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COMPARISONS OF RECENT GLOBAL GEOPOTENTIAL MODELS WITH TERRESTRIAL GRAVITY FIELD OBSERVATIONS OVER NEW ZEALAND AND AUSTRALIA

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ABSTRACT

This study compares global geopotential models (GGMs) released between 1996 and 2002, including four that incorporate data from the CHAMP dedicated satellite gravimetry mission, with terrestrial gravity field-related data over Australia and New Zealand. The GGM-implied gravity anomalies are compared with point free-air gravity anomalies on land; geoid heights compared with discrete geometrical heights from co-located GPS and sprit-levelling data on the local vertical datums; and absolute (Pizzetti) deflections of the vertical at the geoid are compared with absolute (Helmert) vertical deflection estimates at the Earth's surface. The results indicate that EIGEN-2, which uses purely CHAMP data, is currently the best satellite-only GGM over Australia and New Zealand (acknowledging the presence of long-wavelength errors in the 'control' data), whereas the various combined high-degree GGMs are not statistically significantly different from one another over Australia and New Zealand. A hybrid GGM was created from EIGEN-2 to degree 32 and EGM96 from degree 33 to 360, where the cut off was selected using the global error degree variances of each. This GGM makes a very slight improvement on all others, and thus will probably be used in near-future Australian and New Zealand geoid models.

1. INTRODUCTION

It is usually beneficial to select a global geopotential model (GGM) that is a best fit to the local gravity field as the basis for a regional gravimetric geoid model. This is because it will reduce the amount of geoid contribution that must be made by a regional integration of Stokes's formula or some modification thereof. The quotation from Lambeck and Coleman (1983) "*… the various models* [GGMs] *are not as good as they are said to be. If they were, the differences between them should not be so great as they are ...*" provides a secondary motivation for this study.

Kearsley and Holloway (1989) evaluated the fit of some of the GGMs available at that time to the Australian gravity field. This led to the selection of OSU89E (Rapp and Pavlis, 1990) as the basis for the AUSGeoid91 regional geoid model. Zhang and Featherstone (1995) extended this evaluation to some other GGMs, and showed [retrospectively] that OSU91A (Rapp *et al.*, 1991) was an appropriate choice for AUSGeoid93 (Steed and Holtznagel, 1994). Kirby *et al.* (1998) evaluated the EGM test series of GGMs as part of an International Association of Geodesy Working Group, and this led to the use of EGM96 (Lemoine *et al.*, 1998) in AUSGeoid98 (Featherstone *et al.*, 2001). Pearse and Kearsley (1996) also contributed to the above Working Group and showed that "*… EGM96 is marginally superior to OSU91A …*" over New Zealand.

As additional GGMs have now been released into the public domain, notably those including data from the CHAMP dedicated satellite gravimetry mission, and new gravity-field-related datasets have been compiled over Australia and New Zealand, it is important to continue such evaluations to select the most appropriate GGM. This will probably be the basis for a revision to AUSGeoid98, as well as for the production of the first regional gravimetric geoid model of New Zealand for over a decade (cf. Gilliland, 1990). Also, such evaluations in this part of the world may provide information that is of use to the developers of these GGMs.

This paper describes three different types of evaluation of the GGMs released between 1996 and 2002 (Table 1). There is replication for some of the GGMs previously tested (cf. Kirby *et al.*, 1998; Pearse and Kearsley, 1996) so as to quantify the effect of using the new and additional 'control' data now available. The evaluations include comparisons with discrete free-air gravity anomalies on land, GPS-levelling data on the local vertical datums, and Helmert vertical deflections at the Earth's surface. Unlike earlier Australian studies (e.g., Zhang, 1998), ship-track gravity anomalies are not used because of cross-over errors that are now known to exist in this data set (e.g., Featherstone, 2002b); likewise for New Zealand. An additional validation is conducted using Helmert vertical deflections observed in Australia and New Zealand (cf. Jekeli, 1999), which has not been attempted before to the knowledge of the authors.

2. THE GLOBAL GEOPOTENTIAL MODELS TESTED

There are essentially three classes of GGM; in summary:

1. **Satellite-only GGMs** are derived solely from the analysis of the orbits of artificial Earth satellites. Historically, these models were limited in precision due to a combination of: the power-decay of the gravitational field with altitude; the inability to track complete satellite orbits using ground-based stations; imprecise modelling of atmospheric drag, non-gravitational and third-body perturbations; and incomplete sampling of the global gravity field due to the limited number of satellite orbital inclinations available. Therefore, while some satellite-only GGMs are available above degree 70 (Table 1), the higher degree coefficients, say greater than 20 (e.g., Vaníček and Sjöberg, 1991) or 30 (e.g., Rummel *et al.,* 2002), are heavily contaminated by noise; also see Figure 2. However, several of the above limitations have now been redressed by the use of the dedicated satellite gravimetry missions, whose concepts are summarised in Rummel *et al*. (2002) and Featherstone (2002a).

2. **Combined GGMs** are derived from the combination of satellite data, land and ship-track gravity observations, and marine gravity anomalies derived from satellite radar altimetry, and more recently airborne gravity data (e.g., Rapp, 1997b). This generally allows an increase in the maximum spherical harmonic degree of the GGM. However, these models are also limited in precision due to the above-mentioned restrictions on [older] satellite-only GGMs, as well as the spatial coverage and quality of the additional data used. For instance, distortions in and offsets among different vertical geodetic datums cause long-wavelength errors in terrestrial gravity anomalies, among with many other causes (e.g., Heck, 1990). These will generate low-frequency errors in the combined GGMs if not properly high-pass filtered from the combined geopotential solution.

