# Progress towards implementation and development of a New Zealand national vertical datum

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**Abstract.** New Zealand currently uses 13 disparate vertical datums, each connected to a separate tide gauge. In 1998, a new national datum, NZGD2000, was implemented based on GPS observations. This leads to a 3D geocentric datum. As further development of the spatial infrastructure in New Zealand, Land Information New Zealand approved the implementation of a new national vertical datum that is independent of local mean sea level. This new national vertical datum will be based on ellipsoidal heights, and the relationship between the separate existing vertical datums relative to the ellipsoid will be established using a high-precision regional gravimetric geoid model.

Phase one of this programme is the development of a regional geoid model for New Zealand. This paper will present the current status of development of the regional geoid model. Two geoids have been computed to determine the effectiveness of a 'gravity reconstruction technique' in New Zealand. The models computed are based on a combination of the EIGEN-2 satellite-only global geopotential model, which uses CHAMP dedicated satellite gravity data, and EGM96. Residual geoid undulations were computed from 40,000 land gravity observations and satellite altimeter-derived marine gravity anomalies. GPS and first-order spirit levelling data was used in conjunction with the geoid model to estimate offsets among the 13 vertical datums.

**Keywords.** Gravimetric geoid, vertical datum unification, New Zealand

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## 1 Introduction

New Zealand does not currently have a single national vertical datum. Instead, 13 disparate local levelling datums are used. Each of these is based on local mean sea level (MSL) observed at different tide gauges at different times. The MSL determinations were generally over a short time period (less than two weeks in some cases). Despite some early evidence to the contrary, the datums were assumed to be stable and thus capable of being connected by precise levelling, so that they could eventually form a national vertical datum (e.g., Hannah, 2001).

Precise levelling is an accurate means of transferring heights between points, however the long period (~40 years) over which the New Zealand observations were made, means the network will most certainly be subject to uplift or subsidence due to a variety of processes. New Zealand is situated at the active boundary of the Australian and Pacific plates. This uplift and subsidence can be as much as 8.5 metres over ~40 years in localised areas, and ~10 mm/yr over larger areas (Walcott 1984).

Due to computational limitations at the time of calculation, each levelling network was adjusted independently. Even if a national adjustment was performed, New Zealand consists of two primary islands; so at least two vertical datums would result. The use of multiple local datums suited the height transfer technology of the time (i.e., precise levelling or vertical angles) and as most users only dealt with small spatial areas they were not concerned by the overlap (or lack thereof) of adjacent datums.

With the emergence of "modern" satellite based positioning technology (notably GPS) and the adoption of the New Zealand Geodetic Datum 2000 (see next section), both of which reference an ellipsoid as opposed to the local gravity vector, there is now a pressing need for a national height system that can incorporate both ellipsoidal and gravity-related heights.

This paper briefly presents the rationale for a new vertical geodetic datum in New Zealand, followed by recent geoid results, which advance upon those in Amos and Featherstone (2003a).

## 2 The Vertical Geodetic Datum

In 1998, the New Zealand Geodetic Datum 2000 (NZGD2000) was officially released as a replacement for the existing New Zealand Geodetic Datum 1949 (NZGD49) (Grant and Blick, 1998). NZGD49 was a horizontal datum that was realised from over 35 years triangulation observations, coupled with astronomical observations for position and azimuth control.

In contrast to NZGD49, NZGD2000 is a 3D system that was realised using GPS observations and is defined in terms of the International Terrestrial Reference Frame 1996 (ITRF96) at the fixed epoch of 1 January 2000. To partially account for the tectonic dynamics of New Zealand, a horizontal deformation model forms an integral component of the datum. This model is used to transform observations backwards (and forwards) to 1 January 2000 so that consistent comparisons and adjustments can be made. It also assumes that there is zero vertical movement, which - as shown earlier - is clearly not the case. These and other limitations of the current datum, and some potential solutions, are discussed in Blick et al. (2003).

As stated earlier, NZGD2000 is a 3D datum that has its vertical component defined by the GRS80 ellipsoid. While this is a convenient mathematical reference surface, it is not easily conceptualised (or understood) by many users of the geodetic system. Users generally demand heights that are related to the gravity field, primarily to determine fluid flows and to be consistent with the existing geodetic infrastructure in New Zealand. It is therefore apparent that for a large number of applications (i.e., those that demand heights referenced to the local gravity vector) NZGD2000 is essentially a horizontal datum.

