmer and Featherstone 2011a) to improve the quality of levelling-only or combined vertical datums. These deficiencies stem from a combination of height errors in the gravity stations (primarily the result of non-homogenous methods of height measurement: e.g., barometric, ellipsoid, ellipsoid and (unknown) quasi/geoid, and levelling), uncertainties of 500 m or more in the horizontal position (ϕ, λ) of the gravity station, and long-wavelength errors over the entire continent (cf. Featherstone 2005).

However, the availability of satellite data from the Gravity Recovery and Climate Experiment (GRACE) (e.g., Tapley *et al*. 2004a; 2004b) and GOCE missions has improved the long- and medium-wavelength constituents of the Australian quasigeoid. Indeed, Arabelos and Tscherning (2001), Drinkwater *et al*. (2003) and Johannessen *et al*. (2003) all predict that GOCE will realise 1 cm geoid accuracy at spatial resolution of 100 km. This makes the prospect of an Australian geoid-only vertical datum more realistic, but will also improve the accuracy of interpolated gravity at ANLN BMs for gravimetric height corrections (e.g., Filmer *et al*. 2010), and thus will also benefit levelling-only and combined vertical datums. However, for a geoid-only vertical datum (option 3), the spatial resolution of the GOCE models must be improved by the addition of terrestrial or airborne gravity data.

GNSS data

The large amount of GNSS data available across Australia improves the quality of all three vertical datum options: it can be used in closure checks for levelling-only vertical datums (Filmer and Featherstone 2009); it can be used as a constraint in combined vertical datums (Filmer *et al.* 2011), and it is a vital element in geoid-only or geoid-based vertical datums. However, GNSS-derived heights are generally inferior to precise levelling at the localised level (say, <20 km), and are also restricted when used to approximate physical-type heights (e.g., orthometric or normal heights) by the quality of the gravimetric quasi/geoid model. Moreover, their effectiveness as constraints for combined vertical datums, or for testing against levelling-only vertical datums is considerably hindered where the levelled connection to the ANLN is of dubious quality (cf. Filmer and Featherstone 2009).

The current situation, where derived AHD heights at the GNSS station rather than the observed two-way levelling connection between the GNSS station and the ANLN being provided with GNSS data, further increases the likelihood of an erroneous connection. An additional problem may arise where GNSS stations may be tens of km from the nearest ANLN junction point (JP), so that the GNSS station is connected to (or is) a local BM. Any levelling error between the BM and the nearest JP will then introduce a bias into the GNSS-ANLN JP height difference. This is an issue that needs attention, so that apparent differences between any new levelling-based AVD and $h - N$ are not merely the result of incorrect levelling connections between GNSS stations and the ANLN.

CONCLUDING REMARKS

The primary aim of this paper is to “put the issues on the table” so as to help contribute to and hopefully inform any debate on Australia’s future in the third dimension. It is now left open to discuss which of the three options, outlined (or variants thereof) is most suitable for Australia’s long term-future. There are some other considerations, however, including the requirements for improvements in the available data, utility within any future global vertical datum, and consideration of time-dependent heights that could lead to a dynamic vertical datum.

All three proposed vertical datum types have merit, and although it would appear that a geoid-only (or geoid-based) vertical datum is likely to be the preferred long-term option, this is dependent on improvements to Australian gravity data. This is particularly so in the high-frequency component if a centimetre-accurate quasi/geoid is to be realised. There are also a number of other issues that need addressing before a geoid-only vertical datum could be successfully implemented, such that a combined vertical datum that provides large improvements over the AHD may be the best option in the interim. This would require improvement in some parts of the ANLN that are known to be problematic. A levelling-only vertical datum is not likely to be adequate for a new AVD, unless significant re-levelling of many parts of the ANLN was to occur. This seems unlikely, as it would prove rather costly and time-consuming. However, it is recommended that some repairs are made to the levelling network, so that an improved ('unofficial') version of a levelling-only vertical datum can be used for validating new height-based products and other scientific purposes.

DISCLAIMER: The Inter-governmental Committee on Surveying and Mapping (ICSM) has stated that the AHD will remain Australia's 'official' vertical datum for the foreseeable future, so this paper is only intended to initiate and inform debate rather than foreshadow any new AVD.

