Marine Geodesy [submitted]

A re-evaluation of the offset in the Australian Height Datum between mainland Australia and Tasmania

M.S. FILMER AND W.E. FEATHERSTONE

Mick Filmer (corresponding author)
Western Australian Centre for Geodesy & The Institute for Geoscience Research,
Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia
Telephone: +61-8-9266-2218
Fax: +61-8-9266-2703
Email: M.Filmer@curtin.edu.au

Will Featherstone
Western Australian Centre for Geodesy & The Institute for Geoscience Research,
Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia
Telephone: +61-8-9266-2734
Fax: +61-8-9266-2703
Email: W.Featherstone@curtin.edu.au

The adoption of local mean sea level (MSL) at multiple tide-gauges as a zero reference level for the Australian Height Datum (AHD) has resulted in a spatially variable offset between the geoid and the AHD. This is caused primarily by sea surface topography (SSTop), which has also resulted in the AHD on the mainland being offset vertically from the AHD on the island of Tasmania. Errors in MSL observations at the 32 tide-gauges used in the AHD and the temporal bias caused by MSL observations over different time epochs also contribute to the offset, which previous studies estimate to be between ~+100 mm and ~+400 mm (AHD on the mainland above the AHD on Tasmania). This study uses five SSTop models (SSTMs), as well as GNSS and two gravimetric quasigeoid models, at tide-gauges/tide-gauge benchmarks to re-estimate the AHD offset, with the re-evaluated offset between -61 mm and +48 mm. Adopting the more reliable CARS2006 oceanographic-only SSTM, the offset is -12±11 mm, an order of magnitude less than three previous studies that used geodetic data alone. This suggests that oceanographically derived SSTMs should be considered as a viable alternative to geodetic-only techniques when attempting to unify local vertical datums.

Keywords: AHD, mean sea level, sea surface topography modelling, vertical datum unification

Address correspondence to M.S. Filmer. Email: M.Filmer@curtin.edu.au

Introduction

The Australian Height Datum (AHD) was established on the Australian mainland (referred to here as AHD(mainland)) from a least-squares adjustment (LSA) of the then-called Australian Levelling Survey in 1971, fixed to mean sea level (MSL; held to zero height) at 30 tide-gauges (Roelse et al. 1971). MSL for the AHD(mainland) was observed between 1966 and 1968, but with the exception of the Karumba tide-gauge, where MSL was observed between 1957 and 1960. The AHD was established in Tasmania (referred to here as AHD(Tas)) in 1983 through an LSA of the Tasmanian levelling network fixed to MSL (held to zero height) at two tide-gauges for which MSL was observed for only one whole year in 1972 (ICSM 2006, Chapter 8). Hence, the zero-reference level for

AHD(mainland) is observed local MSL for 1966-1968 (Karumba tide-gauge excepted), but the zero-reference level for AHD(Tas) is observed local MSL for 1972.

As such, the AHD(mainland) and AHD(Tas) are technically separate local vertical datums (LVDs) that may be offset vertically from one another. The short period over which MSL was observed at these tide-gauges means that the local MSL estimates at the different tide-gauges are likely to contain biases with respect to the true MSL (see next Section). However, these short-term MSL estimates define the zero-references of the AHD(mainland) and AHD(Tas). It is the offset between these imperfectly determined zero-references that we seek to estimate.

Mean sea surface topography (SSTop) is the spatially varying difference between MSL and the geoid (e.g., Mather 1974; 1975; Merry and Vaníček 1983; Pugh 1987; Hipkin 2000), and is probably a larger cause of any AHD(mainland) – AHD(Tas) offset (herein referred to as O_{Tas}) than the short and different periods over which local MSL was observed. We adopt the sign convention that positive O_{Tas} indicates AHD(mainland) is above AHD(Tas). Determining O_{Tas} is further complicated by the variability of SSTop at different locations around the Australian coastline and over different observation epochs (cf. Hamon and Greig 1972; Mitchell 1973; Coleman et al. 1979; Mather 1979) (see later). An accurate determination of O_{Tas} is needed if AHD(mainland) and AHD(Tas) are to be unified into any single national vertical datum, although in this study, we are not officially unifying AHD(mainland) and AHD(Tas), but testing the methodology and currently available datasets (see Data and Methods Section).

While most estimates of LVD offsets are made using geodetic methods (e.g., Rummel and Teunissen 1988; Catalao and Sevilla 2009; Zhang et al. 2009; Amos and Featherstone 2009; Ardalan et al. 2010), or (geodetic) SSTop modelled from satellite altimetry-derived mean sea surface (MSS) minus gravimetric geoid models at tide-gauges (e.g., Fenoglio and Groten 1995), this study also uses SSTop values modelled only from oceanographic information (Section 3), which is rarely used to estimate LVD offsets (cf. Merry and Vaníček 1983).

Three previous estimates of O_{Tas} have been made by Rizos et al. (1991), Rapp (1994) and Featherstone (2000) using GPS (Global Positioning System) and quasi/geoid models of varying vintage and quality.

1) Rizos et al. (1991) used GPS-observed ellipsoid heights (h) and height anomalies (ζ) computed from the OSU89A global gravitational model (Rapp and Pavlis 1990) to degree and order 360, augmented by local terrestrial gravity observations to add the high-frequency component of ζ. Rizos et al. (1991) used three tide-gauge benchmarks (TGBMs) located on the Victorian coastline at Point Lonsdale, Portland and Lakes Entrance, and three on the northern Tasmanian coastline at Stanley, Burnie and Low Head (cf. Figure 1). The AHD height (H) used at each TGBM is dependent on the levelling connecting the TGBM to the AHD tide-gauges where the AHD zero-reference was defined (see Section 3 for the discussion on levelling errors). Rizos et al.'s (1991) estimate of O_{Tas} was ~+100 mm, although this was later revised up to ~+400 mm (Featherstone 2000). No error estimates were provided.