To establish a "usable" 3D datum, it is proposed to retain the ellipsoid as the "official" height system and to provide offsets between it and the 13 local datums. This will allow users to continue using the local datums, and will also support the use of technology, such as GPS, that references the ellipsoid. It will provide a nationally consistent height system for New Zealand. The obvious method of achieving this is through the use of a geoid model.

## 3 A Geoid Model for New Zealand

Unlike many other countries, New Zealand does not currently have a regional geoid model to support geodetic operations, including the transformation of GPS-derived heights to orthometric heights (e.g., Reilly, 1990). Global geopotential models are available to degree 360 (e.g., EGM96; Lemoine et al. 1998) that have an equivalent spatial resolution of ~50 km. This is insufficient for localised applications, as global geopotential models do not provide much information on the high-frequency variations in the geoid (i.e., the omission error).

Gilliland (1990) computed the first gravimetric co-geoid for New Zealand on a 0.25° grid using gravity data and the OSU81 (Rapp, 1981) global model to degree 180. Unfortunately this regional co-geoid model is no longer available for use. Nevertheless, advances in theory and data availability would now render this model outdated.

Therefore, there is a need to compute a new geoid model for New Zealand. Amos and Featherstone (2003a) computed a very preliminary co-geoid model, but it has since been found that some incorrectly mapped and thus pre-processed gravity data had been used. In addition, the above two co-geoid models omit the primary indirect effect term, which may be greater than ~0.5 m in magnitude at the summit of Aoraki/Mount Cook, the highest mountain in New Zealand (~3754 m above local MSL).

Probably the largest challenge to high-precision gravimetric geoid computation in New Zealand is its use of the 13 separate vertical geodetic datums based on local MSL. As stated earlier, each levelling network (cf. Gilliland 1987) is based on MSL observed at a different tide gauge, often over a very short time period. As well as not averaging out long-period tidal effects, these tide gauges are subject to sea surface topography (SST), which is notoriously difficult to quantify and model in the coastal zone (e.g., Hipkin 2000) or in harbours and estuaries where most of the tide gauges are located.

The effect of SST means that MSL measured at tide gauges departs from a single equipotential surface. This will create offsets between adjacent or overlapping vertical datums that have been based on such measurements (cf. Hipkin 2000). The broad-scale variation in SST estimated by satellite altimetry is 40 cm from the far North to far South of New Zealand (Hannah 2001).

Other oceanographic phenomena, such as storm surges or the outflow of fresh water (a number of gauges are located in river mouths) also act to bias the tide-gauge-measured MSL. Accordingly, the 13 vertical datums in New Zealand are not unified and may be offset from one another by more than 0.2 m (Pearse 1998).

These different vertical datums introduce two primary problems to practical geoid determination.

First, the regional gravity and terrain data used to compute the geoid model refer to different reference surfaces (i.e., MSL carried in-land by spirit levelling in each of the datums). This causes long- and medium-wavelength errors in the computed gravity anomalies (cf. Heck, 1990), which then propagate into the gravimetric geoid model. Secondly, a single geoid model will not be suited for the direct transformation of GPS heights to these local vertical datums. Therefore, the New Zealand vertical datum will be based on a combination of ellipsoidal heights (in the 3D NZGD2000) and a precise regional geoid model. This geoid model will then allow the existing vertical datums to be unified (cf. Kumar and Burke 1998), but first it is necessary to contend with the above-mentioned practical and theoretical difficulties.

## 4 Preliminary Geoid Computations

Two new preliminary gravimetric geoids have been computed for the New Zealand region using a combined EIGEN2-EGM96 global geopotential model (see next paragraph), terrestrial gravity data and satellite derived marine gravity anomalies. The difference between the two models is in the way that the gravity data has been treated. One uses 'traditional' point free-air anomalies and the other uses mean free-air anomalies reconstructed using a DEM (described later).

