New Zealand Vertical Datum 2009 – A Geoid Based Height System for the Unification of Disparate Local Vertical Datums

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SUMMARY

Until recently heights in New Zealand have been referred to 13 separate local vertical datums (LVDs) based on normal-orthometric-corrected precise geodetic levelling from 12 different tide-gauges. In September 2009 a new national vertical datum, New Zealand Vertical Datum 2009 (NZVD2009), was implemented to unify the existing LVDs and to provide a nationally consistent height reference system.

NZVD2009 is unique amongst national vertical datums in that it uses a gravimetric geoid as its reference surface. The conventional approach to vertical datum definition is to fix the height of one or more benchmarks and relate future heights on this. This was the approach that was used for New Zealand's existing local vertical datums.

To enable users to effectively connect to and work in terms of NZVD2009 official transformations have been defined. This makes the conversion of ellipsoidal heights in terms of NZGD2000/WGS84 or normal-orthometric heights in terms of one of the LVDs to NZVD2009 a straight forward undertaking.

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1. INTRODUCTION

Until recently New Zealand did not have a single national vertical datum to which spatial datasets could be consistently referenced. Instead 13 separate local vertical datums (LVDs) based on mean sea level (MSL) observed at 12 tide-gauges have been used (the Dunedin-Bluff 1960 LVD was defined by fixing the heights of two benchmarks from the Dunedin 1958 and Bluff 1955 LVDs instead of using a tide-gauge).

First-order precise levelling was used to transfer heights from the tide-gauges to the hinterland. There is currently >16,000 km of two-way first-order levelling that has been observed since the 1960s (see Figure 1). These networks were observed in a piece-meal fashion and the large loop around the South Island was only completed in the late 1980s. Because gravity observations are not available at the benchmarks approximate normal-orthometric corrections, in terms of GRS67, were applied to the precise levelling observations to give normal-orthometric heights.

2. MOTIVATION FOR A NEW HEIGHT SYSTEM

While the existing LVDs have served New Zealand's heighting requirements well for many years, there are a number of limitations associated with them. Each datum is based on a value of MSL at a fixed point in time ranging from 1926 to 1977. These MSL levels have not been updated since the inception of the datums. Furthermore they were typically determined from less than the 18 years of sea level observations necessary to observe the full metonic cycle. As such the resulting level may not have reliably represented MSL at the time the datum was established let alone now with up to 80 years of subsidence and sea-level rise to account for.

Because the LVDs were extended from the tide-gauges using precise levelling their coverage is limited to the main road networks. Much of the topography of New Zealand is rugged and is not accessible by road. This has resulted in the large gaps identified in Figure 1, particularly the central-south part of the South Island. This has made physically connecting to the vertical datums difficult where a user is not working adjacent to a state highway.

A fundamental problem with the current levelling networks is that the benchmarks representing the heights typically have not been re-levelled since they were first established. This means that the heights in some cases can be up to 50 years old. New Zealand is subject to significant deformation. As such it is likely that many of the published heights are of a lesser accuracy than what is reported. Precise levelling is an expensive undertaking. It is not economically feasible for all the benchmark runs in the country to be re-observed.

A more cost-effective means of determining heights today is to use GNSS technology. This is routinely done in New Zealand for the establishment of control marks and ellipsoidal heights are published for them in terms of the New Zealand Geodetic Datum 2000 (NZGD2000; LINZ, 2007). The existing LVDs can not be efficiently and consistently combined with NZGD2000 on a national basis because until recently no national geoid has been available and the offsets between the LVDs have not been known.

Any new national vertical datum needs to exhibit the following attributes:

- Single consistent reference system across mainland New Zealand and its offshore islands
- Consistent with NZGD2000 geodetic datum
- Compatible with GNSS heighting
- Accessible across all of New Zealand and offshore
- Cost-effective to implement and maintain

