Toitu te Land whenua Information New Zealand

Airborne Gravity for an Improved Vertical Datum

Options for the development of New Zealand's vertical datum

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New Zealand Government

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1 Executive Summary

When the New Zealand Vertical Datum 2009 (NZVD2009) was implemented in 2009 it provided for the first time a nationally consistent height reference system across New Zealand. The geoid based NZVD2009 also includes offsets to 13 local vertical datums that enable the consistent transformation of data by users.

The datum was well received by users and has been widely implemented by customers in their systems and work practices. NZVD2009 has a nominal accuracy of 0.08 metres nationally however this varies between 0.02 and 0.15 metres across the 13 local vertical datums. There are also reports of larger errors in areas where checking is not currently possible due to a lack of data.

Customers have two main requirements of a vertical datum, (1) heights can be accurately referenced in terms of it, and (2) geospatial data held in terms of other vertical datums can be accurately transformed to it.

The needs of most users would be satisfied by improving the vertical datum from its current accuracy of 0.08 metres to an accuracy of better than 0.03 metres. Those users that require a more accurate height system are generally amenable to utilising other systems for their particular applications.

The NZ vertical datum could be improved to a standard that achieves the 0.03 metre customer accuracy requirement by re-computing the national geoid with data from a national airborne gravity survey. The use of airborne gravity to improve geoid modelling is an internationally proven technique.

In parallel to the airborne survey, the quality of the 13 local vertical datum offsets should be improved, and offsets defined to other datums used by customers. Work should also be undertaken to investigate alternative approaches to modelling the offsets between datums. Both of these initiatives will increase the uptake of the national datum by users and facilitate easier integration of datasets, such as those derived from the LINZ Data Service.

The successful completion of this project will provide NZ with a world-class vertical datum that will meet customer's needs for the medium-term. It will also assist LINZ to continue demonstrating leadership in the geospatial arena within NZ and internationally.

2 Introduction

The provision of an integrated national vertical datum is essential for enabling the integration of geospatial data across the land and sea areas of New Zealand. The integration of height information is more difficult than horizontal because the vertical reference surfaces are often less well defined. New Zealand Vertical Datum 2009 (NZVD2009) is the current official vertical datum for New Zealand. It is defined by the NZGeoid2009 geoid surface and provides normal-orthometric heights that are consistent with NZGD2000 and GNSS derived ellipsoidal heights.

NZVD2009 was very well received by users of the geodetic system because it provided a nationally consistent height reference system for the first time. For many users, the more significant benefit of NZVD2009 was that it provided an official transformation surface (geoid) for consistently converting GNSS derived ellipsoidal heights to NZVD2009 and also 13 local vertical datums with an accuracy of 5-10 cm. While the uptake of NZVD2009 has been very good, feedback from users has indicated that its accuracy is limiting its penetration within a number of applications.

This report identifies the accuracy requirements of current and future users of the datum. It then contrasts a number of options for enhancing NZVD2009 to meet these customer needs before recommending a preferred improvement approach.

3 Customer Requirements for a Vertical Datum

3.1 Cadastral Surveys

Section 7(1) of the Cadastral Survey Act 2002 (CSA) specifies the functions and duties of the Surveyor-General. The relevant functions and duties to this discussion are:

(a) to maintain a national geodetic system

(b) to maintain a national survey control system

(c) to determine how the spatial extent (including boundaries) of interests under a tenure system must be defined and described, by setting standards under section 49

These require LINZ to maintain both a vertical datum and a network of heighted marks so that heighted cadastral boundaries can be efficiently related to each other.

The Surveyor-General's Rules for Cadastral Survey 2010, published under Section 49 of the CSA, specify the horizontal and vertical accuracy of boundary points in Rule 3.3.1. Heighted boundaries are most likely to occur in residential areas where Class A accuracy requirements apply.

Ruling LINZR65301 specifies that heighted boundaries refer to NZVD2009 or one of the 13 local vertical datums if the boundary is within 200 m of a heighted control mark. If the NZGD2000 ellipsoidal heights of existing control marks were able to be transformed to NZVD2009 normal-orthometric heights with sufficient accuracy, cadastral surveys would be required to be submitted to LINZ in terms of a consistent vertical datum.

The Class A boundary-to-boundary accuracy must not exceed the following at the 95% confidence level:

$$\sqrt{0.04^2 + (dist \times 0.0001)^2} \text{ m}$$

The accuracy between non-boundary marks (including permanent reference marks) and heighted boundary marks must not exceed the following at the 95% confidence level:

$$\sqrt{0.025^2 + (dist \times 0.0001)^2} \text{ m}$$

For example, this means that the error on a 200 m line from a (non-boundary) permanent reference mark to a boundary mark must not exceed 0.032 m.