Amos and Featherstone (2003b) tested fifteen global geopotential models (GGM) against gravity observations, GPS-levelling observations and deflections of the vertical in New Zealand and Australia. Included in the GGMs tested were two combined models that were constructed by replacing the low-order coefficients of EGM96 with those from EIGEN-2 (Reigber et al. 2002) and UCPH2002_02 (Howe et al. 2002) CHAMP-satellite-only models. They found a marginal improvement over EGM96 when the combined EIGEN2-EGM96 model was used. As such, this model is used as the reference GGM in this investigation.

The 2001 release of the Institute of Geological and Nuclear Sciences (GNS) national gravity database was used for the computation of this gravimetric geoid. This release consists of approximately 40,000 terrestrial and 1 million marine gravity observations.

The satellite altimetry grid of Hwang et al. (2002) was used to provide gravity information in the marine areas surrounding New Zealand. A comparison of the GNS marine data with the satellite altimeter data revealed that numerous errors exist as a result of no crossover analysis being performed. The crossover analysis is currently in progress, so for the purposes of this gravimetric geoid model the GNS marine data has been excluded and altimeter-derived anomalies used instead.

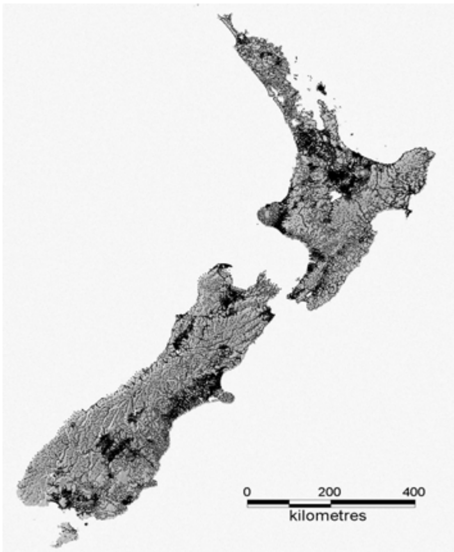


**Figure 1.** Terrestrial gravity coverage in New Zealand

The terrestrial gravity coverage (Figure 1) in New Zealand is, on average, spatially dense; however, the sampling method used is neither random nor regular. Due to the harsh topography in large parts of the country, the practicalities of collecting gravity data in the field mean that gravity is generally observed in the more accessible lowland regions. Table 1 shows a comparison of the elevations of the gravity observations and elevations from a 1.8 arc-second (56 m) Geographx DEM in a one-degree square in the South Island high country.

| | Max | Min | Mean |
|---|---|---|---|
| Gravity | 2023.6 | 107.9 | 492.164 |
| DEM | 2326.0 | 89.0 | 889.841 |

**Table 1.** Comparison of elevations from gravity observations and DEM in the Lewis Pass area of the South Island high country (units in metres)

It can be seen from Table 1 that the average height of the gravity observations is approximately half that of the DEM. This indicates that the locations of the gravity points are not representative of the topography in the area. This will result in an underestimate of the effect of topography in the geoid in this area.

Featherstone and Kirby (2000) describe a procedure where free-air anomalies are "reconstructed" from Bouguer anomalies by the application of a "reverse" Bouguer plate correction from the height of the DEM. This produces a grid of mean free-air anomalies at the same resolution as the DEM. For the purposes of this study, a 250-metre resolution Geographx DEM was averaged onto a 2-arc-minute grid. The abovementioned 56-metre DEM was not used for computational reasons; however, it will be implemented for future models.

The computation procedure employed for the two gravimetric geoids is described fully in Amos and Featherstone (2003c). In summary, two grids of free-air anomalies were compiled. The first arithmetically averaged the free-air anomalies extracted from the GNS database onto a two-arc-minute grid. The second averaged the Bouguer anomalies onto the same 2-arc-minute grid and then used the technique cited above to reconstruct the free-air values from a DEM on the same grid. These will be referred to as the "simple" and "reconstructed" grids respectively. Terrain corrections were taken from the GNS database.