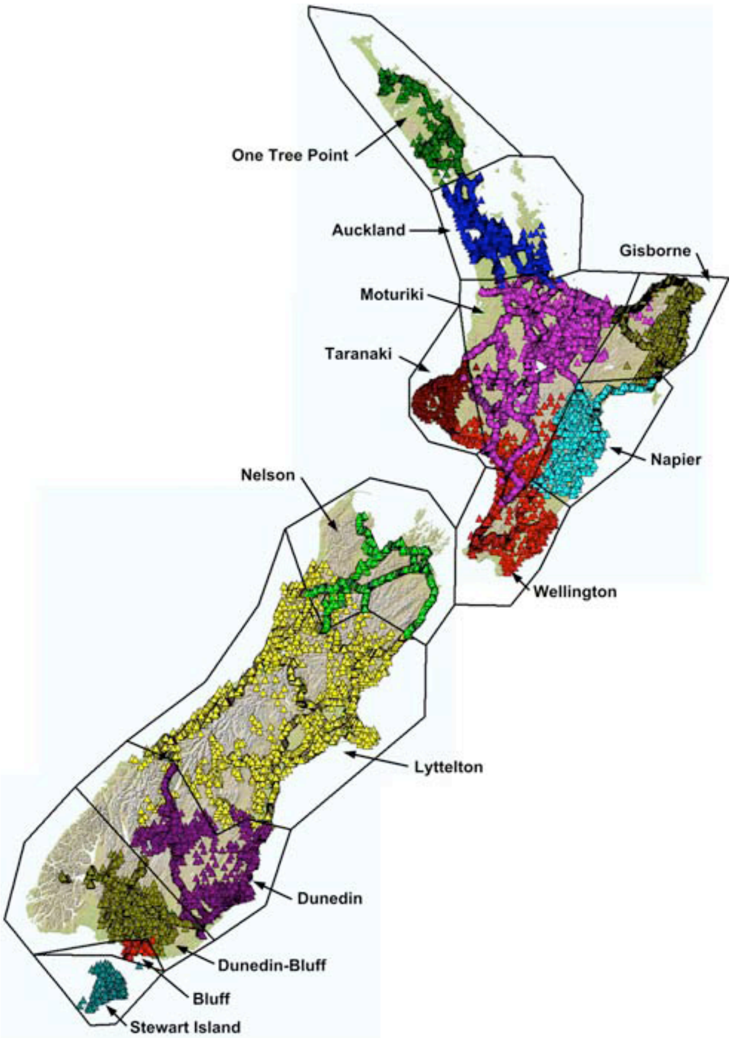

Figure 1: New Zealand local vertical datums

3. NEW ZEALAND VERTICAL DATUM 2009

The New Zealand Vertical Datum 2009 (NZVD2009) was implemented in September 2009 (LINZ, 2009). It provides New Zealand with a nationally consistent vertical reference system for the first time. The new datum has the following characteristics:

- Normal orthometric height system
- Reference surface: New Zealand Quasigeoid 2009 (NZGeoid2009)
- Offsets are defined from NZVD2009 to the 13 LVDs
- Transformations are defined between NZVD2009, NZGD2000 and the 13 LVDs

3.1 Normal-orthometric heights

Because New Zealand does not have surface gravity observations at many of its precise levelling benchmarks it is not possible to compute geopotential numbers, orthometric heights or normal heights. As such the normal-orthometric height system has been retained.

To ensure consistency with the NZGD2000, which refers to the GRS80 ellipsoid, the rigorous normal-orthometric correction equation defined by Heck (2003) is used with the GRS80 gravity flattening constant (f^*). This correction is given as:

$$NOC = -2\frac{f^*}{R}\sum_{P_1}^{P_2}\left(H_k \sin 2A_k \cos\alpha_k \Delta s_k\right)$$

where $f^* = 0.005302440112$, $R = 6371000\mathrm{m}$, H is the height difference in metres, A is the average latitude, α is the azimuth between stations, and Δs the distance between stations in metres.

3.2 New Zealand Quasigeoid 2009 (NZGeoid2009)

The NZGeoid2009 (Figure 2) is the national geoid of New Zealand. It was computed by the Western Australian Centre for Geodesy following the same general procedure that was used for its predecessor NZGeoid05 (Amos, 2007; Amos and Featherstone, 2009).

NZGeoid2009 is a regional gravimetric quasigeoid computed over the extent of New Zealand's continental shelf (160°E – 170°W, 60°S –25°S). It is based on the EGM2008 global gravity model (Pavlis et al. 2008) up to degree and order 2160 and has been enhanced with 40,737 terrestrial gravity observations across New Zealand, marine anomalies from the DNSC08 global model (Andersen et al, 2008), and a 0.0005° (~56 m) digital elevation model to correct for the effect of the topography on the gravity field.