3.2 Local Government

Local government agencies (city, district and regional councils) are significant users of vertical datums. Vertical datums are critical to the design and successful operation of flood protection and irrigation schemes as well as gravity fed sewerage and storm water systems. They are also important for the definition and application of minimum building platform elevations, primarily to protect buildings from water inundation from rivers, lakes or seas as a result of natural disasters or climate change.

This demand has been especially evident in the recovery work resulting from the 2010 and 2011 Canterbury earthquakes. Primary concerns when reconstructing essential services have been ensuring that the heights are reliable and referred to a common consistent datum. This is of particular importance in Christchurch due to the relatively flat topography. The accuracy specification for the re-establishment of the Christchurch City Council bench mark network is 0.03 m.

3.3 GIS Community

In the past the GIS community utilised proprietary software with extensive in-house databases. Updates to datasets were received on physical media and incorporated into the systems by trained operators who understood the data that was being manipulated. The cost of GIS technology restricted its use to large organisations who had the resource to manage the complex systems.

Today GIS has a significantly greater market penetration. It is dominated by web-based applications where datasets are acquired and displayed on-demand and seamlessly integrated into the database of the user. In parallel with this application change has been the enormous increase in the number of datasets available and the related increase in the level of accuracy that is being demanded by users through their desire to apply the technology to more specific applications. The LINZ Data Service is specifically designed to meet the needs of this group of users.

For a vertical datum to meet the needs of these users it must enable the unique representation of heights with an accuracy of better than 0.1 m. Additionally, the relationships between the national datum and other locally used datums should be defined to encourage the migration of existing datasets to the official system. The definition of datum relationships will facilitate the integration of customer datasets with fundamental data from services such as the LDS.

3.4 Topography and Hydrography

Topographic surveying and mapping is usually carried out in terms of a horizontal datum and mean sea level is the origin for heights. This system, where mean sea level represents zero height, allows positive contours for height on land and negative contours (or depth) offshore. The approach serves many practical purposes and is probably the way that most of the public perceive heights. Topographic maps published at a 1:50,000 scale require MSL to be accurate to better than 4 m. This accuracy is commensurate with the vertical accuracy of the 20 metre contour lines (±10 m).

For nautical charting the origin for depths is the Lowest Astronomic Tide (LAT) but for heights (clearances) it is Highest Astronomic Tide (HAT). The accuracy required varies depending on the depth of the water. For shallow surveys (generally less than 30 metres depth, e.g. harbour channels) the depths need to be accurate to 0.25 m or better at the 95% confidence level.

The proposed LINZ project to develop a unified land and sea elevation dataset will require the composite data to align horizontally and vertically to a higher standard. Given the accuracy of the hydrographic data (0.25 m) and the likely accuracy of a national DEM (0.2 m) it can be inferred that a national vertical datum accuracy of 0.15 m would satisfy these needs. Additionally, this project can not be completed without a consistent vertical datum to which the datasets can be related.

3.5 Scientific Research

Research organisations such as NIWA, GNS Science and universities have a range of projects that require different levels of height accuracy and which can utilise different heighting methods.

For example, Earth deformation monitoring is normally concerned with relative changes in heights, rather than the actual height in relation to sea level. As such these surveys can utilise ellipsoidal heights or relative height difference measurements. These high precision studies will often require accuracies at the few-millimetre level.

It is unlikely that the national vertical datum will be able to support these very high accuracy requirements.

Scientific studies that cover large regional or national areas require lesser accuracy at individual points, but require the heights to refer to the Earth's gravity field and be in terms of a consistent datum. These studies are often seeking to determine long-term changes (e.g. environmental) so require a stable reference system and also the ability to integrate legacy data held in terms of older datums. These types of applications generally require heights with an accuracy of 0.5 to 1.0 metres.

NZVD2009 is able to support the height requirements of the regional studies where heights are determined using GNSS. Depending on the quality of the source data, the NZGeoid2009 can be used to transform it from a local vertical datum to NZVD2009 at the required accuracy.

3.6 Engineering

Engineering projects that involve the transportation of fluids have been one of the main users of the precise levelling networks. Whether the projects involve piping liquids, artificial canals or existing waterways, changes in gravity across the project area will affect the project design. They require a vertical datum that can represent the gravity field changes to a sufficient accuracy. Often these applications require a high relative accuracy between adjacent points, e.g. millimetres, but are less concerned with the absolute height which can be up to a metre. Historically, heights in these applications would have been established using precise levelling. The same method is still used today where high accuracy is required.

A geoid based vertical datum may be able to provide relative heights to the high-millimetre-level accuracy for projects with a spatial extent of a few kilometres. It is probably unable to meet the needs of very high accuracy applications.