3. **Tailored GGMs** adjust (and often extended to higher degrees) a satellite-only or combined GGM using gravity data that may not necessarily have been used before (e.g., Wenzel, 1998a, 1998b). This is normally achieved using integral formulas to derive 'corrections' to the existing geopotential coefficients, as opposed to the combination at the normal equation level that is used to construct combined GGMs (e.g., Lemoine et al., 1998). Importantly, tailored GGMs *only* apply over the area in which the tailoring was applied, because spurious effects can occur in areas where no data are available (Kearsley and Forsberg, 1990).

Table 1 lists the GGMs tested in this study, together with the maximum degree of expansion, whether they are satellite-only, combined or tailored solutions, and a citation.

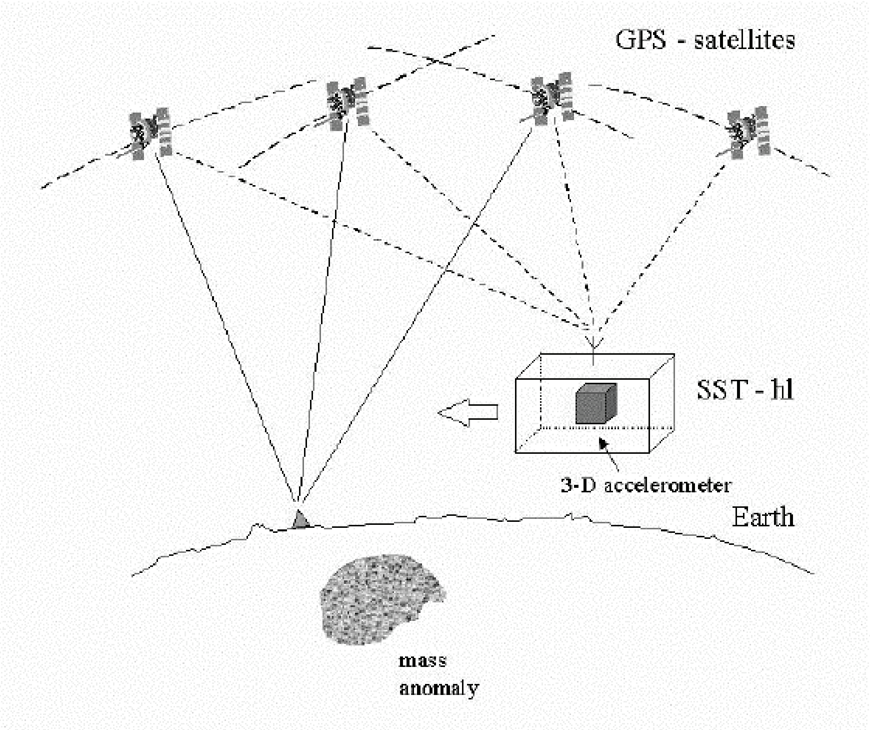

Figure 1. The CHAMP concept of high-low
satellite-to-satellite tracking (from Rummel et al., 2001)

The unique GGMs in Table 1 are EIGEN-1S, EIGEN-2, UCPH2002_02 and TEG-4, all of which include CHAMP (CHAllenging Mini-satellite Payload) high-low satellite-to-satellite tracking (hl-SST) and accelerometry data (Figure 1). EIGEN-2 is a GGM derived purely from CHAMP data. The CHAMP dedicated gravimetry satellite was launched on 15 July 2000, and orbits in a near-circular orbit at an initial altitude of 454 km and an inclination of 87.3° to the equatorial plane (e.g., Reigber et al., 2002). The hl-SST allows a near-global coverage of gravity field data, which was previously unavailable with ground-tracked satellite data. The CHAMP satellite also houses a three-axis accelerometer to help reduce the effect of non-gravitational perturbations.

model	*degree*	*class*	*citation*
JGM-3	70	combined	Tapley *et al.* (1996)
EGM96S	70	satellite-only	Lemoine *et al.* (1998)
UCPH2002_02	90	satellite-only	Howe *et al*. (2002)
GRIM5-S1	99	satellite-only	Biancale *et al.* (2000)
EIGEN-1S	100	satellite-only	Reigber *et al.* (2002)
EIGEN-2	120	satellite-only	Reigber *et al.* (2003)
GRIM5-C1	120	combined	Gruber *et al.* (2000)
TEG-4	200	combined	Tapley *et al.* (2001)
GFZ97	359	combined	Gruber *et al.* (1997)
EGM96	360	combined	Lemoine *et al.* (1998)
EGM96COR	360	combined	*ibid*.; Rapp (1997a)
PGM2000A	360	combined	Pavlis *et al*. (2000)
EIGEN2/EGM96	32/360	combined	see text
UCPH2/EGM96	41/360	combined	see text
GPM98C	1800	tailored	Wenzel (1998b)

Table 1. The global geopotential models tested over Australia and New Zealand

Table 1 also lists two additional hybrid GGMs, which have been created specifically for this study. These are termed EIGEN2/EGM96 and UCPH2/EGM96, where EIGEN-2 coefficients from degrees 2 to 32 (inclusive) and UCPH2002_02 coefficients from degrees 2 to 41 (inclusive), respectively, are used to replace the corresponding EGM96 coefficients. The cut-off degrees of 32 and 41 are chosen because these are the points beyond which the respective error degree variances of EIGEN-2 and UCPH2002_02 are larger than those of EGM96 (Figure 2). These roughly agree with the estimate of degree 30 made by Rummel *et al.* (2002). Also note from Figure 2 that the degree variances (i.e., signal power) of EIGEN-2 and UCPH2002_02 begin to decay with respect to EGM96 beyond degree ~40.