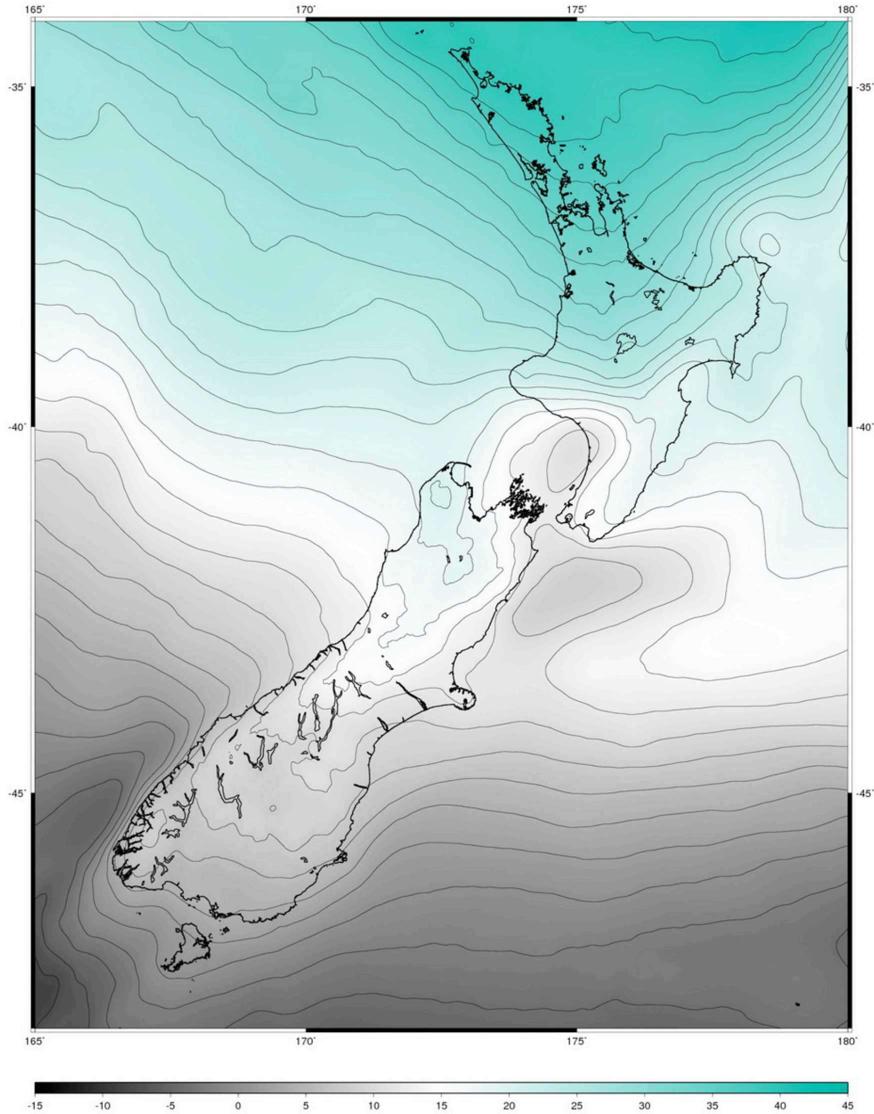

Figure 2: NZGeoid2009 over the New Zealand mainland (2 metre contours)

The model was computed using a remove-compute-restore approach using Stokes integration with a deterministically modified integration kernel (Featherstone et al, 1998) with L = 40 and ψ_0 = 2.5° (L is the spherical harmonic degrees removed from the kernel and ψ_0 the integration cap radius). A detailed description of the computation process for NZGeoid2009 is provided in Claessens et al (2009).

Across the New Zealand mainland the "height" of NZGeoid2009 above the GRS80 ellipsoid varies from 0 m at the South of Stewart Island/Rakiura to approximately 40 m at the north of the North Island. This change is generally in a north-south direction, with some local variations around topographic and geological features. It is published (and was computed) on a 1 x 1 arc-minute grid (~1.9 km in New Zealand) which means that localised variations in the geoid that are smaller than this will not be represented in the model.

3.3 Offsets to local vertical datums

The accuracy of NZGeoid2009 was estimated by comparisons with geometrically determined geoid values at control marks where both ellipsoidal and normal-orthometric heights have previously been observed. In New Zealand there are 1,422 suitable GPS-levelling points that are spread among the 13 LVDs (Figure 3). It can be seen that the spatial coverage of the GPS-levelling points is not uniform, and that large gaps exist in some areas. Furthermore many of the points are located in topographically flat terrain rather than the mountains.

Across all 1422 GPS-levelling points the average standard deviation of the difference to NZGeoid2009 is 0.062 m. The comparisons on a datum-by-datum basis are shown in Table 1 (LINZ 2009). It can be seen that all of the offsets are significantly non-zero. The standard deviation of the Stewart Island 1977 datum is larger than the others because it has been determined from five relatively low-accuracy GPS-levelling points.

