Description and release of Australian gravity field model testing data

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ABSTRACT
Gravimetric geoid and/or quasigeoid models are routinely evaluated using co-located GPS-levelling and/or astrogeodetic vertical deflections, globally and regionally. This short note describes these ground-truth data for Australia as of August 2017, which are provided as Electronic Supplementary Material. We provide ~7500 GPS-derived ellipsoidal heights, normal-orthometric heights from the 1971 adjustment of the Australian Height Datum, normal heights from a readjustment of levelling constrained to a model of the ocean's mean dynamic topography, and ~1000 historical astrogeodetic vertical deflections. Updates to these data will be posted on the Intergovernmental Committee on Surveying and Mapping GitHub repository (https://github.com/icsm-au), together with a readme.txt file describing them.

KEYWORDS
GPS-levelling, vertical deflections, gravity model testing, Australia, vertical datum offsets, heights

Introduction and motivation

When carrier-phase-based relative GPS (Global Positioning System) became a geodetic surveying tool (e.g. Bock, Abbot, Counselman, Gourevitch, & King, 1985; Counselman & Gourevitch, 1981), gravimetric geoid computation encountered a revival (e.g. Engelis, Rapp, & Tscherning, 1984; Engelis, Rapp, & Bock, 1985; Kearsley, 1986; Denker & Wenzel, 1987). This was because of its practical utility in transforming ellipsoidal height differences from relative GPS surveys to orthometric height differences (e.g. Kearsley, 1988a). GPS and a geoid model were, and still are, an attractive alternative to differential levelling over long distances on the grounds of efficiency and cost, but provided that the gravimetric geoid model is sufficiently precise and accurate.

Co-located GPS and levelling data were also used to provide a test of gravimetric geoid models (e.g. Kearsley, 1988b), and continue to be used today (e.g. http://icgem.gfz-potsdam.de/ICGEM/). There is a subtle distinction between the geoid and the quasigeoid on land, where GPS and the geoid are used to determine orthometric heights, and GPS and the quasigeoid are used to determine normal heights (e.g. Featherstone & Kuhn, 2006). GPS-levelling tests of quasi/geoid models can be applied in a relative sense over GPS baselines or in an absolute sense when the GPS ellipsoidal height has been determined at a single point (e.g. Featherstone, 2001). Another test of quasi/geoid models comes from astrogeodetic vertical deflections (e.g. Jekeli, 1999; Hirt, Marti, Bürki, & Featherstone, 2010; Hirt, Gruber, & Featherstone, 2011).

The use of GPS-levelling simply to test gravimetric quasi/geoid models has evolved to the use of GPS and the quasi/geoid to question the veracity of local vertical datums (e.g. Featherstone & Filmer, 2008, 2012; Penna, Featherstone, Gazeaux, & Bingham, 2013). GPS levelling is sometimes used to fit surfaces to account for the separation between the gravimetric model and local vertical datum (e.g. Milbert, 1995; Featherstone, 1998; Smith & Roman, 2001; Brown, Featherstone, Hu, & Johnston, 2011). This short note is motivated by Milbert (1998) so as to document not only the GPS-levelling but also the vertical deflection data available in Australia and release them into the public domain.

GPS-levelling data

GPS-levelling has been used for decades in Australia to test global and regional quasi/geoid models (e.g. Amos & Featherstone, 2003; Claessens, Featherstone, Anjasmara, & Filmer, 2009; Featherstone & Guo, 2001; Featherstone *et al.*, 2001, 2011, 2017; Kearsley & Govind, 1991; Kearsley & Holloway, 1989; Pearse, Kearsley, & Morgan, 1995; Steed & Hotznagel, 1994; Zhang & Featherstone, 1995). A rather outdated (circa year 2000) set of 201 Australian GPS-levelling data is still being used by the ICGEM (http://icgem.gfz-potsdam.de/ICGEM/) to evaluate global Earth gravitational models (EGMs), thus motivating our description and public release of these newer data. As of August 2017, there is a total of 7635 GPS-levelling data points (Figure 1).