3.7 General Public

The general public normally expect heights to be measured in relation to sea level – this is the intuitive height reference surface. The recent influx of consumer grade GNSS receivers has raised the public's interest in height systems. GNSS users are likely to want to be able to determine their height with their GNSS enabled device (e.g. mobile phone) in relation to sea level to the accuracy of the GNSS position. In short, they do not want to be concerned with the ellipsoid to geoid transformation.

The current accuracy of handheld GNSS receivers is no better than 0.5 metres, therefore the national datum is accurate enough to meet the current needs of the general public. However, the rapid improvement in GNSS accuracy may mean that higher accuracy is required in the future. It is unclear what accuracy will be required, although the demand is unlikely to be better than 0.1 m.

An increase in positioning capability from consumer-grade GNSS-enabled devices could place additional demands on the geodetic system. The easier availability of this technology may mean that the vertical datum needs to be more accessible to users. Will customers demand mobile phone applications that can produce official heights and positions? Is this an area that LINZ should be involved in? These are questions that need to be considered when LINZ implements an updated vertical (or geodetic) datum.

3.8 Relationships to Other Datums

The effect of not being able to efficiently determine NZVD2009 heights at the required accuracy means customers are more likely to use other unofficial vertical datums. This can lead to incorrect decisions being made due to inconsistent or insufficient data. For example, combining inconsistent geospatial datasets could lead to drainage systems being designed in which water flows the wrong way (or not at all).

Currently customers are also storing geospatial data in a range of vertical datums. When they wish to integrate their data with other datasets, such as those accessed from the LINZ Data Service, it is necessary to transform them to a consistent datum (such as NZVD2009).

3.9 Summary

The most exacting requirements for a vertical datum arise from the precision science and engineering sectors where accuracy at the millimetre level is needed. However, as shown in sections 3.5 and 3.6 above, these accuracy needs can be met by a geometric datum (such as ITRF) for science or a site specific reference frame for engineering. It is not practicable to provide a national (or arguably even a regional) gravimetric datum with a millimetre-level accuracy.

The local government and cadastral surveying applications need to provide consistent heights with an accuracy of approximately 0.03 m (sections 3.1 and 3.2). Given that a legislative customer of the geodetic system is the cadastral system, the national vertical datum should be able to support its requirements. Equally, as an important customer of the geodetic system, local government needs also should be met by the national datum.

The provision of a national vertical datum with an accuracy of better than 0.03 m would meet the requirements of most geodetic customers.

4 New Zealand Vertical Datum 2009

4.1 Description of Datum

The New Zealand Vertical Datum 2009 (NZVD2009) was implemented in September 2009. It provided for the first time in NZ a nationally consistent vertical datum that was accessible across the entire country. It provides normal-orthometric (gravity-based) heights and compliments the ellipsoidal (geometric) heights provided by the New Zealand Geodetic Datum 2000 (NZGD2000). Most customers require gravity-based heights as they relate to sea level and indicate the direction that fluids will flow.

NZVD2009 is unique in that it uses a regional geoid model, New Zealand Quasigeoid 2009 (NZGeoid2009, see Figure 1), as the reference surface for heights rather than mean sea level defined at tide-gauges. This approach also means that the datum is accessible throughout NZ if GNSS technology is utilised. Previously a user would have needed to physically visit a bench mark to access the datum. This was often inefficient as the bench marks are generally located alongside state highway networks whereas most users are not.