Both of the terrestrial gravity grids were then merged with the altimetry data to give two free-air anomaly grids over the computation area (160°E–10°W, 25°S–60°S). The EIGEN2-EGM GGM was then removed from each to give residual anomalies. The descriptive statistics of these anomalies are shown in Table 2. These differences are expected, as the reconstructed anomalies are more representative of the topography.

| Grid | Max | Min | Mean | STD |
|---|---|---|---|---|
| Simple Mean | 351.90 | -292.80 | 1.75 | 34.36 |
| Reconstructed Mean | 555.19 | -292.80 | 3.74 | 39.76 |
| Residual Simple | 352.53 | -358.80 | -0.15 | 13.41 |
| Residual Reconstructed | 539.18 | -358.80 | 1.83 | 21.38 |

**Table 2.** Descriptive statistics of grided mean 2' by 2' gravity anomalies (units in mGal)

The residual anomaly grids were then subjected to a 1-D-FFT transformation with a deterministically modified Stokes kernel (Featherstone et al. (1998) with $M$=20 and $\psi o$=1°) to evaluate the residual geoid. The resultant grids were then restored using the EIGEN2-EGM GGM and a correction for the primary indirect effect (Wicheincharoen 1982) was applied. The descriptive statistics of the various geoid contributions are shown in Table 3.

| Grid | Max | Min | Mean | STD |
|---|---|---|---|---|
| EIGEN-EGM GGM geoid | 54.051 | -46.607 | 5.981 | 28.258 |
| Residual Simple Undulations | 2.208 | -1.958 | -0.019 | 0.226 |
| Residual Reconstructed Undulations | 15.355 | -1.486 | 0.216 | 1.279 |
| Indirect effect | 0.000 | -0.499 | -0.001 | 0.007 |
| Simple Geoid | 54.131 | -46.541 | 5.959 | 28.252 |
| Reconstructed Geoid | 54.169 | -46.535 | 6.197 | 28.235 |

**Table 3.** Descriptive statistics of contributions to the New Zealand geoid (units in metres)

The resulting 'simple' and 'reconstructed' geoids are shown in Figures 2 and 3 respectively. The effect of the reconstruction can be seen very clearly in Figure 3 where the Southern Alps (running northeast to southwest along the South Island) are now visible. This suggests that the effect of the topography is being treated more realistically.

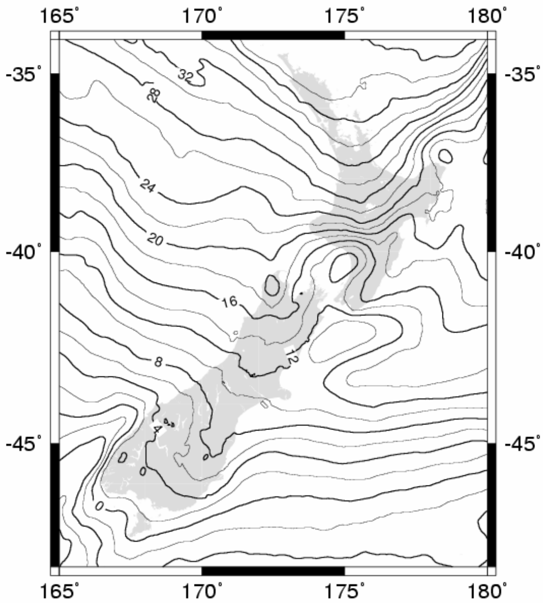


**Figure 2.** Gravimetric geoid of New Zealand using 'simple' gravity anomalies (contours in metres)

The two geoids were then compared against a nation-wide set of 1055 GPS-levelling points. As mentioned earlier, the levelled heights are based on 13 different datums, which will bias the differences computed in Table 4. Regardless of this, there is a significant improvement of the fit of the GPS-levelling to the 'reconstructed' geoid when compared to the 'simple' geoid. This suggests that the use of a higher resolution DEM in the reconstruction technique should be further investigated, as well as the role of topographical corrections.

The two geoids were then tested with GPS-levelling on a datum-by-datum basis. As well as to verify the new geoid models, this gives a *preliminary* indication of the offsets among these 13 vertical datums. The results of this testing with the reconstructed geoid are shown in Table 5. Though all the descriptive statistics are shown, only the mean differences should be interpreted as the preliminary offsets (cf. Featherstone 2000).

| Geoid | Max | Min | Mean | STD |
|---|---|---|---|---|
| EIGEN2-EGM | 3.496 | -1.376 | -0.039 | 0.606 |
| Simple | 4.604 | -0.480 | 0.436 | 0.754 |
| Reconstructed | 0.309 | -1.712 | -0.352 | 0.349 |