2) Rapp (1994) used GPS observations and a combination of the JGM-2 (Nerem et al. 1994; degrees 2 to 70) and OSU91A (Rapp et al. 1991; degrees 71 to 360) global gravitational models from unspecified locations distributed across Australia (85 on the mainland, four on Tasmania) as part of a global study, calculating O_{Tas} to be ~+300 mm. Again, no error estimates were provided, but this estimate is likely to have a larger error than Rizos et al.'s (1991) estimate because the high-frequency component of ζ was not modelled. However, Rapp's (1994) study does not account for the spatial variation of O_{Tas} (cf. Featherstone 2000).

3) Featherstone (2000) conducted a study similar to Rapp (1994), but using 1,013 co-located GPS-AHD heights and the AUSGeoid98 regional geoid model (Featherstone et al. 2001) across Australia, finding O_{Tas} to be +260±330 mm. However, due to the ~1 m north-south slope in the AHD(mainland) (e.g., Featherstone 2004, 2006), and ~0.5 m regional distortions in the AHD (e.g., Filmer and Featherstone 2009), the estimate of O_{Tas} was highly dependent on the location of the GPS stations used (Featherstone 2000). In addition to the nation-wide study that produced a spatially

variable O_{Tas}, Featherstone (2000) attempted to replicate the study of Rizos et al. (1991). This used a subset of 13 GPS-AUSGeoid98 stations along the northern Tasmanian coastline and six along the Victorian coastline, estimating O_{Tas} to be +(120±120) mm.

Thus, two definitions of O_{Tas} have been used: i) the mean offset for the two entire datums (Rapp 1994; Featherstone 2000); and ii) the mean offset between the Victorian and northern Tasmanian coastlines (Rizos et al. 1991; Featherstone 2000).

Definition of O_{Tas}

The spatially variable non-alignment of the AHD with the geoid makes any estimate of O_{Tas} problematic. There are numerous reasons why local MSL is offset from the geoid by different amounts at the different tide-gauges used to define the AHD. SSTop comprises most of this offset, hence the use of modelled SSTop as an estimate of O_{Tas}. However, there are other errors that contribute to this offset, including the short and different tide-gauge observation periods of MSL, tide-gauge malfunction, poor siting of the tide-gauge (e.g., near rivers or in estuaries), vertical movement of the land/structure to which the tide-gauge is fixed (e.g., tectonic motion), spatially variable sea level change, and medium/long period atmospheric or oceanographic events.

As it is difficult to reliably quantify error contributions from each of these sources, crude estimates have to be made. The pole tide has a Chandler period of 433 days, so can affect the one-year MSL observations in AHD(Tas), but its amplitude is only ~10 mm (Currie 1975). The lunar perigee tide has a period of 8.85 years, which can bias three- and one-year MSL observations and has a maximum amplitude of ~20 mm. The lunar node tide has a period of 18.61 years, which is the recommended period for tide-gauge observation of MSL to capture the full tidal signature (e.g., Featherstone and Kuhn 2006). However, the magnitude of error resulting from the time-limited MSL observations and its effect on the AHD is not clear (Dando and Mitchell 2010). Vaníček (1978) modelled a maximum nodal tide of ~20 mm at several northern US sites, but Amin (1993) observed a maximum nodal tide amplitude of up to 47 mm in northern Australia, with Shaw and Tsimplis (2010) observing a maximum amplitude of ~50 mm at an eastern Atlantic tide-gauge. However, Amin (1993) found the nodal tide to decrease for observations in south west Australia, suggesting that the nodal tide may only bias the AHD MSL observations along the southern coast of Australia by ~20 mm.

Mitchell (1973) investigated possible errors in AHD MSL observations, noting that several types of faults in the automatic tide-gauges could cause errors. Some are difficult to discover or quantify, although Mitchell (1973, p. 154) estimates that these errors may amount to a few tens of mm, but are site-dependent. The placement of AHD tide-gauges near rivers, so that the outflow of freshwater affects MSL was also identified by Easton (1968), Easton and Radok (1970), Mitchell (1973) and Morgan (1992). The AHD tide-gauges used in this study comprise: Point Lonsdale, Port Fairy, Burnie and Hobart (Figure 1).

The Point Lonsdale tide-gauge was at the entrance to a bay and installed near the end of a jetty. The Port Fairy tide-gauge was located at the end of a breakwater but only 100 m from the mouth of a river (Easton 1968). No detailed location information is available on the Hobart and Burnie tide-gauges, but it is likely that they are located in harbours as both are port cities. Easton and Radok (1970) summarise AHD tide-gauges during the 1966-1968 period, commenting that Point Lonsdale was an excellent tide-gauge installation, but that Port Fairy had some data gaps and was not adequately checked, and Burnie was not checked regularly. Hobart appears to have adequate records. MSL from the non-AHD tide-gauges of Portland, Lorne and Stony Point in Victoria, and Devonport and Spring Bay in Tasmania (Figure 1) were not used in the AHD definition. These additional tide-gauges/TGBMs are used to add redundancy for the tests in Section 3 but observed MSL was not used. Therefore, MSL errors at these non-AHD locations are not relevant to this study.

Local MSL adopted for the AHD will contain MSL observation errors, but the observed values are what define the AHD zero-reference. These errors are likely to be higher for the two Tasmanian AHD tide-gauges, as these used only one year of observation. In addition, the

AHD(mainland) adopted 1966-1968 local MSL while AHD(Tas) adopted 1972 local MSL. Hence, the true value of O_{Tas} will be contaminated by errors in MSL observations at the different tide-gauges and any variation in MSL from the 1966-1968 and 1972 epochs. However, as O_{Tas} is a relative value, any errors common to mainland and Tasmanian tide-gauges will cancel (e.g., systematic sea-level change).