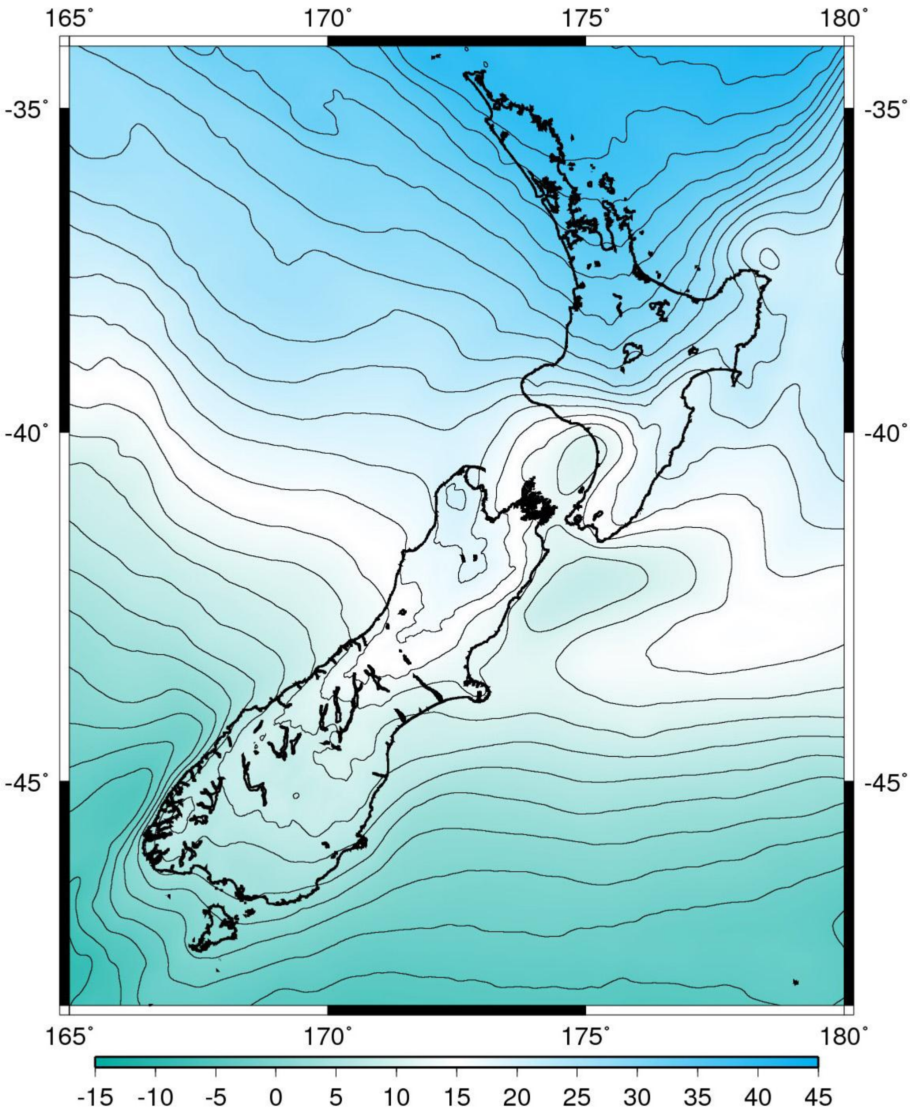

Figure 1 – New Zealand Quasigeoid 2009 (2 metre contours)

NZGeoid2009 is a regional quasigeoid that is based on the EGM2008[1] global gravity model and which has been locally enhanced over NZ. The enhancements were achieved by incorporating terrestrial gravity observations (Figure 2) and topography information from a digital elevation model over land, and satellite altimetry-derived gravity data in marine areas. Incorporating the additional information enabled NZGeoid2009 to be published on a 2x2 arc-minute grid (~1.9 km) across NZ and its continental shelf.

The implementation of NZVD2009 was warmly received by customers because it enabled them to use their GNSS technology to consistently and efficiently determine heights in terms of both NZVD2009 and their existing local vertical datums.

Prior to NZVD2009 customers needed to develop their own height transformations on a site-by-site basis. This led to inconsistencies between different datasets and uncertainty for future data users because it was frequently not clear what transformation was being used. There were also instances of local transformations being retained as proprietary information amongst firms. Following NZVD2009, the need to develop customised transformations has greatly reduced and the detail of the method that has been used to transform height data is more commonly understood.