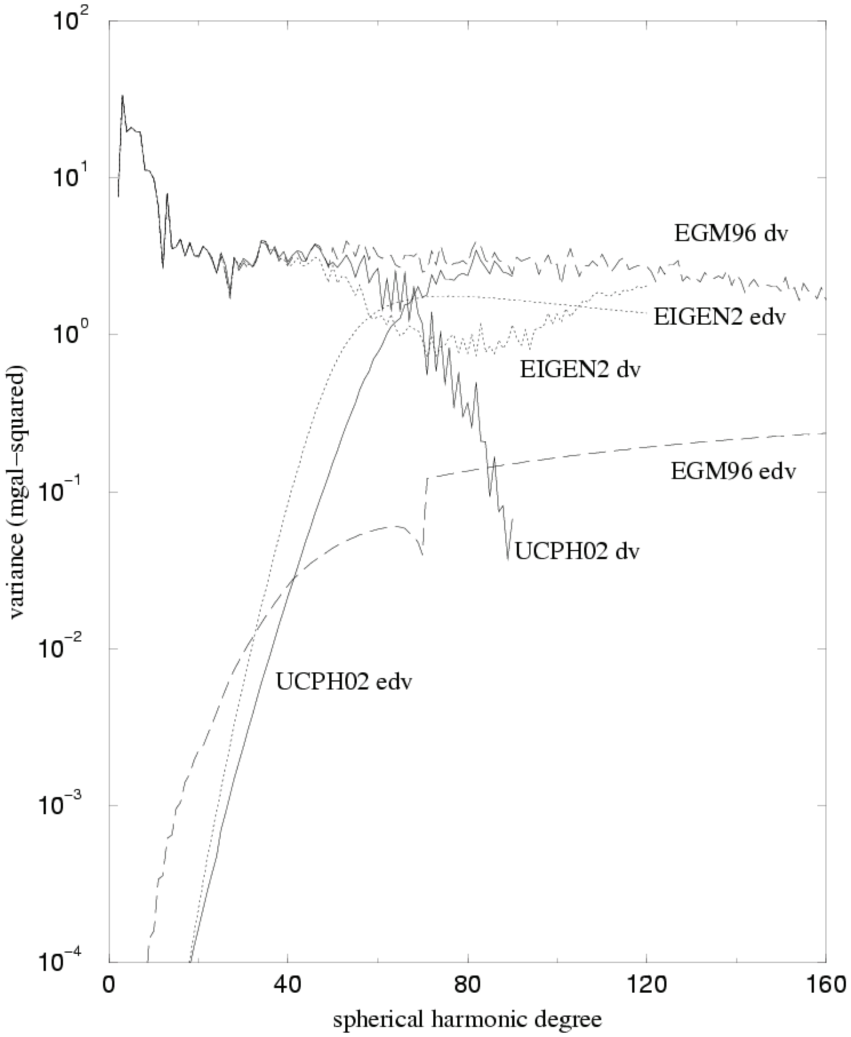

Figure 2. Degree variances (dv) and error degree variances (edv) of new GGMs from CHAMP dedicated satellite gravimetry (see Table 1) in relation to EGM96

Each GGM in Table 1 was evaluated to its maximum available degree and order using `harmonics.f`, which is a derivative of Rapp's (1982) software held at Curtin University of Technology. The computations were performed point-by-point, where the GGM-implied gravity field quantities were evaluated at the geocentric latitude and longitude of each terrestrial data point, then the descriptive statistics of the differences computed. GRS80 (Moritz, 1980) was used as the reference ellipsoid for all computations, but no zero- or first-degree terms were calculated (cf. Kirby and Featherstone, 1997). As such, the mean differences presented for all the datasets should be treated with some caution, and the standard deviations interpreted as the more informative statistic of the fit of each GGM to the terrestrial-gravity-field-related data.