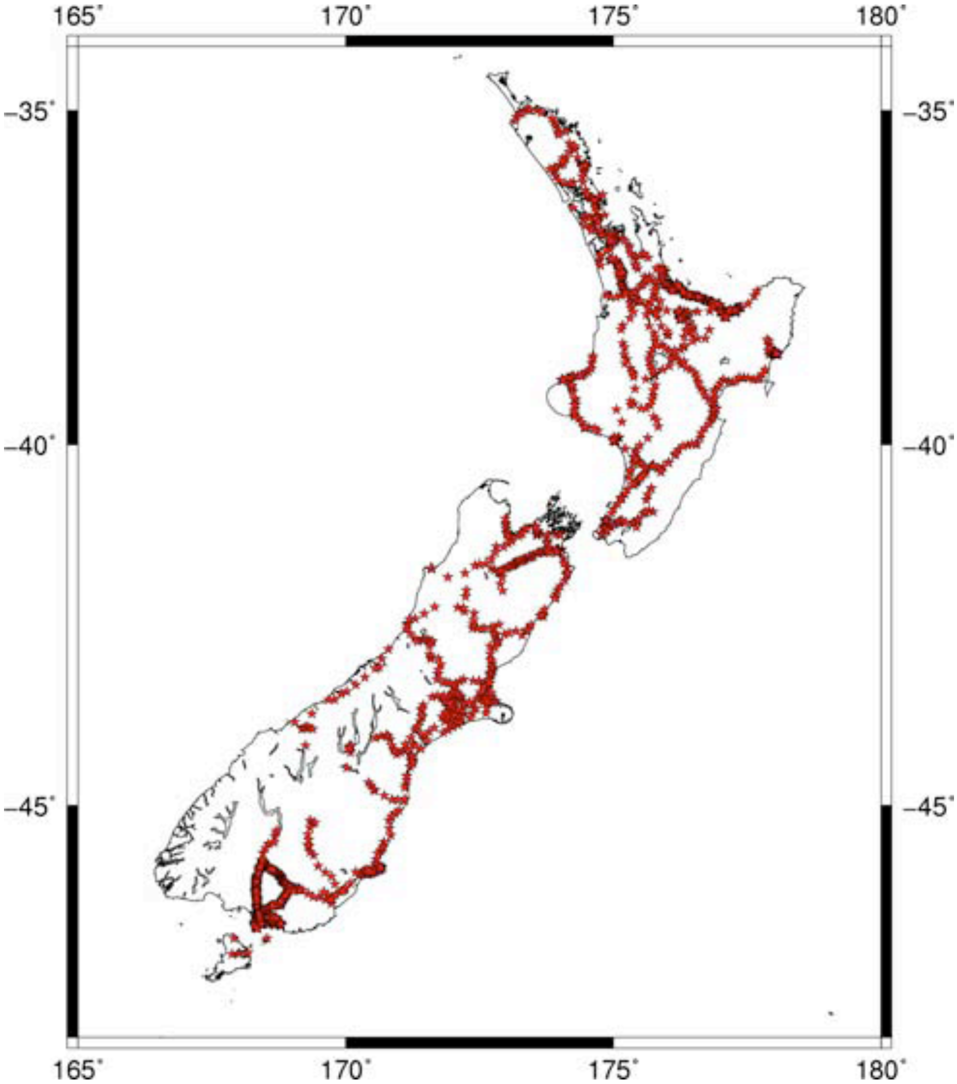

Figure 3: 1422 GPS-levelling points

Datum	Offset to NZVD2009	Standard Deviation
One Tree Point 1964	0.06	0.03
Auckland 1946	0.34	0.05
Moturiki 1953	0.24	0.06
Gisborne 1926	0.34	0.02
Napier 1962	0.20	0.05
Taranaki 1970	0.32	0.05
Wellington 1953	0.44	0.04
Nelson 1955	0.29	0.07
Lyttelton 1937	0.47	0.09
Dunedin 1958	0.49	0.07
Dunedin-Bluff 1960	0.38	0.04
Bluff 1955	0.36	0.05
Stewart Island 1977	0.39	0.15

Table 1: Offsets from NZVD2009 to the 13 LVDs and their standard deviations (metres)

3.4 Height transformations

The relationship between NZVD2009 and the other height systems used in New Zealand is shown diagrammatically in Figure 4. In addition to enabling the transformation of heights from the LVDs to NZVD2009, it is also a straight-forward task to convert both NZVD2009 and LVD heights to and from NZGD2000 ellipsoidal heights, and heights between different LVDs. This enables the integration of the geodetic and vertical datums of New Zealand and encourages the uptake of the new datum by users.