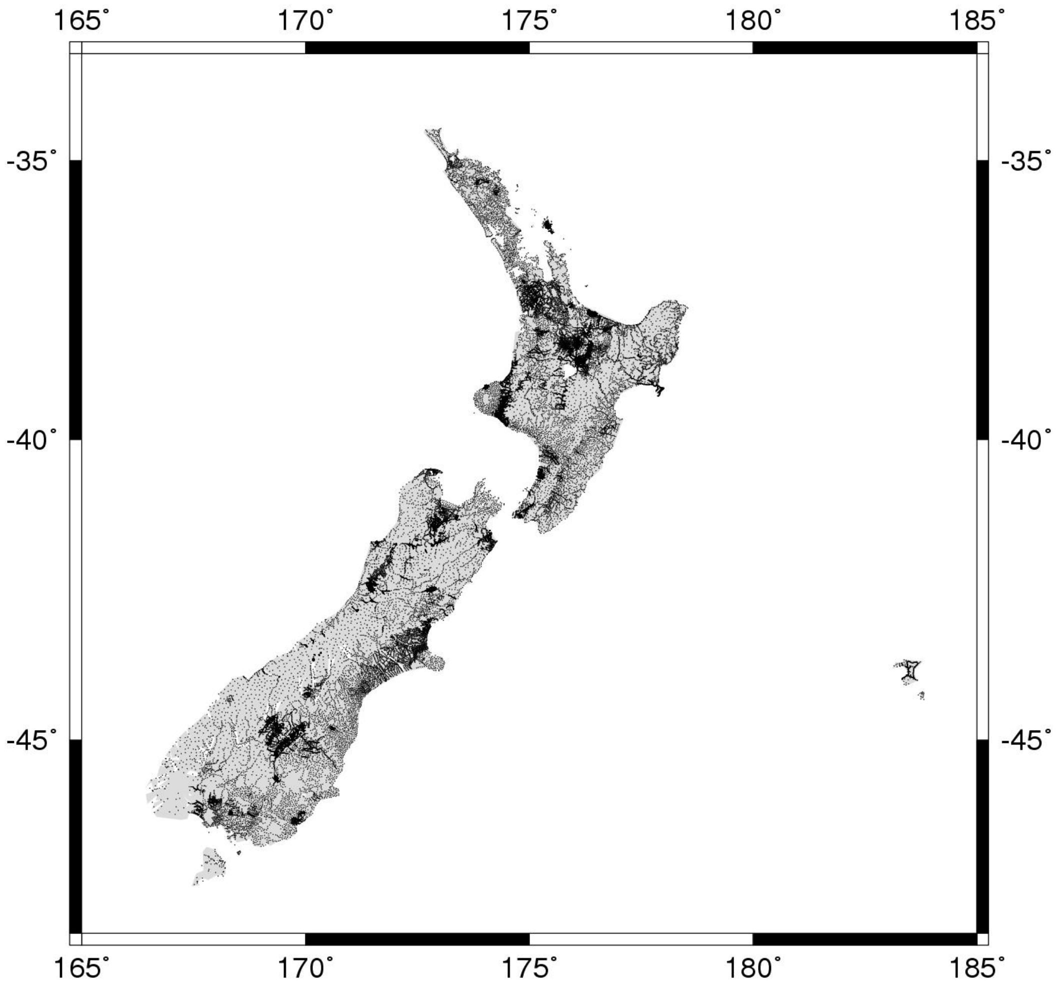

Figure 2 – New Zealand Terrestrial Gravity Observations

[1] Pavlis N, Holmes S, Kenyon S, Factor J (2008) An earth gravitational model to degree 2160: EGM2008, presentation to EGU General Assembly, Vienna, Austria, 13-18 April 2008, available from: http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/egm08_wgs84.html

4.2 Local Vertical Datums

Prior to the implementation of NZVD2009 heights were referenced to a variety of local vertical datums (LVDs). Each LVD was normally referenced to a tide-gauge so that heights in terms of it broadly coincide with mean sea level (MSL). Because MSL is not a constant surface, and the methods of determining it vary, the LVDs are almost always not in terms of each other. This means that datasets held in different datums can not easily be integrated together.

LINZ, through its predecessor agencies, was responsible for the installation of a national network of precisely levelled bench marks with normal-orthometric heights that are referred to 13 major LVDs (Figure 3). Offsets between these LVDs and NZVD2009 were published with the national datum to facilitate the transformation of heights between the systems. The offsets were calculated by comparing bench marks with LVD and NZGD2000 heights with the NZVD2009 value. These marks are often known as GPS-levelling points. The national GPS-levelling dataset is shown in Figure 4.