The raw GPS observations were provided to Geoscience Australia (the national geodetic agency) by Australian State and Territory geodetic agencies. These are static dual-frequency occupations of at least six hours' duration at benchmarks of the Australian Height Datum (AHD). The ellipsoidal heights were computed by Geoscience Australia using Bernese version 5.2 (Dach, Lutz, Walser, & Fridez, 2015) on the Geocentric Datum of Australia 2020 (GDA2020; GRS80 ellipsoid), which is a regional realisation of ITRF2014 (Altamimi, Rebischung, Métivier, & Xavier, 2016), projected to epoch 2020.0 using Australian station velocities. The GDA2020 ellipsoidal heights were output from a least-squares adjustment (LSA) along with the associated positional uncertainty (at one sigma).

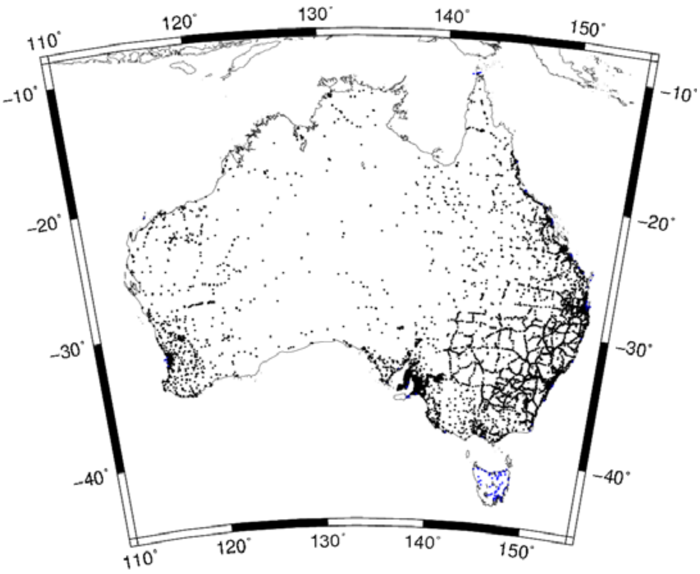

Figure 1: Spatial coverage of the August 2017 Australian GPS-levelling data. Black dots are points on the Australian mainland (a single vertical datum). Blue dots are the separate vertical datums on Tasmania and coastal islands near the mainland. GPS-levelling points on Lord Howe Island, Cocos/Keeling Islands and Christmas Island are not shown, but are provided with the Electronic Supplementary Material.

The utility of GPS-levelling for testing quasi/geoid models can be restricted by distortions in the vertical datum to which the levelling is referred. These distortions are caused by (1) constraining the vertical datum to mean sea level at tide gauges, which is separated from the geoid by the ocean's time-mean dynamic topography (MDT) (e.g. Bowie, 1929) and other oceanographic effects, and (2) errors in the levelling observations.

The levelling data provided for Australia therefore come from two LSAs. Source 1 is the 'official' published AHD heights of the benchmarks from the 1971 LSA (Roelse, Granger, & Graham, 1971), together with an estimate of their uncertainty (at one sigma), which has not previously been publicly available. Source 2 is a LSA of the Australian National Levelling Network (ANLN) that is constrained at 32 tide gauges to mean sea level values that are corrected for the MDT using the Australian Commonwealth Scientific and Industrial Research Organisation Atlas of Regional Seas 2009 (CARS2009; Dunn & Ridgway, 2002; Ridgway, Dunn, & Wilkin, 2002). The use of MDT values from CARS2009 at the tide gauges results in the adjusted levelling network being more closely aligned to the geoid (Featherstone *et al.*, 2017; Filmer, Featherstone, & Claessens, 2014). The rationale for the latter LSA is that there are remaining distortions in the AHD that cannot be removed by a tilted plane alone (Featherstone & Filmer, 2012) owing to uncorrected gross, random and systemic levelling errors (e.g. Morgan, 1992; Roelse *et al.*, 1971; Filmer & Featherstone, 2009, 2011). In addition, the AHD uses normal-orthometric heights through the use of the Rapp (1961) normal-orthometric correction using normal gravity from the Geodetic Reference System 1967 (GRS67; International Association of Geodesy, 1971). The CARS2009-constrained LSA of the ANLN provides normal heights, using gravity values from EGM2008 through the application of the normal correction and GRS80 normal gravity (Moritz, 1980), as described in Filmer, Featherstone and Kuhn (2010).