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REFERENCES

Abeyratne, P.G.V., Featherstone, W.E. and Tantrigoda, D.A. (2010) On the geodetic datums in Sri Lanka. *Survey Review*, vol. 42, no. 317, pp. 229-239, doi: 10.1179/003962610X12572516251880.

Ahmad, Z., Kearsley, A.H.W. and Harvey, B.R. (1993) Optimising GPS, geoid and tide gauge heights in vertical control networks. In: Kearsley, A.H.W., ed. *UNISURV Report S43*. University of New South Wales, Sydney, pp. 127-209.

Amin, M. (1993) Changing mean sea level and tidal constants on the west coast of Australia. *Australian Journal of Marine and Freshwater Research*, vol. 44, no. 6, pp. 911-925, doi:10.1071/MF9930911.

Amos, M.J., and Featherstone, W.E. (2009) Unification of New Zealand’s local vertical datums: iterative gravimetric quasigeoid computations. *Journal of Geodesy*, vol. 83, no. 1, pp. 57-68, doi: 10.1007/s00190-008-0232-y.

Angus-Leppan, P.V. (1975) An investigation of possible systematic errors in levelling along the eastern coast of Australia. In: *UNISURV Report G23*. University of New South Wales, Sydney, pp. 80-91.

Arabelos, D. and Tscherning, C.C. (2001) Improvements in height datum transfer expected from the GOCE mission. *Journal of Geodesy*, vol. 75, no. 5-6, pp. 308-312, doi:10.1007/s001900100187.

Balasubramania, N. (1994) Definition and realization of a global vertical datum. *Report 427*, The Ohio State University, Columbus, USA.

Balazs, E. I., and Young, G.M. (1982) Corrections applied by the National Geodetic Survey to precise leveling observations. NOAA Technical Memorandum 34, National Geodetic Survey, Rockville, USA.

Barlow, B.C. (1977) Data limitations on model complexity; 2-D gravity modelling with desk-top calculators. *Bulletin of the Australian Society of Exploration Geophysics*, vol. 8, no. 4, pp. 139-143, doi:10.1071/EG977139.

Bellamy, C.J. and Lodwick, G.D. (1968) The reduction of barometric networks and field gravity surveys. *Survey Review*, vol. 19, no. 147, pp. 216-227, doi: 10.1071/EG977139.

Belperio, A.P. (1993) Land subsidence and sea-level rise in the Port Adelaide estuary: Implications for monitoring the greenhouse effect. *Australian Journal of Earth Sciences*, vol. 40, no. 4, pp. 359-368, doi:10.1080/08120099308728087.

Boal, D., Gareau, R. and Young, F. (1985) Status of vertical control networks in Canada. In: *Proceedings of the Third International Symposium on the North American Vertical Datum - NAVD Symposium '85*. National Oceanic and Atmospheric Administration, Rockville, USA, pp. 1-10.

Bouin, M.N. and Wöppelmann, G. (2010) Land motion estimates from GPS at tide gauges: a geophysical evaluation. *Geophysical Journal International*, vol. 180, no. 1, pp. 193-209, doi:10.1111/j.1365-246X.2009.04411.x.

Brown, N.J., Featherstone, W.E., Hu, G. and Johnston, G.M. (2011) AUSGeoid09: a more direct and more accurate method of converting ellipsoidal heights to AHD heights, *Journal of Spatial Science* vol. 56, no. 1, pp. 27-37, doi: 10.1080/14498596.2011.580498.

Carrera, G.H. (1984) Heights on a deforming Earth. *Technical Report 107*, University of New Brunswick, Fredricton, Canada.

Chi, S.C. and Reilinger, R.E. (1984) Geodetic evidence for subsidence due to groundwater withdrawal in many parts of the United States of America. *Journal of Hydrology*, vol, 67, no. 1-4, pp. 155-182, doi:10.1016/0022-1694(84)90239-7.

Christie, R.R. (1994) A new geodetic heighting strategy for Great Britain. *Survey Review*, vol. 32, no. 252, pp. 328-343.

Church, J.A. and White, N.J. (2006) A 20th century acceleration in global sea-level rise. *Geophysical Research Letters*, vol. 33, article no. L01602, doi:10.1029/2005GL024826.