The transformations have been defined in LINZ (2009) as:

NZGD2000 to NZVD2009 $\quad H_{NZVD2009} = h - N$

LVD to NZVD2009 $\quad H_{NZVD2009} = H_A - o_A$

LVD A to LVD B $\quad H_B = H_A + o_A - o_B$

LVD to NZGD2000 $\quad h = H_A + N + o_A$

where *H* are normal-orthometric heights in terms of the subscripted datums, *h* is the NZGD2000 ellipsoidal height, *N* is the bi-linearly interpolated NZGeoid2009 height, *o* is the offset for the subscripted datum.

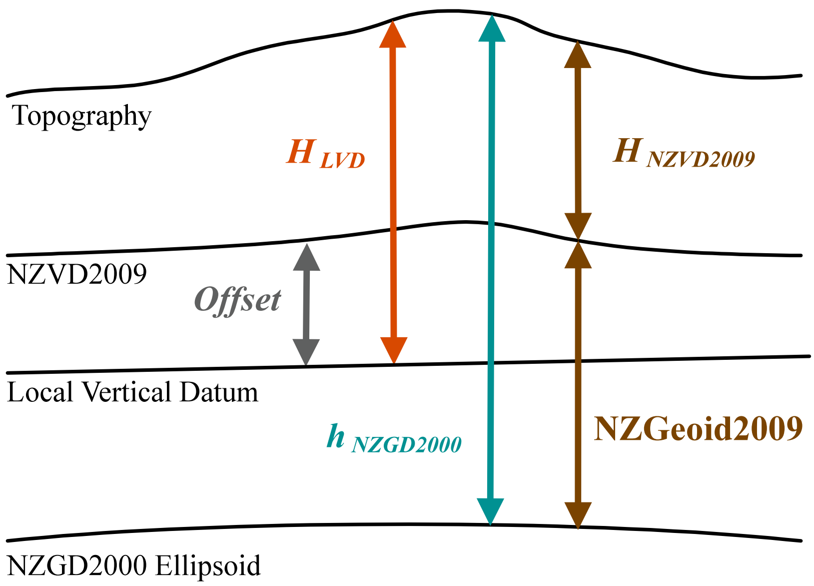

Figure 4: Relationships between heights

4. CONCLUSION

New Zealand is the first country to physically implement a national vertical datum that uses a gravimetric geoid as its reference surface. It is acknowledged that a number of other jurisdictions are also progressing towards this approach for their modernised vertical datums.

The new vertical datum, NZVD2009, provides New Zealand with a single vertical reference system that can be easily accessed using GNSS technology anywhere within New Zealand. Existing datasets that are held in terms of the LVDs can be easily converted to NZVD2009 using a consistent transformation, the NZGeoid2009 model and the appropriate offset.

REFERENCES

Amos, MJ, 2007, Quasigeoid modelling in New Zealand to unify multiple local vertical datums, PhD Thesis, Department of Spatial Sciences, Curtin University of Technology, Perth

Amos, MJ, Featherstone, WE, 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

Anderson, OB, Knudsen, P, Berry, P, Kenyon, S, 2008, The DNSC08 ocean wide altimetry derived gravity field, Paper presented at the 2008 General Assembly of the European Geosciences Union, Vienna, Austria, April 13-18, 2008

Classens, S, Hirt, C, Featherstone, WE, Kirby, JF, 2009, Computation of a new gravimetric quasigeoid model for New Zealand, technical report prepared for Land Information New Zealand by Western Australia Centre for Geodesy, Available at: http://www.linz.govt.nz/geodetic/standards-publications/technical-reports/index.aspx

Featherstone, WE, Evans, JD, Olliver, JG, 1998, A Meissl-modified Vanicek and Kleusberg kernel to reduce the truncation error in gravimetric geoid computations, Journal of Geodesy, 72(3): 154-160, doi: 10.1007/s001900050157

Heck, B, 2003, Rechenverfahren und Auswertemodelle der Landesvermessung, 3rd edn. Wichman, Karlsruhe, Germany

LINZ, 2007, Standard for New Zealand Geodetic Datum 2000, LINZS25000, Land Information New Zealand, Wellington, Available at: http://www.linz.govt.nz/geodetic/standards-publications/standards/index.aspx

LINZ, 2009, Standard for the New Zealand Vertical Datum 2009, LINZS25004, Land Information New Zealand, Wellington, Available at: http://www.linz.govt.nz/geodetic/standards-publications/standards/index.aspx

Pavlis, NK, Holmes, SA, Kenyon, SC, Factor, JK, 2008, An Earth Gravitational Model to degree 2160: EGM2008, Paper presented at the 2008 General Assembly of the European Geosciences Union, Vienna, Austria, April 13-18, 2008

BIOGRAPHICAL NOTES

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