The GPS-levelling data include some of Australia's offshore territories, which are technically on separate vertical datums, as is the AHD on Tasmania (Featherstone, 2000; Filmer & Featherstone, 2012; Rizos, Coleman, & Ananga, 1991). Although they are all termed AHD heights, they refer to mean sea level observed at a tide gauge(s) on each island. These comprise: Lord Howe Island (1 point), Cocos/Keeling Islands (14 points), Christmas Island (20 points), Tasmania (76 points) and coastal islands close to the Australian mainland (138 points). We identified the coastal islands using the full-resolution shoreline in the Generic Mapping Tools (GMT; Wessel, Smith, Scharroo, Luis, & Wobbe, 2013) software (http://www.soest.hawaii.edu/wessel/gshhg/), which is an update of Wessel and Smith (1996). However, even the highest resolution shoreline option in GMT was not always able to discriminate between peninsulas and islands, so visual inspection of satellite and aerial imagery via Google Earth was used for confirmation.

Using these GPS-levelling data, we estimated the offset to these vertical datums (excepting Tasmania) by taking the mean of the GPS-levelling minus the EGM2008 global quasigeoid model (Pavlis, Holmes, Kenyon, & Factor, 2012, 2013) as a proxy for the offsets between the remote island vertical datums and the AHD mainland. However, this is problematic owing to the north–south tilt in the AHD, which causes the vertical datum offsets to be a function of latitude (Featherstone, 2000). Therefore, we removed the north–south tilt in the AHD of 22.2 mm/degree from Featherstone and Filmer (2012) before calculating the vertical datum offsets (Table 1). The small sample sizes on the islands prevent a more robust estimate of the vertical datum offsets, but this may be refined as more data become available. The standard deviations in Table 1 are determined from linear propagation of the standard deviations of fit to each vertical datum, assuming independence.

The GPS-levelling data are provided as Electronic Supplementary Material to this article in a Microsoft Excel file named 'AustralianGPSlevellingAug2017.xlsx'. This contains two tabs, one called AHD with the 'official' AHD normal-orthometric heights, and another called CARS2009 with the readjusted normal heights. The AHD tab comprises eight columns of an (A) ID number, (B) GDA2020 longitude in decimal degrees, (C) GDA2020 latitude in decimal degrees, (D) GDA2020 ellipsoidal height (h) in metres, (E) standard deviation of the GDA2020 ellipsoidal height in metres (scaled up by a factor of 10 from the optimistic output of the GDA2020 LSA; cf. Rothacher, 2002, (F) AHD normal-orthometric height (H) in metres, (G) standard deviation of the AHD height in metres, and (E) geometrically computed quasigeoid height relative to the GRS80 reference ellipsoid ($\zeta = h–H$). The CARS2009 tab is the same but replaces the AHD heights by the readjusted normal heights (column F) and recomputes the geometric quasigeoid height (column E). The island stations are located at the bottom of each tab.

Island vertical datum	Points	Offset from AHD (m)	STD (m)
Christmas Island	20	-0.261	±0.122
Cocos/Keeling Islands	14	-0.404	±0.140
Lord Howe Island	1	+0.709	N/A

Table 1: Estimated offsets (m) between Australian island vertical datums and the AHD (mainland)