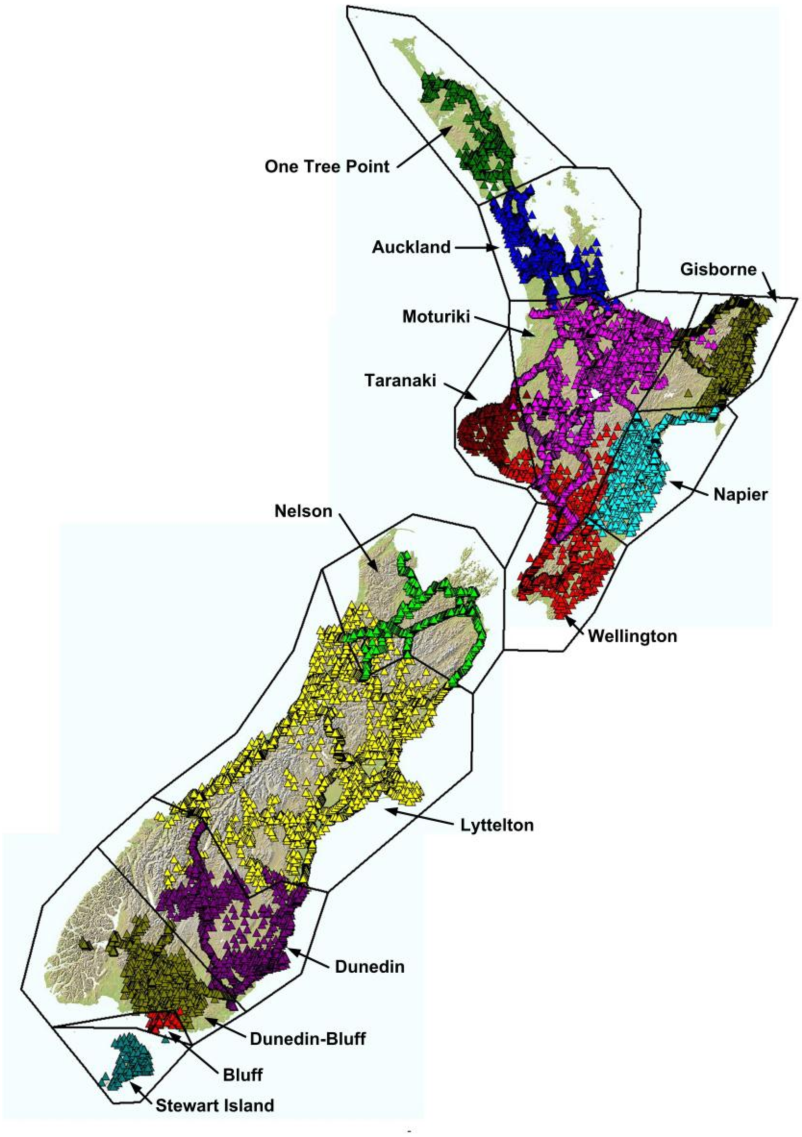

Figure 3 – Local vertical datum extents and coverage

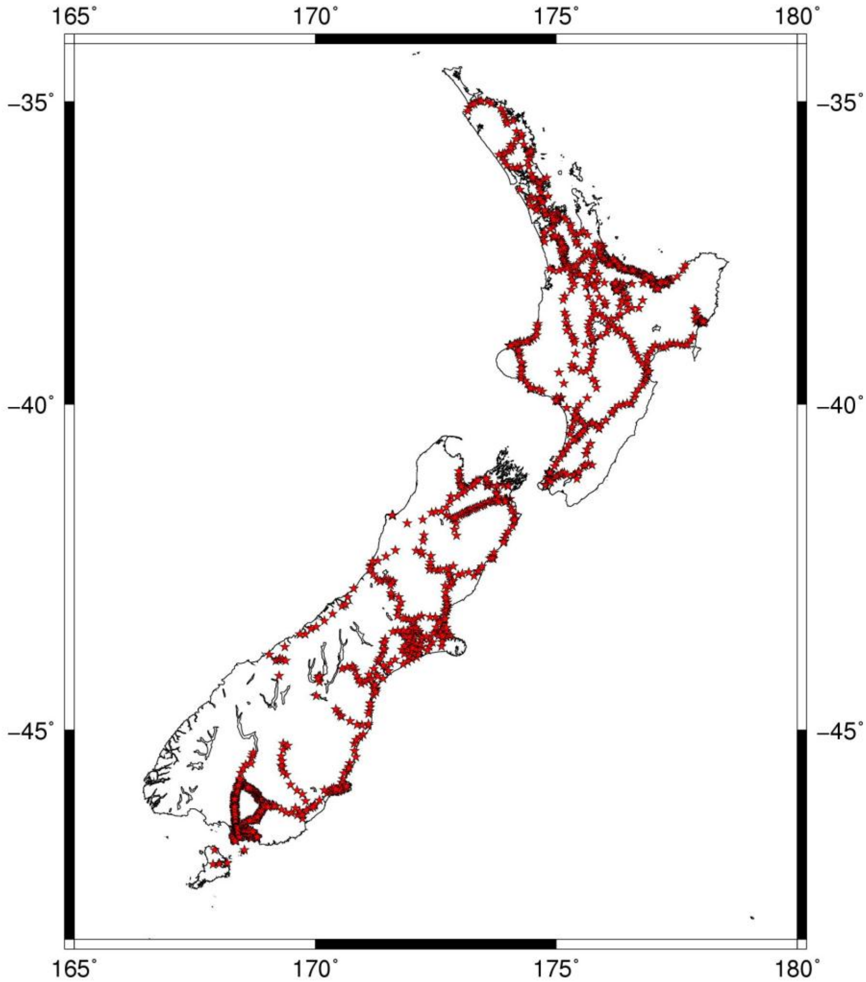

Figure 4 – GPS-levelling points

The relationship between NZVD2009 and the 13 major LVDs are defined as a single offset per datum. This simplistic approach assumes that the difference between the datums is uniform across their extent. It is also reliant on the regular spatial distribution of GPS-levelling points across the datum.

The spatial coverage requirement is not achieved in many of the datums (cf. East Cape on Figure 4). This means that while the GPS-levelling statistics (see section 4.3) give good agreement, the computed offset may not be representative of the parts of the datum that are not sampled. There is anecdotal evidence to suggest that in some areas the use of a constant offset is not the best way to model the difference between datums. In the Dunedin datum the GPS-levelling residuals along the east coast are relatively consistent. However the residuals on the north-west line heading to Central Otago systematically increase away from the coast. This implies that an inclined plane may be a better modelling option.

It may be possible to improve the quality of the offsets by investigating different techniques of modelling the relationships between the datums, for example inclined planes or polynomial surfaces. These options should be investigated in conjunction with the datum improvement project.

In addition to the 13 major LVDs, many other local datums are also used around the country. These are frequently defined by local or regional authorities for planning, infrastructure or flood protection purposes. As these datums do not have official offsets to NZVD2009 users need to develop their own transformation to take advantage of GNSS technology.