3. THE AUSTRALIAN AND NEW ZEALAND DATA

3.1 Land Gravity Observations

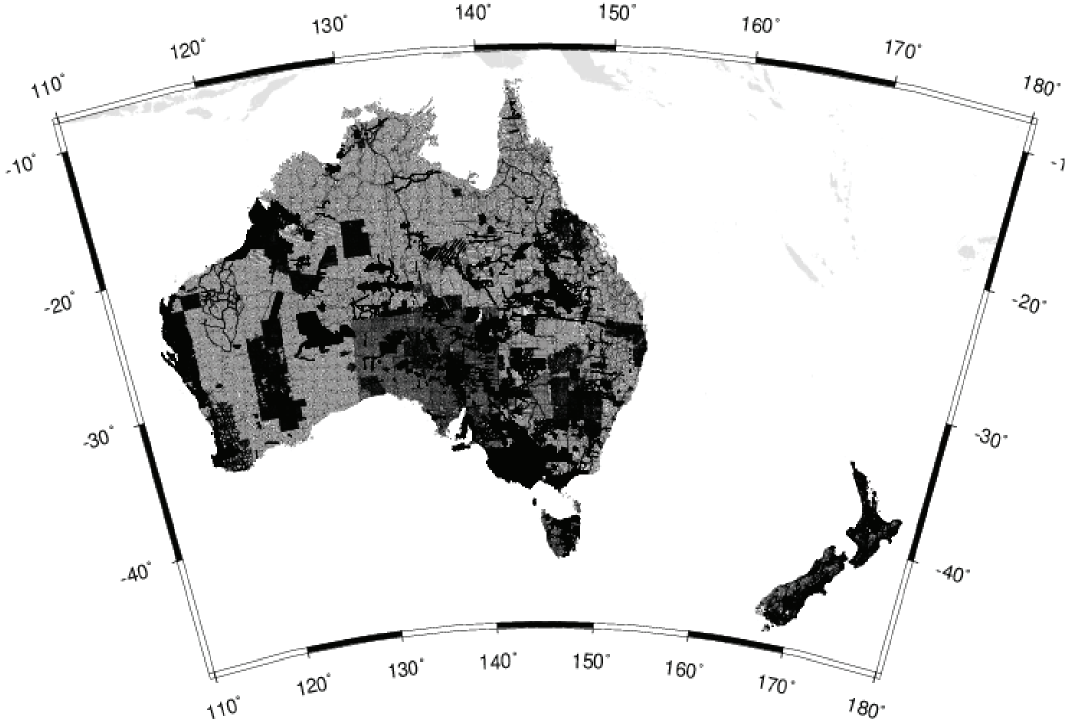

Figure 3. Spatial coverage of the 768,992 Australian land gravity observations in the 2001 data release from GA and the 40,737 New Zealand land gravity observations in the 2001 data release from GNS (Lambert projection)

- *Australia*: 768,992 land gravity observations from a corrected version of the 2001 release of Geoscience Australia's (GA; formerly AGSO) national gravity database (cf. Murray, 1997) were used over Australia (Figure 3). These gravity observations refer to the IsoGal84 gravity datum (Wellman *et al.*, 1985), which is tied to the IGSN71 (Morelli *et al.*, 1971). Second-order, atmospherically corrected, free-air gravity anomalies were recomputed using the procedures outlined in Featherstone *et al.* (1997). No horizontal datum transformation was necessary because the 2001 land gravity data release is claimed to be on the Geocentric Datum of Australia (GDA94), though the transformation technique used by GA are presently unknown.

- *New Zealand*: 40,737 land gravity observations from the national gravity database held by the Institute of Geological and Nuclear Sciences (GNS) Ltd (cf. Robertson and Reilly, 1960; Reilly, 1972) were used over New Zealand (Figure 3). These gravity observations were originally based on the Potsdam (New Zealand) gravity datum. Therefore, a constant value of 15.21 mGal (Woodward, 2001 pers. comm.) was subtracted to transform them to IGSN71. Second-order, atmospherically corrected, free-air gravity anomalies were computed using the same procedures as used for the Australian data. The horizontal coordinates of the gravity observations were first transformed from the New Zealand Geodetic Datum 1949 (NZGD49) to the geocentric New Zealand Geodetic Datum 2000 (NZGD2000) using a similarity transformation with parameters published by Land Information New Zealand (LINZ) (Office of the Surveyor-General, 1997).

3.2 GPS-levelling Heights on Land

- *Australia*: 1,013 GPS-levelling-derived estimates of the geometrical ‘geoid’ height (Figure 4), supplied by the National Mapping Division (NMD) of GA (formerly AUSLIG), were used over Australia (cf. Featherstone and Guo, 2001). The spirit-levelling observations are tied to the Australian Height Datum (AHD; Roelse *et al.*, 1971). The quotation marks are used around the term geoid, because these are not estimates of the classical equipotential geoid, mainly due to deficiencies in the AHD (e.g., Featherstone, 1998). In addition, the quality of these GPS data is variable, with them being compiled from a variety of vintages (Johnston and Luton, 2001).
- *New Zealand*: 1,055 GPS-levelling-derived estimates of the geometrical ‘geoid’ height (Figure 4), supplied by LINZ, were used over New Zealand. The quotation marks used here have more relevance here because the spirit-levelled heights used are not connected to a single national vertical datum. Instead, New Zealand uses 13 separate vertical datums tied by (normal-orthometrically corrected) spirit levelling to 12 separate tide gauges (e.g., Gilliland, 1987). Accordingly, the results using these data will be afforded less weight in the comparisons.