Claessens, S. J., Hirt, C., Amos, M.J., Featherstone, W.E. and Kirby, J.F. (2011) The NZGEOID09 model of New Zealand. *Survey Review*, vol. 43, no. 319, pp. 2-15, doi:10.1179/003962610X12747001420780.

Claessens, S.J., Featherstone, W.E., Anjasmara, I.M. and Filmer, M.S. (2009) Is Australian data really validating EGM2008, or is EGM2008 just in/validating Australian data? *Newton's Bulletin*, vol. 4, pp. 207-251.

Colombo, O.L. (1980) A world vertical network. *Report 296*, The Ohio State University, Columbus, USA.

Craymer, M. R., Vaníček, P. and Castle, R.O. (1995) Estimation of rod scale errors in geodetic levelling. *Journal of Geophysical Research*, vol. 100, no. B8, pp. 15,129-15,145, doi:10.1029/95JB00614.

Dando, N.J. and Mitchell, W. (2010) Reconciling height datums in Australia: the bathymetric component. *Final report for the Co-operative Research Centre for Spatial Information CRC-SI Project 1.14*, Geoscience Australia, Catalogue no. 70624, http://www.ga.gov.au/cedda/publications/47.

Dawson, J.H. (2008) Satellite radar interferometry with application to the observation of surface deformation in Australia. *PhD Dissertation*, Australian National University, Canberra, Australia.

Dawson, J.H., Cummins, P., Tregoning, P. and Leonard, M. (2008) Shallow intraplate earthquakes in Western Australia observed by interferometric synthetic radar. *Journal of Geophysical Research*, vol. 113, article no. B11408, doi:10.1029/2008JB005807.

de Freitas, S.R.C., Schwab, S.H.S., Marone, E., Pires, A.O. and Dalazoana, R. (2002) Local effects in the Brazilian vertical datum. In: Ádám, J. and Schwarz, K.-P., eds. *Vistas for Geodesy in the New Millenium.* Springer, Berlin, pp. 102-107.

Dentith, M.C. and Featherstone, W.E. (2003) Controls on intra-plate seismicity in southwestern Australia. *Tectonophysics*, vol. 376, no. 3-4, pp. 167-184, doi:10.1016/j.tecto.2003.10.002.

Drinkwater, M.R., Floberghagen, R., Haagmans, R., Muzi, D. and Popescu, A. (2003) GOCE: ESA's first Earth explorer core mission. *Space Science Reviews*, vol. 108, no. 1-2, pp. 419-432, doi:10.1023/A:1026104216284.

Entin, I. (1959) Main systematic errors in precise levelling. *Bulletin Géodésique*, vol. 33, no. 2, pp. 37–45, doi:10.1007/BF02526861.

Featherstone, W.E. (1998) Do we need a gravimetric geoid or a model of the Australian Height Datum to transform GPS heights in Australia? *The Australian Surveyor*, vol. 43, no. 4, pp. 273-280.

Featherstone, W.E. (2000) Towards the unification of the Australian Height Datum between mainland and Tasmania using GPS and AUSGeoid98. *Geomatics Research Australasia*, vol. 73, pp. 33-54.

Featherstone, W.E. (2002) Prospects for the Australian Height Datum and geoid model. In: Ádám, J. and Schwarz, K.-P., eds. *Vistas for Geodesy in the New Millenium.* Springer, Berlin, pp. 96-101.

Featherstone, W.E. (2004) Evidence of a north-south trend between AUSGeoid98 and the AHD in southwest Australia. *Survey Review*, vol. 37, no. 291, pp. 334-343.

Featherstone, W. E. (2005). Long-wavelength discrepancies between the Australian gravity field and EIGEN-2 CHAMP data. In: Sansó, F., ed. *A Window on the Future of Geodesy*. Springer, Berlin, pp. 300-305.

Featherstone, W.E. (2006) Yet more evidence for a north-south slope in the AHD. *Journal of Spatial Science*, vol. 51, no. 2, pp. 1-6.

Featherstone, W.E. (2008) GNSS-heighting in Australia: current and emerging issues. *Journal of Spatial Science*, vol. 53, no. 2, pp. 115-133.

Featherstone, W.E. and Dent, V. (2002) Transfer of vertical control using only one GPS receiver: a case study. *The Australian Surveyor*, vol. 47, no. 1, pp. 31-37.