LINZ should give consideration to publishing official offsets to other local datums. This would enable consistent transformations to be made by customers and therefore improve the integration of these datasets with those held in other datums.

4.3 NZVD2009 Accuracy

The accuracy of NZVD2009 can be assessed by comparing NZGeoid2009 values at GPS-levelling points (marks with both LVD and NZGD2000 heights). The average difference for all points on a datum is the datum offset. The standard deviation of this average gives a measure of the offset accuracy. The offsets and standard deviations for each of the 13 LVDs are provided in Table 1. The offset errors represent the combined uncertainty of the offset and the NZGeoid2009.

It can be seen in Table 1 that the standard deviation varies between 0.02 and 0.15 m across the datums, the larger errors are indicative of either relatively few GPS-levelling points (e.g. Stewart Island) or very large areas of coverage (e.g. Lyttelton, Moturiki). The accuracy of NZVD2009 across all of NZ is 0.08 m.

Local Vertical Datum	NZGeoid2009 Offset (metres)	Standard Deviation (metres)
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 – NZGeoid2009 offsets to major local vertical datums

Anecdotal evidence from users also indicates that the accuracy of NZVD2009 is variable across NZ. The lower accuracy areas are primarily where the spacing and location of gravity observations was insufficient to represent the true gravity field in an area. Examples include:

- Banks and Otago Peninsulas where the gravity field inferred from the gravity observations does not accurately represent the volcanic structures causing these features.
- Marine areas adjacent to the coast, including fiords and harbours, are generally absent of data as ships can not get close to the shore to observe gravity and satellite altimetry is unreliable close to the coast. This results in a data discontinuity and consequent error when computing a geoid.

The result is that the geoid model departs from the actual geoid. This situation can be improved by using additional gravity observations in the geoid computation.

The NZVD2009 accuracy described above refers to the accuracy of a single point in relation to the NZGeoid2009 surface (network accuracy). Many users of the vertical datum are more interested in the difference in height between adjacent marks, rather than the absolute height itself. The relative height accuracy (local accuracy) is generally more accurate than the network accuracy because it refers to the slope of the geoid at the point of interest rather than its physical height. Physical metrics of this accuracy are not available; however users have indicated that height differences can often be derived with a reliability of 1-2 cm.

The present 0.08 m accuracy of NZVD2009 is insufficient to meet the 0.03 m required by users.

When a height is transformed to NZVD2009, the accuracy of the resulting height is a combination of the offset error (Table 1) and the error of the original height. The transformed height can not be more accurate than the source data.

The accuracy of a gravimetric geoid-based vertical datum can be improved by improving the accuracy of the geoid on which it is based. The primary limitation on the accuracy of the NZGeoid2009 model is the quality of the terrestrial gravity observations that were used to enhance it from EGM2008. This quality was limited by the accuracy of the actual gravity values as well as errors in their positions and heights. The imbalanced spatial coverage of the gravity observations also affects the ability of the resulting geoid to accurately represent the Earth’s gravity field. There are significant data gaps in areas of rough topography, over lakes, and in the marine areas adjacent to the coast where satellite altimetry is unreliable. The national geoid model could be improved if additional gravity observations with better spatial coverage and accuracy were acquired across NZ.

The LVD offsets can be improved by acquiring additional GPS-levelling points throughout each datum. This will ensure that the offset is representative of the entire datum area. The same approach can be employed to determine official offsets to other local datums, such as those used by local councils.

5 Options for Improving the Vertical Datum

The following sections describe a range of options that could be implemented, in full or in part, to provide an improved vertical datum.

5.1 Improved geoid computation techniques

The NZGeoid2009 was computed in 2009 using software and theory that was current at that time. As geoid computation is an active area of research the theory is continuously developing, thereby enabling the computed models to more closely depict reality.

While it is possible to compute an updated NZ geoid from the existing data holdings using improved theory and software, the improvements to the model are unlikely to be significant on their own. In a similar vein to improving the reference GGM (section 5.1), users are unlikely to go to the expense of adopting a new geoid if the improvements over the existing model are minor. If new terrestrial or airborne gravity data is obtained then the most modern geoid theory should be applied to the computation of the new model.

Pros	**Cons**
Relatively cheap and simple upgrade to geoid	Will not significantly improve local-scale geoid representation in model
Geoid will be the best that can be obtained from the existing data	Geoid still limited by accuracy and spacing of existing gravity observations
	Only improving the computation technique will probably not result in a significant improvement to NZGeoid2009

5.2 Improved satellite models and computation techniques

The NZGeoid2009 was computed by enhancing the EGM2008 GGM with local terrestrial gravity and satellite altimetry data. At the time of computation EGM2008 was established as the best GGM available in New Zealand. GGMs are being continuously updated, generally as a result of new data being acquired from the on-going GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite missions.