Strictly, O_{Tas} should only be estimated between AHD tide-gauges (or closely connected TGBMs) where the AHD is defined with respect to local MSL, and thus less sensitive to levelling errors. This is because the AHD zero-reference is defined only at AHD tide-gauges, so any point afar from the AHD tide-gauge is subject to errors in the levelling. However, due to the spatial variability of SSTop, O_{Tas} will still depend on which AHD tide-gauges are selected (cf. Featherstone 2000). An examination of modelled SSTop (see next Section) indicates that its spatial variability along the Victorian and northern Tasmanian coastlines is no more than ~20 mm, with levelling between tide-gauges and reasonably close TGBMs containing relatively small errors (details later). Thus, using non-AHD tide-gauges to provide redundancy, and therefore a more reliable estimate of O_{Tas}, should be beneficial, i.e., by reducing the influence of site-dependent errors on estimated O_{Tas}.

We first define O_{Tas} as the mean difference between SSTop along the Victorian and northern Tasmanian coastlines at five Victorian tide-gauges or their TGBMs (Portland, Port Fairy, Lorne, Point Lonsdale, and Stony Point; Figure 1) and two northern Tasmanian tide-gauges or their TGBMs (Burnie and Devonport; Figure 1). This O_{Tas} definition is later refined with two additional tide-gauges in southern Tasmania (Hobart and Spring Bay; Figure 1) used to determine if there is any north-south slope in AHD(Tas), as there is in AHD(mainland) (Featherstone 2000; 2004; 2006). If no AHD(Tas) slope is detected, Hobart and Spring Bay will be used to add redundancy to the O_{Tas} estimate.

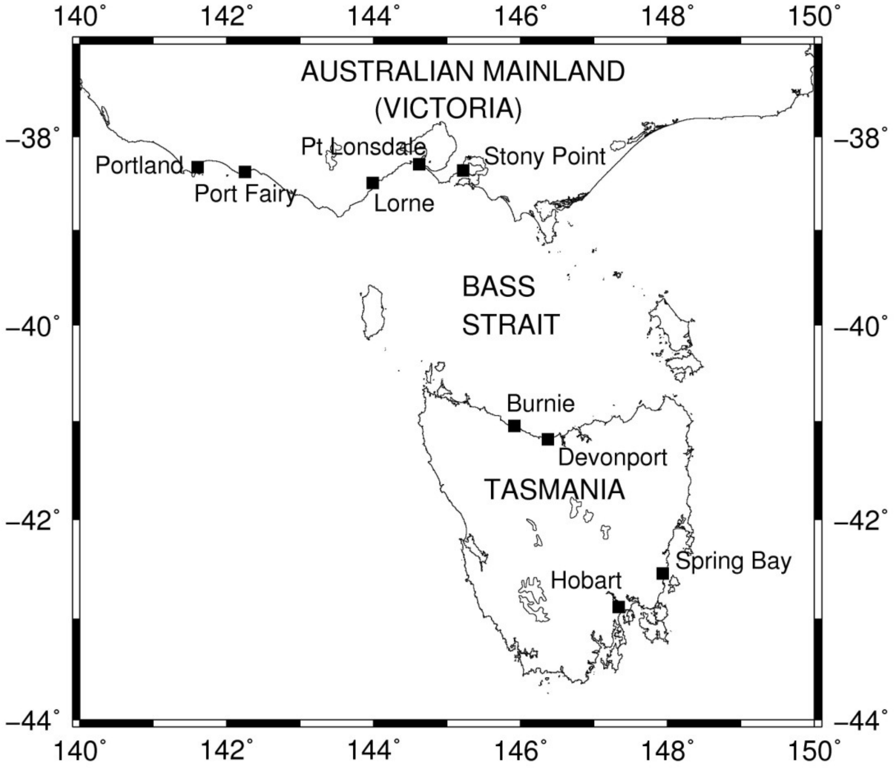

Figure 1. AHD(mainland) and AHD(Tas) tide-gauges (black squares) used to estimate O_{Tas}.

Mercator projection.

Data and methods

The SSTop models (SSTMs) used comprise: CSIRO Atlas of Regional Seas 2006 (CARS2006; Ridgway et al. 2002; an oceanographic-only model); Rio05 combined mean dynamic topography (Rio05 CMDT; Rio and Hernandez 2004; a combined geodetic-oceanographic model); GRACE Gravity Model 02 dynamic ocean topography (GGM02 DOT; Tapley et al. 2003; 2005; a geodetic-only model); a second DOT model from GRACE/JPL (http://grace.jpl.nasa.gov/data/dot/) DOT_DNSC08 MSS-EGM08_gau_ave_111km_dpc.txt (herein referred to as JPL08; available at ftp://podaac.jpl.nasa.gov/pub/tellus/dot/200808/; a geodetic-only model); and the Danish National Space Centre 2008 MDT (DNSC08 MDT; Andersen and Knudsen 2009; a geodetic-only model).

The GNSS (Global Navigation Satellite Systems) h at tide gauges or their TGBMs come from a nation-wide set of 1,052 3D GNSS geodetic coordinates (Hu 2009, supplied by Geoscience Australia; N. Brown 2009, pers. comm.) in the International Terrestrial Reference Frame 2005 (ITRF2005; Altamimi et al. 2007) at epoch 2000. The two quasigeoid models used are the gravimetric component of the regional AUSGeoid09 model (AGQG09; Featherstone et al. 2011) and the EGM2008 global gravitational model (Pavlis et al. 2008).

The estimated standard deviation (STD; 1σ) for most GNSS h at TGBMs (σ_h) is ~±5 mm, but reaches ±16 mm for Devonport TGBM (Brown 2009, pers. comm.). Estimating errors for the other data is more problematic, because there are no formal error estimates for AGQG09 or CARS2006, and although EGM2008 commission error over Australia is shown to be ~50 mm (Pavlis et al. 2008), determining the omission error is more difficult. Featherstone et al. (2011) found that the 'fit' of AGQG09 at ~1000 GNSS points to a LSA of the ANLN fixed at 32 AHD tide-gauges to SSTop-corrected MSL was ±130 mm. However, this value is a coarse estimate for all Australia, and may be inflated by levelling errors and GNSS h blunders (e.g., antenna height errors) so is likely to be an upper estimate for the TGBMs used in this study. Quasigeoid modelling in coastal regions is problematic, due mostly to sparse gravity coverage, errors in satellite-altimeter-derived gravity anomalies close to the coast and steep geoid gradients at some coastal boundaries (e.g., Hipkin 2000). Even allowing for this, we "guesstimate" that AGQG09 (and also assumed for EGM2008) STD at the TGBMs (σ_ζ) for this study is ~±100 mm.