Vertical deflection data

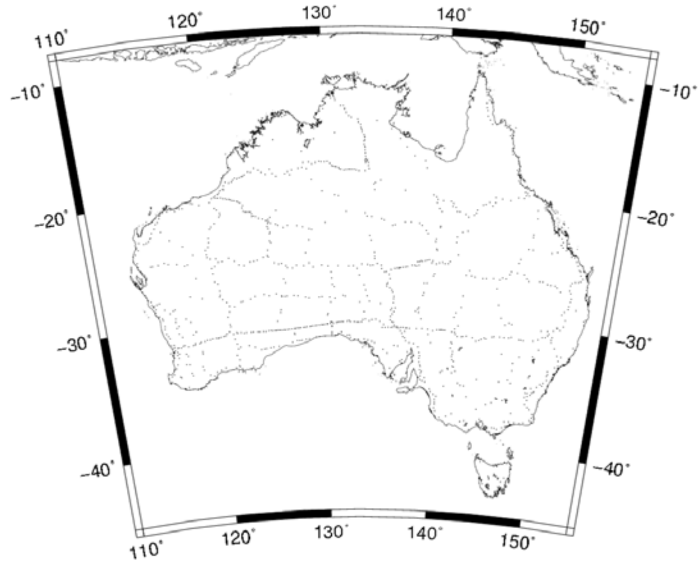

Figure 2: Spatial coverage of the August 2017 Australian vertical deflection data.

Vertical deflections/deviations (the angular difference between the ellipsoidal normal and gravity vector) provide a more powerful test of the high-frequency gravity field than GPS-levelling because they are a higher-order derivative of the disturbing potential (e.g. Hirt *et al.*, 2010, 2011; Jekeli, 1999). They comprise a north–south component (ξ) and an east–west component (η) and are typically a few to tens of arc-seconds in magnitude. There are also some subtleties with the definition of the vertical deflection because of the curvature and torsion of the plumbline, notably Helmert on the Earth's surface *vs* Pizzetti at the geoid (e.g. Jekeli, 1999), and absolute/geocentric *vs* relative (e.g. Featherstone & Rüeger, 2000).

A historical (typically 1960s and 1970s) set of 1080 Australian vertical deflections was discovered by the first author in an archive at Oxford University (Figure 2). This had been sent in hardcopy format to Brigadier Guy Bomford, reader in geodesy at Oxford, by his son Anthony Bomford, a former director of the then National Mapping Agency (thereafter AUSLIG and now Geoscience Australia). These astrogeodetic vertical deflections used timed star observations of astrogeodetic latitude and longitude over several nights per station (e.g. Bomford, Cook, & McCoy, 1970) and follow the Helmert definition as they are at the Earth's surface (e.g. Jekeli, 1999). Subsets of these historical deflections have been used to (1) determine parameters for the Australian National Spheroid (ANS; Lambert, 1962), (2) for the establishment of the (regional, not geocentric) Australian Geodetic Datum 1966 (AGD66; Bomford, 1964, 1967), (3) compute geoid maps with respect to the local ANS (Fisher & Slutsky, 1967; Fryer, 1970, 1972), and (4) relate the AGD66 and ANS to the Earth's centre of mass (Mather, 1970; Mather & Fryer, 1970a, 1970b).

These relative vertical deflections have since been converted to absolute values (i.e., with respect to the geocentric GRS80 ellipsoid) and used for gravity field model testing in a variety of guises over Australia: the global EGM2008 (Pavlis *et al.*, 2012, table 9) and regional quasigeoid models (Featherstone, 2006; Featherstone & Morgan, 2007; Featherstone *et al.*, 2017), assessment of satellite-derived geoid models (Hirt *et al.*, 2011), and even in an attempt to fit a regional quasigeoid model to them (Featherstone & Lichti, 2009). However, the historical nature of vertical deflections makes them prone to larger uncertainty (cf. Featherstone & Olliver, 2013).

No per-station formal error estimates are known for these historical Australian vertical deflections. Instead, some general error estimates have been made for subsets of the whole database. Bomford *et al.* (1970, p. 2) give estimates of ± 0.38" for ξ and ± 0.76" for η from 510 observations made between 1967 and 1969. Fryer (1970, table 3.1, p. 51) gives estimates for different instruments that range from ± 0.22" to ± 0.60" for ξ and from ± 0.40" to ± 1.00" for η. Kearsley (1976, p. 135) uses the values of ± 0.25" for ξ and ± 0.45" for η taken from Fryer (1970), and provides a more detailed error analysis for four stations in areas of rugged terrain.