Featherstone, W.E. and Filmer, M.S. (2008) A new GPS-quasigeoid-based evaluation of distortions in the Australian Height Datum in Western Australia. *Journal of the Royal Society of Western Australia*, vol. 91, no. 2, pp. 199-206.

Featherstone, W. E. and Guo W. (2001) Evaluations of the precision of AUSGeoid98 versus AUSGeoid93 using GPS and Australian height datum data. *Geomatics Research Australasia*, vol. 74, pp. 75-102.

Featherstone, W.E. and Kuhn, M. (2006) Height systems and vertical datums: a review in the Australian context. *Journal of Spatial Science.*, vol. 51, no. 1, pp. 21-42.

Featherstone, W.E. and Sproule, D.M. (2006) Fitting AUSGeoid98 to the Australian Height Datum using GPS-levelling and least squares collocation: application of a cross-validation technique. *Survey Review*, vol. 38, no. 301, pp. 573-582.

Featherstone, W.E., Kirby, J.F., Hirt, C., Filmer, M.S., Claessens, S.J., Brown, N.J., Hu, G. and Johnston, G.M. (2011) The AUSGeoid09 model of the Australian Height Datum. *Journal of Geodesy*, vol. 85, no. 3, pp. 133-150, doi: 10.1007/s00190-010-0422-2.

Filmer, M.S. (2011) An examination of the Australian Height datum. *PhD Dissertation*, Curtin University of Technology, Perth, Australia.

Filmer, M.S. and Featherstone, W.E. (2009) Detecting spirit-levelling errors in the AHD: recent findings and some issues for any new Australian height datum. *Australian Journal of Earth Sciences*, vol. 56, no. 4, pp. 559-569, doi: 10.1080/08120090902806305.

Filmer, M.S., Featherstone, W.E. and Kuhn, M. (2010) The effect of EGM2008-based normal, normal-orthometric and Helmert orthometric height systems on the Australian levelling network, *Journal of Geodesy*, vol. 84, no. 8, pp. 501-513, doi: 10.1007/s00190-010-0388-0.

Filmer, M.S. and W.E. Featherstone (2011a) Error propagation for three common height-system corrections to differential levelling, *Journal of Spatial Science* vol. 56, no. 1, pp. 39-58, doi:10.1080/14498596.2011.567410.

Filmer, M.S. and Featherstone, W.E. (2011b) A re-evaluation of the Australian Height Datum offset between mainland Australia and Tasmania, *Marine Geodesy* (submitted).

Filmer, M.S., Featherstone, W.E. and Claessens, S.J. (2011) Upgrading a local vertical datum from a combined adjustment of a levelling network, a sea surface topography model, GNSS and quasigeoid, *Journal of Geodesy* (submitted).

Fraser, A.R., Moss, F.J. and Turpie, A. (1976) Reconnaissance gravity survey of Australia. *Geophysics*, vol 41, no. 6, pp. 1337-1345, doi: 10.1190/1.1440683.

Granger, H.W. (1972) The Australian Height Datum. *The Australian Surveyor*, vol. 24, no. 4, pp. 228-237.

Helmert, F.R. (1890) Die Schwerkraft im Hochgebirge, Insbesondere in den Tyroler Alpen (Gravity in high mountains with focus on the Tyrol Alps). No. 1, Veröff. Königl. Preuss. Geod. Inst.

Hipkin, R. 2000. Modelling the geoid and sea-surface topography in coastal areas. *Physics and Chemistry of the Earth (A)*, vol. 25, no. 1, pp. 9-16, doi:10.1016/S1464-1895(00)00003-X.

Hirt, C., Filmer, M.S. and Featherstone, W.E. (2010) Comparison and validation of recent freely-available digital elevation models ASTER-GDEM ver1, SRTM ver4.1 and GEODATA DEM-9S ver3 digital elevation models over Australia. *Australian Journal of Earth Sciences,* vol. 57, no. 3, pp. 337-347, doi:10.1080/08120091003677553.

Hirt, C. and Flury, J. (2008) Astronomical-topographic levelling using high-precision astrogeodetic vertical deflections and digital terrain model data. *Journal of Geodesy*, vol. 82, no. 4–5, pp. 231–248, doi:10.1007/s00190-007-0173.