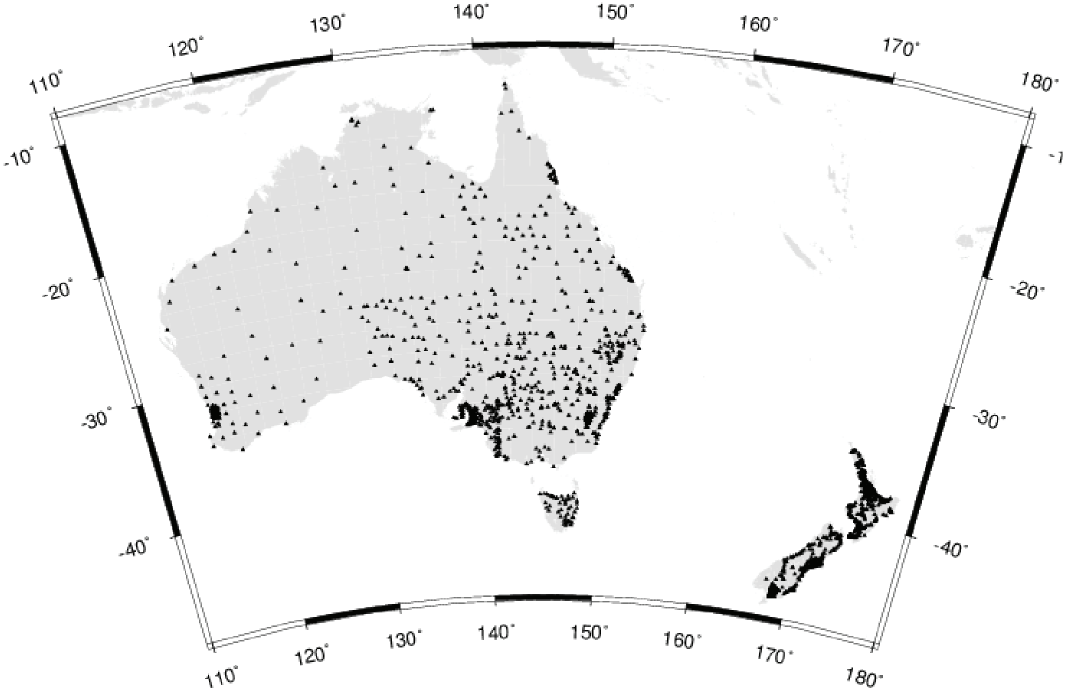

Figure 4. Spatial coverage of the 1,013 Australian GPS-levelling data from NMD and the 1,055 New Zealand GPS-levelling data from LINZ (Lambert projection)

3.3 Astrogeodetic (Helmert) Vertical Deflections at the Earth's Surface

There is a distinction between Helmert deflections of the vertical at the Earth's surface and Pizzetti deflections of the vertical at the geoid (e.g., Jekeli, 1999). To relate these two quantities requires the curvature of the plumbline through the topography, which is notoriously difficult to estimate (e.g., Bomford, 1971; Papp and Benedek, 2000). Therefore, Pizzetti deflections implied by the GGMs will be compared with the astrogeodetically determined Helmert deflections over Australia and New Zealand.

- *Australia*: 1,054 Helmert vertical deflections (Figure 5), observed at Laplace stations as part of the establishment of the Australian Geodetic Datum (Bomford, 1967) and supplied by NMD, were used over Australia. GDA94 geodetic coordinates were used to compute the absolute (as opposed to relative) Helmert vertical deflections (cf. Featherstone and Rüeger, 2000; Jekeli, 1999).
- *New Zealand*: 33 Helmert vertical deflections (Figure 5), observed at Laplace stations as a part of the establishment of the NZGD49 and supplied by LINZ, were used over

New Zealand. As for Australia, NZGD2000 geodetic coordinates were used to compute the absolute Helmert vertical deflections (*ibid.*).

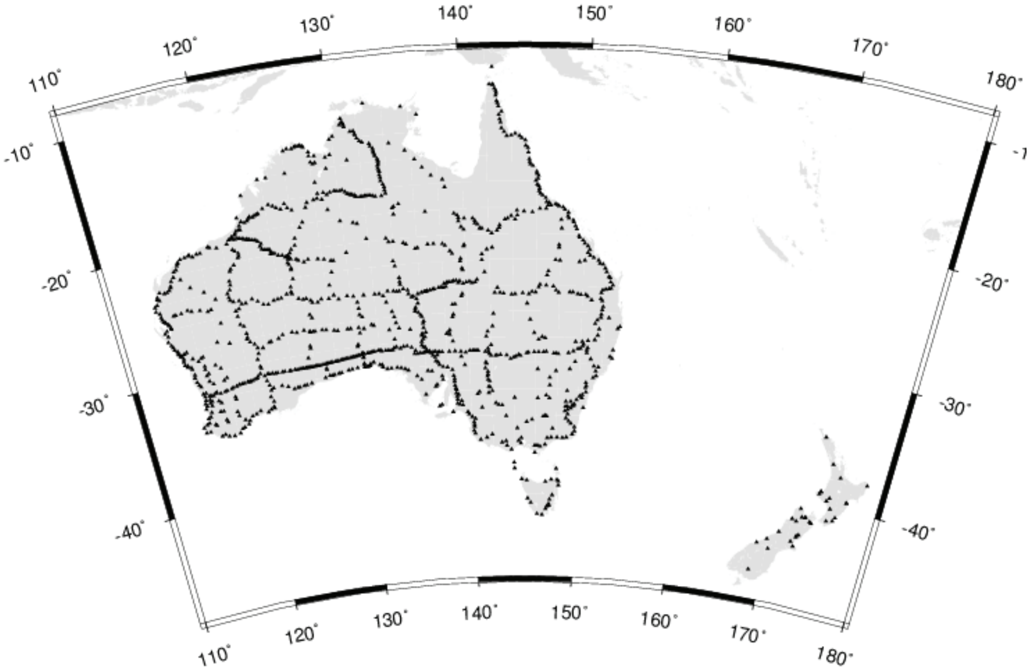

Figure 5. Spatial coverage of the 1,054 Australian astrogeodetic vertical deflections from NMD and the 33 New Zealand astrogeodetic vertical deflections from LINZ (Lambert projection)

3.4 Comments on the ANZ Marine Gravity Data

Unlike the evaluations in Australia by Zhang and Featherstone (1995), Zhang (1998) and Kirby *et al.* (1998), ship-track gravity observations will not be used here. This is because these data have not been crossover adjusted and are thus unreliable (cf. Wessel and Watts, 1998). Featherstone (2002b) demonstrates this by a simple comparison between ship-track gravity anomalies and those derived from multi-mission satellite radar altimetry. Unfortunately, this was not known at the time that AUSGeoid98 was produced (Featherstone et al., 2001). Such comparisons with satellite altimetry also show that the ~1.3 million marine gravity observations surrounding New Zealand have not yet been crossover adjusted, which was confirmed by Woodward (2001, pers. comm.). Finally, satellite altimeter-derived gravity anomalies were not used in these evaluations because they are based on a high-degree combined GGM (usually EGM96) and thus offer little independent low-frequency control on other GGMs.