No formal CARS2006 error estimate is available, but Rio and Hernandez (2005) estimate that Rio05 has an RMS of ±(100 – 140) mm in areas of strong currents and ±(40 – 50) mm in low variability regions. From this, we suggest that an error of ~±100 mm is possible for Rio05 and CARS2006 in coastal regions, with GGM02 error perhaps ~±150 mm. Andersen and Knudsen (2009) estimate an approximate error of ±(90 – 120) mm for DNSC08 MDT, but have found outliers of up to 0.80 m compared to tide-gauges in the UK, suggesting that high-frequency noise can degrade DNSC08 MDT in coastal regions.

Two methods to estimate O_{Tas} are used; one using the SSTMs and the other using TGBM h (h_{TGBM}) and ζ at the TGBM (ζ_{TGBM}). These are independent methods, thus adding to the veracity of the results compared to the previous GNSS-quasigeoid-only assessments (cf. Rizos et al. 1991; Rapp 1994; Featherstone 2000).

Method 1: The SSTM LVD unification method computes differences between geodetically and oceanographically modelled SSTop values at the Victorian and Tasmanian tide-gauges in Figure 1. SSTop values were extrapolated to the tide-gauge positions from the various SSTM grids using tensioned splines in the GMT package (Smith and Wessel 1990; Wessel and Smith 1998). The mean of the differences (Victoria minus Tasmania) for each SSTM is adopted as the O_{Tas} estimate, with the standard deviation (STD) used as a proxy for the standard error for each. As such, this error estimate ignores errors in the SSTM values themselves and their extrapolation to the tide-gauges or TGBMs, also noting that SSTop is difficult to model oceanographically in the coastal zone (e.g., Merry and Vaníček 1983; Hipkin 2000; Dunn and Ridgway 2002).

Method 1 assumes that O_{Tas} comprises only SSTop and is estimated by modelled mean SSTop. It excludes any errors in the AHD MSL observations (e.g., Coleman et al. 1979; Mitchell 1973) (cf. previous Section) that may contaminate the true value of O_{Tas}. As such, the error estimates quoted herein (Tables 1 and 2) are the relative errors between modelled mean SSTop at the location of the tide-gauges used. SSTop is also temporally variable so that the epoch for each data set (e.g., CARS2006 contains oceanographic data from the last 50 years and Rio05 contains satellite altimetry data between 1993-1999) do not exactly coincide with the mean SSTop in 1966-1968 or 1972. However, it is currently not possible to estimate this error reliably (cf. Dando and Mitchell 2010).

Method 2: The GNSS-quasigeoid LVD unification method first computes the AHD offset (O_{AHD}) from the quasigeoid model at the tide-gauge or TGBM (cf. Featherstone 2000)

$$O_{AHD} = (h_{TGBM} - \zeta_{TGBM}) - H_{TGBM} \tag{1}$$

where H_{TGBM} is the AHD normal-orthometric height of the TGBM. It is assumed that O_{AHD} at the closest AHD tide-gauge is the same as (or very close to) O_{AHD} at the TGBM. For the AHD tide-gauges in Victoria (Point Lonsdale and Port Fairy) and Tasmania (Burnie and Hobart), the distance between the TGBM and the tide-gauge is generally <2 km (cf. Hipkin et al. 2004). However, TGBMs for non-AHD tide-gauges (Lorne, Stony Point, Portland, Devonport and Spring Bay) are considerably further from the AHD tide-gauges and thus depend upon the levelling connection. For third-order levelling, the STD will propagate according to $4.2\sqrt{d}$ mm (cf. Kearsley et al 1993; Filmer and Featherstone 2009; Filmer et al. 2011) where d is the distance between the AHD tide-gauge and TGBM.

For example, the distance between the Portland TGBM and Port Fairy AHD tide-gauge is ~70 km, while Port Lonsdale AHD tide-gauge to Lorne and Stony Point TGBMs is ~100 km, resulting in STDs for the AHD height at the TGBMs of ±35 mm and ±42 mm, respectively. The distances between the Burnie AHD tide-gauge and Devonport TGBM and Hobart AHD tide-gauge and Spring Bay TGBM are also ~70-100 km, so a maximum STD estimate for AHD heights at TGBMs (σ_H) of ±40 mm appears reasonable. Thus, using the linear propagation of independent variances, an estimate of total O_{AHD} error could be as large as ±108 mm computed as $\sqrt{\sigma_h^2 + \sigma_\zeta^2 + \sigma_H^2}$, where σ_h is ±10 mm, σ_ζ is ±100 mm, and σ_H is ±40 mm.

O_{AHD} is thus an estimate of SSTop at the tide-gauge, with O_{Tas} then computed as the average of the differences between O_{AHD} at the Victorian and Tasmanian TGBMs. Because O_{Tas} is a relative rather than absolute value, it is likely that the error in GNSS-ζ estimated O_{Tas} may be somewhat less than ±108 mm, as any long-wavelength errors in AGQG09 and EGM2008 may be common to the Tasmanian and Victorian tide-gauges. It is also assumed that the quasigeoid is coincident with the geoid and the levelled AHD normal-orthometric height is coincident with a normal height (and thus compatible with the quasigeoid) (cf. Filmer et al. 2010), which is a reasonable assumption given the low-lying topography close to the coasts.