**Table 4.** Descriptive statistics of the comparison of geoid models with 1055 GPS-levelling points (units in metres)

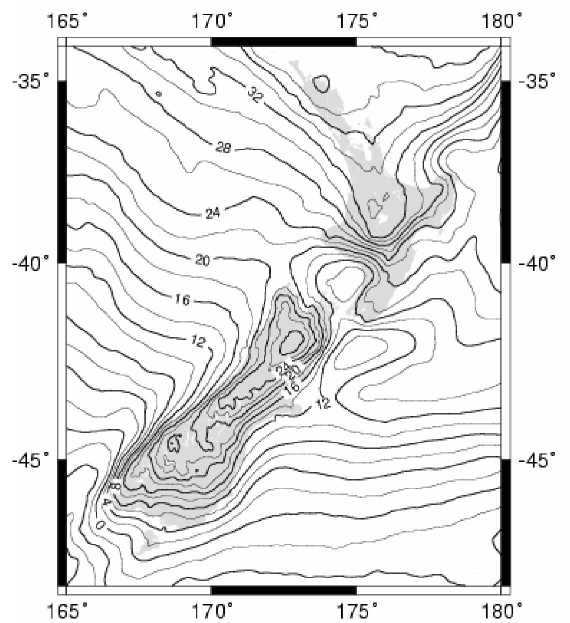


**Figure 3.** Gravimetric geoid of New Zealand using 'reconstructed' gravity anomalies (contours in metres)

The values in Table 5 show broad agreement with observed differences between adjacent datums, which are in a restricted-access database held by Land Information New Zealand. However, the GPS-levelling points used in their derivation are often not representative of the entire datum. A program to acquire additional GPS positions at benchmarks is currently underway, the outcome of which will be a GPS-levelling point approximately every 7-10 km along levelling lines.

## 5 Conclusions

A new national vertical geodetic datum is proposed for New Zealand that will unify the 13 independent datums that are currently used. This datum will consist of a regional gravimetric geoid model that will provide the ability to transform heights from the local datums to the official ellipsoidal system. This will enable the retention of the disparate datums that are currently used to good effect and allow the use of technology such as GPS to obtain heights in terms of them.

The technique of 'reconstructing' free-air anomalies (Featherstone and Kirby 2000) using a 2-arc-minute DEM has shown significant improvements in accounting for topography. This is especially apparent in areas of harsh relief where gravity observations are often made in the valleys and do not sample as thoroughly the more inaccessible surrounding mountains.

| Datum | Pts | Max | Min | **Mean** | STD |
|---|---|---|---|---|---|
| Auckland | 84 | -0.006 | -0.612 | **-0.373** | 0.145 |
| Bluff | 91 | 0.280 | -0.078 | **0.050** | 0.057 |
| Dud-Bluff | 170 | 0.309 | -0.098 | **0.114** | 0.083 |
| Dunedin | 58 | 0.234 | -0.778 | **-0.288** | 0.170 |
| Gisborne | 57 | -0.508 | -0.778 | **-0.620** | 0.080 |
| Lyttelton | 164 | 0.194 | -1.712 | **-0.556** | 0.263 |
| Moturiki | 163 | -0.087 | -0.673 | **-0.338** | 0.146 |
| Napier | 26 | -0.297 | -0.551 | **-0.438** | 0.081 |
| Nelson | 46 | -0.690 | -1.185 | **-1.021** | 0.085 |
| One Tree | 34 | 0.001 | -0.253 | **-0.105** | 0.065 |
| Taranaki | 57 | -0.314 | -0.726 | **-0.535** | 0.107 |
| Tararu | 13 | -0.221 | -0.775 | **-0.530** | 0.230 |
| Wellington | 67 | -0.540 | -0.964 | **-0.816** | 0.137 |

**Table 5.** Descriptive statistics of comparison of reconstructed geoid with GPS-levelling points on each vertical datum, datum offset in bold (units in metres)

Of the two geoid models computed, the 'reconstructed' model has a significantly better fit to GPS-levelling than the simple model and other previously computed prototype models. The standard deviation of the differences is ~0.35 m for the 'reconstructed' model, which compares favourably to the ~0.75 m and 0.60 m from the 'simple' and

GGM models, respectively. The computed offsets of each datum from the geoid are also better resolved. These estimates will be confirmed when a high-precision GPS survey at each of these points is completed later in 2003.

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