4. RESULTS AND DISCUSSION

4.1 Problems with Evaluating GGMs using Terrestrial Data

Firstly, it is important to point out that terrestrial free-air gravity anomalies do not form an equivocal test of GGMs, especially the satellite-only GGMs derived from the new dedicated satellite gravity field missions. This is because terrestrial gravity data are highly susceptible to medium- and long-wavelength errors due to factors such as errors in vertical geodetic datums, which are used implicitly to compute gravity anomalies, and to gravimeter drift, which tends to accumulate over long distances. Heck (1990) gives a review of the systematic errors in terrestrial gravity anomalies.

Secondly, GPS-levelling data are also equivocal, predominantly because of the aforementioned distortions in and offsets among vertical geodetic datums. However, simple blunders such as the neglect of the GPS antenna height add ~1.5 m errors in single points, which can be difficult to discriminate between vertical datum and geoid errors if the surrounding GPS-levelling ‘control’ is sparse. In addition, the GPS data used have been collected over a reasonably long period of time, during which processing algorithms and data availability (notably precise orbits) have matured. This is certainly the case for the Australian GPS-levelling data (Johnston and Luton, 2001).

Thirdly, observed vertical deflections, in addition to the aforementioned caveat on Helmert versus Pizzetti deflections, are also subject to their own error budget, notably the precision with which the astrogeodetic measurements could be made. However, these data offer the most independent validation of GGMs because they have not been used in the construction of these models. That is, they were observed using astrogeodetic techniques and are thus based fundamentally on horizontal, as opposed to vertical, geodetic observation techniques.

Finally, and importantly, the terrestrially determined ‘control’ values contain all frequencies of the gravity field, whereas the GGMs do not because of the finite spherical harmonic expansion that renders them subject to the so-called omission error. As such, it is expected that the agreements will improve as the maximum degree of the GGM increases. This is simply due to a reduction in the omission error and should not necessarily be interpreted as an improvement in the low frequencies (i.e., a correspondingly smaller commission error) modelled by these GGMs.

4.2 Results for Australia and New Zealand (ANZ)

Table 2 shows the descriptive statistics of the fit (i.e., terrestrial data minus GGM) of the various GGMs to the ANZ point free-air gravity anomalies on land. Table 3 shows the fit to the ANZ GPS-levelling data (recall that New Zealand uses 12 separate vertical datums). Tables 4 and 5 show the fit of the Pizzetti deflections from the GGMs to the ANZ (Helmert) deflections.

		Australia (768,992 points)				*New Zealand (40,737 points)*			
model	*degree*	*max*	*min*	*mean*	***std***	*max*	*min*	*mean*	***std***
raw data		248.590	-112.321	2.236	25.112	195.785	-163.178	15.921	43.210
JGM-3	70	220.073	-100.940	-0.641	20.975	193.866	-180.249	-1.005	41.337
EGM96S	70	230.386	-99.918	-0.314	22.544	193.855	-183.327	-1.048	41.847
UCPH02	90	224.826	-99.709	-0.906	21.915	193.724	-180.864	-0.624	41.528
GRIM5-S1	99	226.757	-104.719	-0.161	21.932	193.528	-182.117	-0.565	41.811
EIGEN-1S	100	220.658	-108.232	-0.328	21.623	193.266	-181.525	-0.843	41.681
EIGEN-2	120	215.611	-105.875	-1.063	21.419	193.288	-182.501	-1.305	41.695
GRIM5-C1	120	202.758	-94.333	-1.467	18.429	194.682	-179.519	-1.537	40.912
TEG-4	200	211.887	-97.740	-1.749	15.270	193.657	-177.085	-1.693	40.555
GFZ97	359	216.479	-95.959	-0.367	11.103	192.809	-175.652	-1.424	40.391
EGM96	360	220.046	-95.110	-0.722	11.097	192.494	-176.004	-1.770	40.438
EGM96COR	360	220.046	-95.110	-0.722	11.097	192.497	-176.001	-1.750	40.438
PGM2000A	360	219.517	-95.154	-0.675	11.085	192.466	-176.052	-1.823	40.440
EIGEN2/EGM96	32/360	219.949	-95.376	-0.707	11.100	192.369	-176.047	-1.847	40.457
UCPH2/EGM96	41/360	219.978	-99.589	-0.346	11.238	192.260	-175.948	-1.824	40.458
GPM98C	1800	204.165	-96.957	-1.432	14.093	193.012	-176.606	-1.828	40.558

Table 2. Fit of the geopotential models to free-air gravity anomalies on land [mGal]