Holdahl, S.R. (1981) A model of temperature stratification for correction of levelling refraction. *Bulletin Géodésique*, vol. 55, no. 3, pp. 231-249, doi:10.1007/BF02530864.

Holloway, R. (1988) The integration of GPS heights into the Australian Height Datum. *UNISURV Report S-33*, University of New South Wales, Sydney.

Hwang, C. (1997) Height system of Taiwan from satellite and terrestrial data. *Journal of Surveying Engineering,* vol. 123, no. 4, no. 162-180, doi:10.1061/(ASCE)0733-9453.

Hwang, C., Hsiao, Y.S., Shih, H.C., Yang, M., Chen, K.H., Forsberg, R. and Olesan, A.V. (2007) Geodetic and geophysical results from a Taiwan airborne gravity survey: Data reduction and accuracy assessment. *Journal of Geophysical Research*, vol. 112, article no. B04407, doi:10.1029/2005JB004220.

Ihde, J. Augath, W. and Sacher, M. (2002) The vertical reference system for Europe. In: Drewes. H., Dodson, A.H., Fortes, L.P.S., Sánchez, L. and Sandoval P., eds. *Vertical Reference Systems*. Springer, Berlin, pp. 345-350.

Ihde, J. and Sánchez, L. (2005) A unified global height reference system as a basis for IGGOS. *Journal of Geodynamics*, vol. 40, no. 4-5, pp. 400-413, doi:10.1016/j.jog.2005.06.015.

Iliffe, J., Ziebart, M., Cross, P., Forsberg, R., Strykowski, G. and Tscherning, C. (2003) OGSM02: a new model for converting GPS-derived heights to local height datums in Great Britain and Ireland. *Survey Review,* vol. 37, no. 290, pp. 276-293.

Johannessen, J.A., Balmino, G., Le Provost, C., Rummel, R., Sabadini, R., Sünkel, H., Tscherning, C.C., Visser, P., Woodworth, P., Hughes, C.W., Legrand, P., Sneeuw, N., Perosanz, F., Aguirre-Martinez, M., Rebhan, H. and Drinkwater, M. (2003) The European gravity field and steady-state ocean circulation explorer satellite mission: its impact on geophysics. *Surveys in Geophysics*, vol. 24, no. 4, pp. 339-386, doi:10.1023/B:GEOP.0000004264.04667.5e.

Kearsley, A.H.W., Rush, G.J. and O'Donnell, P.W. (1988) The Australian Height Datum - problems and proposals. *The Australian Surveyor*, vol. 34, no. 4, pp.363-380.

Kearsley, A.H.W., Ahmad, Z. and Chan, A. (1993) National height datums, levelling, GPS heights and geoids. *Australian Journal of Geodesy, Photogrammetry and Surveying*, vol. 59, pp. 53-88.

Lachapelle, G. and Gareau, R. (1980) Status of geodetic vertical networks in Canada. In: Lachapelle, G., ed. *Second International Symposium on Problems Related to the Redefinition of the North American Vertical Geodetic Networks: NAD Symposium 1980, Ottawa, Canada*. Canadian Institute of Surveying, pp. 49-71.

Luz, R. T., Guimarães, V.M., Rodrigues, A.C. and Correia, J.D. (2002). Brazilian first order levelling network. In: Drewes. H., Dodson, A.H., Fortes, L.P.S., Sánchez, L. and Sandoval P., eds. *Vertical Reference Systems*. Springer, Berlin, pp. 20-22.

Marti, U. and Schlatter, A. (2002) The new height system in Switzerland. In: Drewes. H., Dodson, A.H., Fortes, L.P.S., Sánchez, L. and Sandoval P., eds. *Vertical Reference Systems*. Springer, Berlin, pp. 50-55.

Merry, C.L. (2003) The African geoid project and its relevance to the unification of African vertical reference frames. In *Proceedings of the 2nd. FIG Regional Conference, Marrekech, Morocco*. www.fig.net/pub/morocco/proceedings/TS9/TS9 3 merry.pdf.

Merry, C.L. and Vaníček, P. (1983) Investigation of local variations of sea-surface topography. *Marine Geodesy*, vol. 7, no. 1-4, pp. 101-126, doi:10.1080/15210608309379477.