Unlike the SSTM estimate of O_{Tas}, any MSL errors at AHD tide-gauges, or levelling errors between non-AHD TGBMs and AHD tide-gauges will contaminate the GNSS-quasigeoid-implied O_{Tas} through O_{AHD} (Equation 1). The GNSS-quasigeoid method is essentially the same as that used by Rizos et al. (1991), Rapp (1994) and Featherstone (2000), and thus subject to largely the same error sources. The GNSS-quasigeoid-implied O_{Tas} is, in theory, most likely to replicate 'true' O_{Tas} than the SSTM method because it includes the MSL observation errors at the AHD tide-gauges, and also the temporal effect of using MSL from different epochs. However, it remains to be seen whether the quasigeoid models will have the necessary accuracy for this method to be sufficiently reliable. The SSTM method relies on the assumption that O_{Tas} is predominately SSTop, and that MSL errors at AHD tide-gauges and the different epochs make only a minor contribution to O_{Tas}.

O_{Tas} is first estimated using five Victorian (Portland, Port Fairy, Point Lonsdale, Lorne and Stony Point) and two northern Tasmanian (Burnie and Devonport) tide-gauges for both SSTM and GNSS-quasigeoid methods (10 differences). Subsequently, differences between SSTop at Burnie and Devonport tide-gauges, and two southern Tasmanian tide-gauges (Spring Bay and Hobart) are used to determine whether there is any north-south slope in the AHD(Tas) (cf. Featherstone 2004, 2006). The absence of any statistically significant north-south AHD(Tas) slope (see next Section) suggests that an O_{Tas} estimate using all four Tasmanian tide-gauges (Figure 1) can be used to provide additional redundancy (20 versus 10 differences), for both the GNSS-quasigeoid method (Equation 1), and the SSTM method.

Results and Discussion

Estimates of O_{Tas} using five Victorian tide-gauges and two northern Tasmanian tide-gauges are shown in Table 1. O_{Tas} (represented by the means in Table 1) varies depending on the data used, but is between -58 mm (Rio05) and +48 mm (JPL08). Recall that a positive value indicates that AHD(mainland) is above AHD(Tas) and *vice versa*. The smaller STDs for CARS2006-, Rio05-, GGM02- and JPL08-derived O_{Tas} indicate that these results are more reliable, although this could also be interpreted as the smoothness of the SSTMs rather than their precision. The STDs for O_{Tas} are much less than the ±100 mm STD 'guesstimates' for the individual SSTM values at tide-gauges, suggesting that the redundancy from using five Victorian and two Tasmanian tide-gauges has provided a more reliable O_{Tas}, but also that the SSTMs have generally performed better than could be expected from their 'guesstimated' formal errors. O_{Tas} from DNSC08 MDT of -20 mm is similar to the other SSTM-based estimates, but the larger STD of ±145 mm (cf. Andersen and Knudsen's (2009) error estimate of ±(90-120) mm) indicate that this SSTM is not suitable for estimating O_{Tas} because it appears to contain a lot of noise in these coastal regions.

	SSTM method					GNSS-quasigeoid method	
Statistic	CARS2006	Rio05	GGM02	JPL08	DNSC08	AGQG09	EGM2008
Mean or O_{Tas}	-3	-58	+42	+48	-20	-12	-33
Max	+7	-31	+49	+77	+147	+67	+78
Min	-12	-81	+33	+18	-306	-90	-167
STD	±6	±17	±6	±24	±145	±52	±78
B-H	-22	-1	-15	-30	-8	+53	+42

Table 1. Statistics for O_{Tas} (in mm) between five Victorian and two northern Tasmanian tide-gauges (cf. Figure 1) for five SSTM and two GNSS-quasigeoid estimates. The bottom row (B-H) shows height differences between MSL at Burnie and Hobart tide-gauges. Positive O_{Tas} indicates that AHD(mainland) is above AHD(Tas).

From Table 1, the AGQG09- and EGM2008-implied O_{Tas} (-12±52 mm and -33±78 mm, respectively) are within the range of the SSTM-implied O_{Tas} estimates, but exhibit relatively large STDs (excepting the noisy DNSC08 MDT). These GNSS-quasigeoid estimates may be contaminated by one, more or all of h, ζ, MSL and levelling errors (discussed above), in addition to temporal errors caused by the combination of datasets and models generated during different epochs. It is not possible to determine whether the relatively large STDs for AGQG09- and EGM2008-implied O_{Tas} (although less than the estimated formal error of ±108 mm for O_{AHD} at each TGBM) can be attributed to AGQG09 and EGM2008 alone, or also to h, ζ, MSL and H errors (the so-called separation problem; cf. Featherstone 2004), but it does appear that AGQG09 is slightly superior to EGM2008 in the Bass Strait region if only because it shows a lower STD.

The bottom row of Table 1 (B-H) gives the height difference between the Hobart and Burnie tide-gauges, which are ≤ 30 mm in magnitude for all SSTMs, indicating Hobart to be higher than Burnie for the SSTM method. However, the GNSS-quasigeoid method indicates that Burnie is higher than Hobart by ~50 mm. This is enigmatic, as the different methods give opposing conclusions as to the direction of any north-south slope in the AHD(Tas). For verification, these values were compared with the levelled height difference (from a minimally constrained LSA of the Tasmanian levelling network fixed at Hobart), which gives a value of – (38 ±44) mm (Hobart higher than Burnie), thus supporting the SSTM over the GNSS-quasigeoid estimates, although acknowledging that the STD of the levelled difference between Hobart and Burnie also allows a zero value. Since the quasigeoid is difficult to model in the coastal zone, it is likely that errors in EGM2008 and AGQG2009 swamp any reliable determination, especially for such a small sample size.