		Australia (1,013 points)				*New Zealand (1,055 points)*			
model	*degree*	*max*	*min*	*mean*	***std***	*max*	*min*	*mean*	***std***
raw data		71.301	-3.880	11.298	23.106	3.583	39.410	16.235	10.817
JGM-3	70	4.024	-3.838	-0.018	1.156	3.661	-5.350	0.740	1.691
EGM96S	70	5.674	-4.563	0.630	1.665	4.520	-8.392	0.936	2.848
UCPH2002	90	6.240	-4.426	0.061	1.327	4.444	-5.948	1.240	2.152
GRIM5-S1	99	6.527	-4.006	-0.190	1.660	4.558	-7.210	1.254	2.695
EIGEN-1S	100	6.251	-4.114	0.046	1.487	4.462	-6.616	0.940	2.265
EIGEN-2	120	6.376	-3.675	0.054	1.331	3.359	-7.595	0.647	2.259
GRIM5-C1	120	3.492	-2.259	-0.145	0.718	3.248	-4.707	0.000	1.191
TEG-4	200	3.053	-2.543	-0.105	0.499	3.373	-2.397	0.002	0.694
GFZ97	359	3.750	-2.584	-0.052	0.497	4.636	-0.963	0.303	0.697
EGM96	360	3.537	-2.441	-0.015	0.441	3.712	-1.338	0.027	0.616
EGM96COR	360	3.538	-2.442	-0.005	0.434	3.734	-1.332	0.035	0.620
PGM2000A	360	3.466	-2.312	-0.012	0.439	3.660	-1.388	-0.022	0.611
EIGEN2/EGM96	32/360	3.387	-2.514	-0.019	0.425	3.496	-1.376	-0.039	0.606
UCPH2/EGM96	41/360	3.529	-2.517	-0.025	0.458	3.458	-1.284	-0.040	0.604
GPM98C	1800	3.351	-2.459	-0.003	0.491	3.325	-2.152	-0.028	0.675

Table 3. Fit of the geopotential models to GPS-levelling data [m]

		East-west vertical deflections				*North-south vertical deflections*			
model	*degree*	*max*	*min*	*mean*	***std***	*max*	*min*	*mean*	***Std***
raw data		12.935	-20.994	-4.893	3.346	15.092	-27.424	-3.486	4.074
JGM-3	70	19.861	-17.082	0.028	2.941	15.352	-21.449	-0.186	3.453
EGM96S	70	18.250	-15.082	0.173	3.199	16.605	-24.259	-0.066	3.708
UCPH2002	90	19.939	-16.120	0.008	2.983	15.899	-21.726	-0.284	3.748
GRIM5-S1	99	18.707	-15.168	0.136	3.209	16.880	-23.770	-0.125	3.687
EIGEN-1S	100	18.666	-15.890	0.161	3.096	16.889	-23.321	-0.123	3.566
EIGEN-2	120	20.077	-15.349	0.152	3.053	16.582	-20.428	-0.123	3.547
GRIM5-C1	120	20.766	-14.068	0.020	2.672	14.558	-20.142	-0.225	3.156
TEG-4	200	18.727	-9.751	-0.081	2.215	13.608	-15.958	-0.150	2.706
GFZ97	359	21.565	-7.276	-0.130	1.821	14.566	-13.889	-0.123	2.218
EGM96	360	20.574	-7.314	-0.100	1.791	14.453	-13.328	-0.084	2.189
EGM96COR	360	20.574	-7.314	-0.100	1.791	14.453	-13.328	-0.084	2.189
PGM2000A	360	20.620	-7.328	-0.089	1.790	14.567	-13.178	-0.084	2.190
EIGEN2/EGM96	32/360	20.611	-7.332	-0.105	1.788	14.557	-13.315	-0.090	2.187
UCPH2/EGM96	41/360	20.426	-7.530	-0.156	1.819	14.385	-13.168	-0.116	2.207
GPM98C	1800	19.158	-7.777	-0.089	2.154	13.444	-14.088	-0.200	2.525

Table 4. Fit of the geopotential models to 1054 Helmert vertical deflections over Australia ["]

		East-west vertical deflections				*North-south vertical deflections*			
model	*degree*	*max*	*min*	*mean*	***std***	*max*	*min*	*mean*	***Std***
raw data		15.759	-27.797	-2.714	9.183	15.844	-16.798	0.154	8.289
JGM-3	70	14.072	-18.273	1.604	7.564	14.540	-12.869	0.015	7.145
EGM96S	70	16.480	-20.981	1.981	8.450	15.316	-14.222	0.283	7.759
UCPH2002	90	15.196	-19.465	1.752	7.901	14.401	-13.634	0.010	7.238
GRIM5-S1	99	14.790	-21.967	1.416	8.377	16.055	-14.561	0.658	7.747
EIGEN-1S	100	15.524	-21.088	1.766	8.268	14.178	-13.695	0.026	7.192
EIGEN-2	120	15.858	-20.595	2.037	8.260	15.960	-14.337	-0.180	7.753
GRIM5-C1	120	15.141	-14.838	2.122	7.148	10.185	-12.070	-0.444	6.355
TEG-4	200	15.464	-7.118	2.762	5.635	10.076	-12.504	0.081	6.199
GFZ97	359	17.585	-7.210	3.180	5.543	10.198	-12.946	0.082	5.742
EGM96	360	13.671	-7.380	2.605	4.688	9.852	-12.596	-0.012	5.258
EGM96COR	360	13.671	-7.380	2.606	4.688	9.852	-12.596	-0.013	5.252
PGM2000A	360	13.670	-7.363	2.615	4.681	9.908	-12.610	-0.013	5.257
EIGEN2/EGM96	32/360	13.577	-7.500	2.559	4.681	9.840	-12.648	-0.040	5.254
UCPH2/EGM96	41/360	13.569	-7.296	2.570	4.646	10.005	-12.535	-0.008	5.279
GPM98C	1800	16.924	-5.926	2.274	5.196	9.549	-10.364	-0.450	5.369