These 1080 astrogeodetic vertical deflection data are provided as Electronic Supplementary Material to this article in a Microsoft Excel file named 'AustralianVerticalDeflectionsAug2017.xlsx'. These have been recalculated for the horizontal geodetic coordinates on GDA2020 (i.e., absolute Helmert deflections). The file contains a single tab comprising nine columns. Column A is the station name, and columns B and C are the astrogeodetic/natural latitude (Φ) and longitude (Λ), respectively from the original star observations. Column D gives the AHD heights in metres, but these should not be used with column G to calculate ($\zeta = h–H$) as several points in column D have not been levelled, instead coming from less precise trigonometrical heighting. Columns E, F and G respectively give the GDA2020 latitude (φ), longitude (λ) (decimal degrees) and ellipsoidal height (metres) from the national LSA. Column H is the calculated north–south deflection component ($\xi = \Phi – \varphi$) and column I is the calculated east–west component [$\eta = (\Lambda – \lambda)\tan\varphi$]; both are in arc-seconds.

	EGM2008		AGQG2009		AGQG2017	
	NS (ξ)	EW (η)	NS (ξ)	EW (η)	NS (ξ)	EW (η)
Max	2.94	2.94	2.38	2.97	2.43	2.89
Min	-2.87	-2.91	-2.86	-2.85	-2.80	-2.78
mean	-0.22	-0.10	-0.22	-0.10	-0.21	-0.08
STD	±0.71	±0.94	±0.60	±0.88	±0.58	±0.85
Outliers	16	27	13	23	12	25

Table 2: Differences (arc-seconds) between 1,080 Australian astrogeodetic deflections and model-based vertical deflections after rejection of points that exceed a threshold of 3 arc-seconds in magnitude.

We compared the GDA2020-based absolute Helmert astrogeodetic deflections with deflections calculated from EGM2008 (Pavlis *et al.*, 2012, 2013), AGQG2009 (Featherstone *et al.*, 2011) and AGQG2017 (Featherstone *et al.*, 2017) (Table 2). Deflections were synthesised from EGM2008 at the GDA2020 ellipsoidal height of each astrogeodetic station (column G) using the *isGrafLab* software (Bucha & Janák, 2014). Deflections were calculated from the longitudinal and latitudinal horizontal gradients of the AGQG2009 and AGQG2017 gravimetric quasigeoid models (e.g. Featherstone & Rüeger, 2000). Even though the Australian astrogeodetic deflections are historical data, there are surprisingly few outliers. We have retained these in the data release, but they have been removed by a 3 arc-second rejection threshold for the results in Table 2 (cf. Pavlis *et al.*, 2012). The larger standard deviations for the east–west vertical deflections (η) most likely reflect timing errors in these historical observations, though they could also be due to errors in the star catalogues used. This is also reflected in the estimated precision of subsets of the astronomical observations (Bomford *et al.*, 1970; Fryer, 1970; Kearsley, 1976).

Summary and concluding remarks

This short note has described GPS-levelling and vertical deflection ground-truth data for testing gravity field models in Australia (release August 2017), which are provided as Electronic Supplementary Materials. Updates to the GPS-levelling and vertical deflection data will be posted on the Intergovernmental Committee on Surveying and Mapping GitHub repository (https://github.com/icsm-au) together with a readme.txt file describing them. We have used the GPS-levelling data to estimate offsets between some local vertical datums and used the vertical deflections to assess one global and two regional quasigeoid models.

These data can not only be freely used to assess global gravity field models on a continental scale (cf. http://icgem.gfz-potsdam.de/ICGEM/), but also be used to assess Australian quasigeoid models computed by other groups using their own techniques and software (cf. Duquenne, 2007; Ismail & Jamet, 2015; Valty, Duquenne, & Panet, 2009; Yildiz, Forsberg, Ågren, Tscherning, & Sjöberg,2011). This is possible because Australian land gravity and terrain data are freely available via Geoscience Australia's GADDS system (http://www.geoscience.gov.au/cgi-bin/mapserv?map=/nas/web/ops/prod/apps/mapserver/gadds/wms_map/gadds.map&mode=browse). We would be pleased to collaborate and cooperate with any such interested parties.

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