If it is assumed, based on the relatively small Burnie to Hobart height differences (Table 1), that AHD(Tas) does not contain a demonstrable north-south slope, all four Tasmanian tide-gauges (Figure 1) may be used to re-compute O_{Tas}. Using the additional tide-gauges increases the sample size slightly and perhaps so the reliability of the O_{Tas} estimate. Table 2 indicates that there are only minor differences when compared with Table 1 (O_{Tas} and STDs decrease in some cases), further suggesting that O_{Tas} is closer to zero than the previous geodetic-only estimates, but also that using different tide-gauges/TGBMs in this region have only a small effect on the computed O_{Tas}.

To test if the differences using non-AHD TGBMs/tide-gauges with AHD tide-gauges significantly affect O_{Tas} estimates, O_{Tas} was re-computed using only three AHD tide-gauges (Point

Lonsdale, Port Fairy, and Burnie) and compared to O_{Tas} in Table 1. With the exception of DNSC08 MDT (+67 mm different) and EGM2008 (+30 mm different), AHD-only O_{Tas} were found to be <10 mm different (in magnitude) to O_{Tas} in Table 1 using non-AHD tide-gauges/TGBMs with AHD tide-gauges. This indicates that using additional non-AHD tide-gauges/TGBMs in the O_{Tas} calculation does not significantly change the theoretically 'pure' O_{Tas} defined at only AHD tide-gauges, but adds to the reliability of the estimate because of a slightly larger sample size. It also suggests that DNSC08 MDT and EGM2008 are less reliable than the other datasets used to model SSTop, noting that DNSC08 MDT is based on EGM2008 (Andersen and Knudsen 2009).

	SSTM method					GNSS-quasigeoid method	
Statistic	CARS2006	Rio05	GGM02	JPL08	DNSC08	AGQG09	EGM2008
Mean or O_{Tas}	-12	-61	+32	+32	-33	+6	-33
Max	+7	-31	+49	+77	+147	+119	+120
Min	-26	-92	+8	-15	-352	-90	-167
STD	±11	±17	±12	±28	±145	±61	±77

Table 2. Statistics for O_{Tas} (in mm) between five Victorian and four Tasmanian tide-gauges (cf. Figure 1) for five SSTM and two GNSS-quasigeoid estimates. Positive O_{Tas} indicates that AHD(mainland) is above AHD(Tas).

Part of the studies conducted here approximately replicate those of Rizos et al. (1991) and the second part of Featherstone (2000), with the results in Tables 1 and 2 comparable to the initial estimate of ~+100 mm by Rizos et al. (1991) and +(120±120) mm from Featherstone (2000). It is acknowledged that different sets of TGBMs were used for the different studies, but comparisons between different sets of tide-gauges/TGBMs described above suggest that this generally causes relatively minor differences where there is sufficient redundancy and the different tide-gauges/TGBMs are located within the same region. Although the estimate of Rizos et al. (1991) was later revised up to ~+400 mm, no error estimates were given. However, the estimate of Featherstone (2000) allows probabilistically for a zero value for O_{Tas}, which is also possible from this re-evaluation, but also backed up by the additional independent use of oceanographic SSTM values (Tables 1 and 2).

The differences among the previous studies are likely to be caused by a combination of quasigeoid modelling errors, which are problematic in the coastal zone, GNSS h, levelling and SSTM errors. However, the values from this study (compared to Rizos et al. 1991; Rapp 1994; Featherstone 2000) are likely to be the result of recent improvements in quasigeoid modelling (e.g., Pavlis et al. 2008; Featherstone et al. 2011), Australian GNSS h datasets (e.g., Hu 2009; Brown et al. 2011), and SSTMs (e.g., Ridgway et al. 2002; Dunn and Ridgway 2002). Importantly, the SSTM methods (excepting the noisy DNSC08 MDT) give lower STDs than the GNSS-quasigeoid methods (Tables 1 and 2), indicating them to be the better source of information for unifying LVDs.

Therefore, the problem now reduces to which SSTM to use to compute an acceptable O_{Tas}. CARS2006 provides the most reliable estimate of SSTop differences at the tide-gauges because of its tailored computation methods in coastal regions (Dunn and Ridgway 2002), as well as it being independent of geodetic data. CARS2006 is a purely oceanographic SSTM, whereas the other SSTMs used here assimilate (Rio05) or use solely geodetic data (GGM02 DOT, JPL08, DNSC08 MDT). However, the SSTM-implied O_{Tas} do not include errors in the AHD MSL observations at tide-gauges, or the temporal bias between the Victorian and Tasmanian tide-gauges that is embedded in the actual value for O_{Tas}, although the relatively good agreement among these independent methods suggest that SSTop subsumes the other errors that may affect O_{Tas}. CARS2006 (using five Victorian and four Tasmanian tide-gauges) suggests that O_{Tas} is – (12±11) mm (AHD(mainland) below AHD(Tas)), although this does permit a zero offset in probability, as did the study of Featherstone (2000).

Conclusion

We have used five SSTMs and GNSS and two quasigeoid models to reassess the offset between the AHD(mainland) and AHD(Tas), showing O_{Tas} to range between – (61±17) mm and +(48±24) mm when using height differences between five Victorian tide-gauges and first two, then four Tasmanian tide-gauges. A positive value indicates that the AHD(mainland) is above the AHD(Tas). The O_{Tas} derived from the gravimetric quasigeoid models are deemed less reliable than from the SSTMs because (i) they contradict the levelled height difference between Burnie and Hobart, (ii) give consistently higher STDs than the SSTMs (suggesting noisier data), and (iii) the geoid is notoriously difficult to model in the coastal zone, principally because of the lack of terrestrial and marine gravity data. CARS2006 provides the best SSTM estimate of O_{Tas} -(12±11 mm), because it uses totally independent oceanographic data, provides a better agreement with the levelled height difference between Burnie and Hobart and generally has the smallest STD. Although CARS2006 does not account for any MSL observation error at the AHD tide-gauges, this appears to be largely subsumed with O_{Tas} coming primarily from SSTop. It is recommended that CARS2006 (or its successors) is used to unify the mainland and Tasmanian levelling networks in the development of any new levelling-based Australian vertical datum. While the Burnie-Hobart SSTM-based O_{Tas} estimate is opposite to and one order of magnitude smaller than previous geodetic-only estimates, both allow probabilistically for a near-zero value for O_{Tas}. Nevertheless, it has been shown that oceanographic SSTMs are now a realistic alternative or complement to geodetic-only methods for LVD unification.