Table 5. Fit of the geopotential models to 33 Helmert vertical deflections over NZ ["]

4.3 Discussion of Results

Recall that due to the omission of the zero-degree term, the standard deviations (std) in Tables 2 through 5 will be used to infer the best fits of the various GGMs to the terrestrial-gravity-field-related data (and *vice versa*). Firstly, a number of somewhat expected observations are evident from Tables 2 through 5; these are:

- The fits of the GGMs to the Australian data are consistently better (up to a factor of about four) than for the New Zealand data. This is due to a combination of the different terrestrial 'control' data used and the different geological settings. Australia is an old and heavily weathered continent, whereas New Zealand is at the active boundary of the Australian and Pacific tectonic plates. New Zealand hosts considerably more rugged terrain than Australia. Therefore, the New Zealand gravity field, as sensed by terrestrial observations, contains more variability and power in the high frequencies than Australia, which cannot be described by the GGMs (cf. Jekeli, 1999). Simply comparing the descriptive statistics of the raw data in Tables 2, 4 and 5 confirms the former point.

- Generally, the lower the spherical harmonic degree, the poorer the fit of the GGMs to the ANZ data. This is entirely as expected because the higher degree expansions have smaller omission errors (but not necessarily smaller commission errors in the low degrees). The exception to this trend is GPM98C (cf. Zhang et al., 2002), which does not include ANZ data because of data confidentiality clauses.

- The combined GGMs always give better fits to the ANZ gravity data than the satellite-only models (cf. Table 1), which is expected because most of the former include terrestrial gravity data from this part of the world. However, this observation is also correlated with the reduced omission error associated with the higher degree spherical harmonic expansions. Nevertheless, it is plausible that the satellite-only GGMs, notably those derived from the CHAMP mission data, are more precise than the combined GGMs in the low frequencies because the latter will have been contaminated by long- and medium- wavelength errors in the terrestrial gravity data (described earlier). Therefore, comparisons with terrestrial gravity data are necessarily not such a good means of assessing the precision of satellite-only GGMs (cf. Reigber *et al*., 2002).

Secondly, there are some specific inferences that can be made by comparing the results among Tables 2 through 5:

- The fit of the GGMs to the New Zealand GPS-levelling data is consistently (by about 20%) worse than that for the Australian GPS-levelling data (Table 3). Acknowledging the presence of GPS and levelling errors, as well as the more rugged topography and gravity field in New Zealand, this larger difference is also likely to be caused by the 13 separate vertical datums used in New Zealand. Amos and Featherstone (2002) estimate that the offsets could be as large as 0.5 m.

- The fits of the GGMs to the vertical deflections in Australia broadly agree with those observed in North America (cf. Jekeli, 1999). However, the fits to the New Zealand data are consistently poorer, typically by a factor of 2 to 3. Given that vertical deflections are most sensitive to the high-frequencies, this result is probably due to a combination of the rugged topography and hence gravity field in New Zealand (as evidenced by the larger standard deviations of the raw vertical deflections (cf. Tables 4 and 5) that is not sensed by the GGMs (due to the omission error), as well as the [theoretically in-appropriate] comparison of observed Helmert deflections with Pizzetti deflections from the GGMs.

- The UCPH2002_02 and EIGEN-2 CHAMP-satellite-only GGMs generally give a better fit to the ANZ data than the other satellite-only GGMs (cf. Table 1). UCPH2002_02 gives a slightly better fit than EIGEN-2, but the difference is statistically insignificant when considering the error budget of the ANZ 'control' data. Assuming for the moment that there are no low-frequency errors in the ANZ data, this vindicates the use of CHAMP hl-SST and accelerometry data. Therefore, if a satellite-only GGM is to be used for Australian and New Zealand geoid models (cf. Vanicek and Sjöberg, 1991), UCPH2002_02, EIGEN-2 or subsequent GGMs that include dedicated satellite gravity data should be used.
- It is virtually impossible to select the combined GGM that gives the best fit to the ANZ data. All the high-degree models give results that are not statistically significantly different from one another when considering the errors in the 'control' data. Therefore, the choice becomes somewhat more arbitrary.
- The hybrid GGMs that replaced the low-degree coefficients of EGM96 with EIGEN-2 and UCPH2002_02 (Table 1 and the discussion thereafter) show a minor (though not statistically significant) improvement over EGM96. This is somewhat expected since these combined models essentially extend the degree and order of the CHAMP derived models. Of the two, EIGEN2/EGM96 gives a marginally better fit, but again the amount of improvement is not statistically significant. Given the theoretical benefits of using dedicated satellite gravimetry data (e.g., Rummel et al., 2002; Featherstone, 2002a), it is likely that this type of hybrid GGM will be adopted for future ANZ geoid computations.

5. CONCLUSIONS AND RECOMMENDATIONS

The results of these comparisons of recent GGMs with terrestrial gravity data, GPS-levelling and vertical deflections over Australia and New Zealand show general trends that can be expected given the omission errors in the models and the expected quality of the 'control' data. In terms of selecting the optimal GGM for the computation of future Australian and New Zealand regional gravimetric geoid models, a number of GGMs present themselves as suitable candidates. If the regional geoid is to be based on a satellite-only GGM, then EIGEN-2 should be used. Any of the high-degree combined GGMs can be used. If the regional geoid is to be based on a so-called hybrid GGM, then the EIGEN2/EGM96 is a suitable candidate. The GPM98 tailored GGM should not be used over Australia or New Zealand because it has not included terrestrial gravity data from these regions.

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