Milbert, D.G. (1988) Treatment of geodetic levelling in the integrated geodesy approach. *Report 396*, The Ohio State University, Columbus, USA.

Milbert, D.G. (1995) Improvement of a high resolution geoid height model in the United States by GPS height on NAVD 88 benchmarks. *New geoids in the world*, IGes bulletin 4, International Geoid Service, Milan, pp. 13-36.

Mitchell, H.L. (1973) Relations between mean sea level and geodetic levelling in Australia. *UNISURV Report S-9*, University of New South Wales, Sydney.

Morgan, P. (1992) An analysis of the Australian Height Datum: 1971. *The Australian Surveyor*, vol. 37, no. 1, pp. 46-63.

Murray, A. (1997) The Australian national gravity database, *AGSO Journal of Australian Geology & Geophysics*, vol, 17, no. 1, pp. 145-155.

NGS, (2007) The GRAV-D project: gravity for the redefinition of the American vertical datum, Report, National Geodetic Survey, http://www.ngs.noaa.gov/GRAV-D/pubs/GRAV-D_v2007_12_19.pdf.

NGS (2008) The National Geodetic Survey ten-year plan: mission, vision and strategy 2008-2018, Report, National Geodetic Survey, http://www.ngs.noaa.gov/INFO/NGS10yearplan.pdf.

Pavlis, N.K., Holmes, S.A., Kenyon, S.C. and Factor, J.K. (2008) An Earth gravitational model to degree 2160: EGM2008. *Presented at EGU-2008*, Vienna, Austria, April 13-18, http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/index.html.

Poutanen, M. (1999) Use of GPS in unification of vertical datums and detection of levelling network errors. In: Lilje, M., ed. *Geodesy and surveying in the future – The Importance of Heights*. Gävle, Sweden, pp. 301-312.

Rangelova, E., Sideris, M.G. and Fotopoulos, G. (2009) A dynamic reference surface for heights in Canada. *Geomatica*, vol. 63, no. 4, pp. 333-340.

Rapp, R.H. (1994) Separation between reference surfaces of selected vertical datums. *Bulletin Géodésique*, vol. 69, no. 1, pp. 26-31, doi: 10.1007/BF00807989.

Rapp, R.H. and Balasubramania, N. (1992) A conceptual formulation of a world height system. *Report 427*, The Ohio State University, Columbus, USA.

Ridgway, K.R., Dunn, J.R., and Wilkin, J.L. (2002) Ocean interpolation by four-dimensional weighted least squares-application to the waters around Australasia. *Journal of Atmospheric and Oceanic Technology*, vol. 19, no. 9, pp. 1357-1375.

Rizos, C., Coleman, R., and Ananga, N. (1991) The Bass Strait GPS survey: preliminary results of an experiment to connect Australian height datums. *Australian Journal of Geodesy, Photogrammetry and Surveying*, vol. 55, pp. 1-25.

Roelse, A., Granger, H.W. and Graham, J.W. (1971; 1975, 2nd. ed) The adjustment of the Australian levelling survey 1970-1971. *Technical Report 12*, Division of National Mapping, Canberra, Australia.

Rüeger, J.M. (1997) Staff errors in and the adjustment of ordinary levelling runs. *The Australian Surveyor*, vol. 42, no. 1, pp. 16–24.

Rummel, R. and Teunissen, P. (1988) Height datum definition, height datum connection and the role of the geodetic boundary value problem. *Bulletin Géodésique*, vol. 62, no. 4, pp. 477-498, doi:10.1007/BF02520239.

Sánchez, L. (2002) A reference surface for the unified height system in the northern part of South America. In: Ádám, J. and Schwarz, K.-P., eds. *Vistas for Geodesy in the New Millenium.* Springer, Berlin, pp. 84-89.

Schwarz, K-P. and Li, Y.C. (1996) What can airborne gravimetry contribute to geoid determination? *Journal of Geophysical Research*, vol. 101, no. B8, pp. 17,873-17,881, doi:10.1029/96JB00819.

Serpas, J.G. and Jekeli, C. (2005) Local geoid determination from airborne vector gravimetry. *Journal of Geodesy*, vol. 78, pp. 577-587. doi:10.1007/s00190-004-0416-z.