Acknowledgements

Mick Filmer received financial support from an Australian Postgraduate Award, Curtin University's The Institute for Geoscience Research (TIGeR) and the CRC for Spatial Information. Will Featherstone was the recipient of an Australian Research Council Professorial Fellowship (project number DP0663020). The views expressed herein are those of the authors and are not necessarily those of the ARC or the CRC for Spatial Information. We would like to thank Geoscience Australia for supplying the GNSS dataset and Dr Xiaoli Deng (University of Newcastle) for supplying us with CARS2006 (data originally from CSIRO Marine Laboratories) and Rio05 (AVISO). We also acknowledge DNSC (DNSC08 MDT), NASA/JPL (JPL08, GGM02 DOT) and NGA (EGM2008) for their freely available datasets. We would also like to thank the three anonymous reviewers and editor for their comments on this manuscript. This is TIGeR publication number XX.

References

Altamimi, Z., X. Collileux, J. Legrand, B. Garayt, and C. Boucher. 2007. ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters. *Journal of Geophysical Research*, 112:B09401. doi:10.1029/2007JB004949.

Amin, M. 1993. Changing mean sea level and tidal constants on the west coast of Australia. *Australian Journal of Marine and Freshwater Research.* 44(6):911-925. doi:10.1071/MF9930911.

Amos, M.J. and W.E. Featherstone. 2009. Unification of New Zealand's local vertical datums: iterative gravimetric quasigeoid computations. *Journal of Geodesy.* 83(1):57-68. doi: 10.1007/s00190-008-0232-y.

Andersen, O.B. and P. Knudsen. 2009. DNSC08 mean sea surface and mean dynamic topography models. *Journal of Geophysical Research.* 114:C11001. doi:10.1029/2008JC005179.

Ardalan, A.A., Karimi, R. and M. Poutanen. 2010. A bias-free geodetic boundary value problem approach to height datum unification. *Journal of Geodesy*. 84(2):123-134. doi: 10.1007/s00190-009-0348-8.

Brown, N.J., W.E. Featherstone, G. Hu and G.M. Johnston. 2011. AUSGeoid09: a more direct and more accurate method of converting ellipsoidal heights to AHD heights. *Journal of Spatial Science*. 56(1): 27-37. doi: 10.1080/14498596.2011.580498.

Catalao, J. and M.J. Sevilla. 2009. Mapping the geoid for Iberia and the Macaronesian Islands using multi-sensor gravity data and the GRACE geopotential model. *Journal of Geodynamics*. 48(1):6-15. doi: 10.1016/j.jog.2009.03.001.

Coleman, R., C. Rizos, E.G. Masters, and B. Hirsch. 1979. The investigation of the sea surface slope along the north eastern coast of Australia. *Australian Journal of Geodesy, Photogrammetry and Surveying*. 31:686-99.

Currie, R.G. 1975. Period, Q_p and the amplitude of the pole tide. *Geophysical Journal of the Royal Astronomical Society*. 43(1):73-86. doi:10.1111/j.1365-246X.1975.tb00628.x.

Dando, N.J. and W. Mitchell. 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.

Dunn, J.R. and K.R. Ridgway. 2002. Mapping ocean properties in regions of complex topography. *Deep-Sea Research I.* 49(3):591-604. doi:10.1016/S0967-0637(01)00069-3.

Easton, A.K. 1968. A handbook of selected Australian tide gauges. Survey Paper 6, Horace Lamb Centre for Oceanographical Research, Flinders University, Adelaide, Australia.

Easton, A.K. and R. Radok. 1970. Tidal programme 1966-1967. Memorandum 5, Horace Lamb Centre for Oceanographical Research, Flinders University, Adelaide, Australia.

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

Featherstone, W.E. 2004. Evidence of a north-south trend between AUSGeoid98 and the AHD in southwest Australia. *Survey Review*. 37(291):334-343.

Featherstone, W.E. 2006. Yet more evidence for a north-south slope in the Australian Height Datum. *Journal of Spatial Science*. 51(2): 1-6.

Featherstone, W.E. and M. Kuhn. 2006. Height systems and vertical datums: a review in the Australian context. *Journal of Spatial Science.* 51(1): 21-42.

Featherstone, W.E., J.F. Kirby, A.H.W. Kearsley, J.R. Gilliland, G.M. Johnston, J. Steed, R. Forsberg, and M.G. Sideris. 2001. The AUSGeoid98 geoid model of Australia: data treatment, computations and comparisons with GPS-levelling data. *Journal of Geodesy*. 75(5-6):313-330. doi:10.1007/s001900100177.

Featherstone, W.E., J.F. Kirby, C. Hirt, M.S. Filmer, S.J. Claessens, N. Brown, G. Hu, and G.M. Johnston. 2011. The AUSGeoid09 model of the Australian Height Datum. *Journal of Geodesy*. 85(3):133-150. doi: 10.1007/s00190-010-0422-2.

Fenoglio, L. and E. Groten. 1995. Mean sea level determination in small ocean basins from altimetry and tide-gauge data. *Manuscripta Geodaetica*. 20(6):394-407.

Filmer, M.S. and W.E. Featherstone. 2009. Detecting spirit-levelling errors in the AHD: recent findings and some issues for any new Australian height datum. *Australian Journal of Earth Sciences*. 56(4):559-569. doi:10.1080/08120090902806305.

Filmer, M.S., W.E. Featherstone, and M. Kuhn. 2010. The effect of EGM2008-based normal, normal-orthometric and Helmert orthometric height systems on the Australian levelling network. *Journal of Geodesy*. 84(8): 501-513. doi: 10.1007/s00190-010-0388-0.