Ses, S. and Mohamed, A. (2009) The second precise levelling network of peninsular Malaysia. *Survey Review*, vol. 41, no. 314, pp. 384-394, doi:10.1179/003962609X451627.

Shaw, A.G.P., and Tsimplis, M.N. (2010) The 18.6 yr nodal modulation in the tides of Southern European coasts. *Continental Shelf Research*, vol. 30, no. 2, pp. 138-151, doi:10.1016/j.csr.2009.10.006.

Smith, D.A., and Edwards, K. (2010) Taking the “Boulder” step from static to dynamic geoid, *Eos*, vol. 91, no. 5, p. 46.

Smith, D.A. and Milbert, D.G. (1999). The GEOID96 high-resolution geoid height model for the United States. *Journal of Geodesy*, vol. 73, no.5, pp. 219-236, doi:10.1007/s001900050239.

Smith, D. A. and Roman, D.R. (2001). GEOID99 and G99SSS: 1-arc-minute geoid models for the United States. *Journal of Geodesy*, vol. 75, no. 9-10, pp. 469-490, doi:10.1007/s001900100200.

Tapley, B.D., Bettadpur, S., Ries, J.C., Thompson, P.F. and Watkins, M.M. (2004a) GRACE measurements of mass variability in the Earth system. *Science*, vol. 305, no. 5683, pp. 503-505, doi:10.1126/science.1099192.

Tapley, B.D., Bettadpur, S., Watkins, M. and Reigber, C. (2004b) The gravity recovery and climate experiment: Mission overview and early results. *Geophysical Research Letters*, vol. 31, article L09607, doi:10.1029/2004GL019920.

Tregoning, P. and Jackson, R (1999) The need for dynamic datums, *Geomatics Research Australasia* 71: 87-102.

Vaníček, P. (1978) To the problem of noise reduction in sea-level records used in vertical crustal movement detection. *Physics of the Earth and Planetary Interiors*, vol. 17, no. 3, pp. 265-280. doi:10.1016/0031-9201(78)90041-9.

Vaníček, P. (1991) Vertical datum and NAVD 88. *Surveying and Land Information Systems*, vol. 51, no. 2, pp. 83-86.

Vaníček, P., Carrera, G.H. and Craymer, M.R. (1985) Corrections for systematic errors in the Canadian levelling network. Contract Report 85-001, Geodetic Survey of Canada.

Vaníček, P. Castle, R.O. and Balazs, E.I. (1980) Geodetic levelling and its applications. *Reviews of Geophysics and Space Physics*, vol. 18, no. 2, pp. 505-524, doi: 10.1029/RG018i002p00505.

Vermeer, M. (1998) The geoid as a product. *Report 98*, no. 4, pp. 63-69, Finnish Geodetic Institute, Helsinki.

Véronneau, M., Duval, R., and Huang, J. (2006) A gravimetric geoid model as a vertical datum in Canada. *Geomatica*, vol. 60, no. 2, pp. 165-172.

Voigt, C., Denker, H. and Hirt, C. (2009) Regional astrogeodetic validation of GPS/levelling data and quasigeoid models. In: Sideris M.G., ed. *Observing our changing Earth*, Springer, New York, pp 413–420.

Wellman, P. and Tracey, R. (1987) Southwest seismic zone of Western Australia: measurement of vertical ground movements by repeat levelling and gravity measurements. *BMR Journal of Australian Geology and Geophysics*, vol. 10, pp. 225-232.

Whalen, C.T. (1980) Status of the national geodetic vertical control network in the United States. In: Lachapelle, G., ed. *Second International Symposium on Problems Related to the Redefinition of the North American Vertical Geodetic Networks: NAD Symposium 1980, Ottawa, Canada*. Canadian Institute of Surveying, pp. 11-24.

Yang, M., Chen, K.H., and Shiao, S.W. (2003) A new height reference network in Taiwan. *Survey Review*, vol. 37, no. 290, pp. 260-268.

Zilkoski, D.B., Richards, J.H. and Young, G.M. (1992) Results of the general adjustment of the North American Vertical Datum of 1988. *Surveying and Land Information Systems*, vol. 52, pp. 133-149.