Filmer, M.S., W.E. Featherstone, and S.J. Claessens. 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).

Hamon, B.V. and M.A. Greig. 1972. Mean sea level in relation to geodetic land levelling around Australia. *Journal of Geophysical Research*. 77(36):7157-7162. doi:10.1029/JC077i036p07157.

Hipkin, R. 2000. Modelling the geoid and sea-surface topography in coastal areas. *Physics and Chemistry of the Earth (A)*. 25(1):9-16. doi:10.1016/S1464-1895(00)00003-X.

Hipkin, R., K. Haines, C. Beggan, R. Bingley, F. Hernandez, J. Holt, and T. Baker. 2004. The geoid EDIN2000 and the mean sea surface topography around the British Isles. *Geophysical Journal International*. 157(2):565-577. doi:10.1111/j.1365-246X.2004.01989.x.

Hu, G. 2009. Analysis of regional GPS campaigns and their alignment to the International Terrestrial Reference Frame (ITRF). *Journal of Spatial Science*. 54(1):15-22.

ICSM. 2006. Geocentric Datum of Australia Technical Manual. Version 2.3(1), Inter-Governmental Committee on Surveying and Mapping, Canberra, Australia http://www.icsm.gov.au/icsm/gda/gdatm/gdav2.3.pdf .

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

Mather, R.S. 1974. On the solution of the geodetic boundary value problem for the definition of sea surface topography. *Geophysical Journal of the Royal Astronomical Society*. 39(1):87-109. doi:10.1111/j.1365-246X.1974.tb05441.x.

Mather, R.S. 1975. On the evaluation of sea surface topography using geodetic techniques. *Bulletin Géodésique*. 115(1):65-82. doi:10.1007/BF02523944.

Mather, R. S. 1979. The analysis of GEOS3 altimeter data in the Tasman and Coral Seas. *Journal of Geophysical Research*. 84(B8):3853-3866.doi:10.1029/JB084iB08p03853.

Merry, C. L. and P. Vaníček. 1983. Investigation of local variations of sea-surface topography. *Marine Geodesy*. 7(1-4):101-126. doi:10.1080/15210608309379477.

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

Morgan, P. 1992. An analysis of the Australian Height Datum: 1971. *The Australian Surveyor*. 37(1):46-63.

Nerem, R.S. et al. 1994. Gravity model development for TOPEX/Poseidon – Joint Gravity Model-1 and Model-2. *Journal of Geophysical Research – Oceans*. 99(C12):24421-24447. doi:10.1029/94JC01376.

Pavlis, N.K., S.A. Holmes, S.C. Kenyon, and J.K. Factor. 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/egm08 wgs84.html.

Pugh, D. 1987. *Tides, Surges and Mean Sea-level*. Chichester, New York, Brisbane, Toronto, Singapore: John Wiley.

Rapp, R.H. 1994. Separation between reference surfaces of selected vertical datums. *Bulletin Géodésique*. 69(1):26-31. doi: 10.1007/BF00807989.

Rapp, R.H. and N.K. Pavlis. 1990. The development and analysis of geopotential coefficient models to spherical harmonic degree 360. *Journal of Geophysical Research*. 95(B13):21885-21911. doi: 10.1029/JB095iB13p21885.

Rapp, R.H., Y.M. Yang and N.K. Pavlis. 1991. The Ohio State 1991 geopotential and sea surface topography harmonic coefficient models. Report 410, The Ohio State University, Columbus, USA.

Ridgway, K.R., J.R. Dunn, and J.L. Wilkin. 2002. Ocean interpolation by four-dimensional weighted least squares-application to the waters around Australasia. *Journal of Atmospheric and Oceanic Technology*. 19(9):1357-1375.

Rio, M.H. and F. Hernandez. 2004. A mean dynamic topography computed over the world ocean from altimetry, in situ measurements, and a geoid model. *Journal of Geophysical Research*. 109:C12032. doi:10.1029/2003JC002226.

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

Roelse, A., H.W. Granger, and J.W. Graham. 1971. The adjustment of the Australian levelling survey 1970-1971. Technical Report 12, Division of National Mapping, Canberra, Australia.

Rummel, R. and P. Teunissen. 1988. Height datum definition, height datum connection and the role of the geodetic boundary value problem. *Bulletin Géodésique*. 62(4):477-498. doi: 10.1007/BF02520239.

Shaw, A.G.P. and M. N. Tsimplis. 2010. The 18.6 yr nodal modulation in the tides of Southern European coasts. *Continental Shelf Research*. 30(2):138-151. doi:10.1016/j.csr.2009.10.006.

Smith, W.H.F and P. Wessel 1990. Gridding with continuous curvature splines in tension. *Geophysics*. 55(3):293-305. doi: 10.1190/1.1442837.

Tapley, B.D., D.P. Chambers, S. Bettadpur, and J.C. Ries. 2003. Large scale ocean circulation from the GRACE GGM01 geoid. *Geophysical Research Letters*. 30(22):2163-2166. doi:10.1029/2003GL018622.

Tapley, B., J. Ries, S. Bettadpur, D. Chambers, M. Cheng, F. Condi, B. Gunter, Z. Kang, P. Nagel, R. Pastor, T. Pekker, S. Poole, and F.Wang. 2005. GGM02 - An improved Earth gravity field model from GRACE. *Journal of Geodesy*. 79(8):467-478. doi:10.1007/s00190-005-0480-z.

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*. 17(3):265-280. doi:10.1016/0031-9201(78)90041-9.

Wessel, P. and W.H.F. Smith 1998. New, improved version of Generic Mapping Tools released. *EOS, Transactions, American Geophysical Union*. 79(47):579.

Zhang, L., F. Li, W. Chen, and C. Zhang. 2009. Height datum unification between Shenzhen and Hong Kong using the solution of the linearized fixed gravimetric boundary value problem. *Journal of Geodesy*. 83(5):411-417. doi:10.1007/s00190-008-0234-9.