GGMs derived solely from recent satellite-based gravity observations are likely to provide an accuracy approaching 1 cm at wavelengths over 100 km. This means that geoid changes at scales smaller than 100 km will not be well represented in the global models. The incorporation of improved global models in the regional NZ geoid will improve the long-wavelength component, that is realised as datum offsets, but will make little difference to the high frequency changes. In practise this will improve the network accuracy of heights but not substantially change the local accuracy as this is affected by high-frequency geoid changes.

The advantage of this approach is that the global models are free, but their implementation into a NZ geoid is not likely to cause large height changes or geoid improvements either. A datum only improved by this approach will be unlikely to be widely adopted by users due to the inconvenience of doing so, thereby resulting in datasets potentially mixed between different systems.

Improving the reference GGM alone is unlikely to provide a national datum with a 2-3 cm accuracy at a local-scale. An updated global model could be incorporated if a geoid was being re-computed for another reason, e.g. to incorporate additional airborne or terrestrial gravity data.

Pros	Cons
Global satellite models are free	Will not improve local-scale geoid representation in model
Improve geoid alignment with World Height System	Will not provide 2-3 cm accuracy at local scale
	Only improving the reference GGM will probably not result in a significant improvement to NZGeoid2009

5.3 Densify terrestrial gravity

A major accuracy limitation of the NZGeoid2009 model is that it was computed from gravity observations that are spaced with variable density. On average, the 40,737 existing terrestrial gravity observations are spaced every 7.5 km across NZ, however much closer spacing is provided in areas of geological interest (e.g. Hanmer Springs) and much sparser where the topography is rough or physical access is difficult (e.g. Fiordland). Even at local scales, the observation sampling regime is biased. In general observations have been acquired along access routes such as roads, tracks and rivers, this means that the sampling is not representative of the local topography.

High density observations can be aggregated during geoid computation to remove the bias that they may create in the resulting model. The data gaps can be filled by the acquisition of additional terrestrial gravity observations. Most of the gap areas are either remote or in steep/rugged topography, therefore physically accessing the area to make the observations will be difficult. Even with extensive helicopter support, the observations are still likely to be located either on the hill tops (where the helicopter can land) or in the valleys (where people can walk) because physically accessing the steep slopes in between is difficult.

Data gaps in marine areas such as lakes, rivers and seas and can be filled by collecting data from a ship mounted gravimeter. Marine gravity measurements have been acquired extensively in the seas around NZ. The operational requirements of the ships carrying the gravimeters mean that observations can not be made close to the coast. This leads to an area devoid of gravity data along the length of the NZ coastline.

Terrestrial and marine gravity observations are good at measuring high-frequency changes in the gravity field however this is generally coupled with a relatively high "per-km" cost for their collection.

Pros	Cons
Fills some of the gaps in existing data holdings	Gravity observations can only efficiently be collected along convenient access routes, perpetuates irregular spacing
Provides verification of existing data	Collection is slow, will take many years to achieve desired observation density
	Limited to dry land, observations can not be acquired over lakes, rivers, fiords or sea close to the coast
	Very expensive if national coverage is required

5.4 Airborne gravity

Airborne gravity is currently the most common technique for improving regional-scale geoids. The technique works by mounting a gravimeter in an aircraft that is flown along a series of parallel lines to cover the area of interest, then a smaller number of perpendicular check lines are flown to verify the data from the main lines. The key advantage of airborne gravity is that the collection process is not affected by the topography of the survey area; as such a regular grid of observations is obtained across mountainous, remote, flat and marine areas. This is the only method that can provide gravity observations in the near-shore and inter-tidal zones, thereby providing a transition between terrestrial, ship-based and satellite altimetry derived gravity observations.

Airborne surveys are relatively quick to undertake in comparison to terrestrial collection. A national survey over NZ could be completed in as little as 60 days of flying. This means that it is possible to get a "snap-shot" of the gravity field at a particular time. In comparison the terrestrial data was collected over 20-30 year period. The computation of a national geoid would also be simplified if a consistent dataset was acquired because the iterative approach adopted for NZGeoid2009 (and NZGeoid05) to account for the inconsistent data, would not need to be employed.

Airborne gravity surveys for the determination of geoids are routinely used internationally. Examples of countries currently or recently commissioning surveys to improve their height systems include: USA, Malaysia, Indonesia, Nepal, Greenland and Mongolia. The most relevant example to these discussions is USA. This is a 10-year (US$35 million) project that seeks to acquire consistent gravity observations across the contiguous United States, Alaska and Hawaii.

The major operational variables of these surveys are height, speed and line spacing. Each variable has an effect on the usefulness of the gravity observations for specific applications. The major trade-offs are:

- Speed – slower speed enables more observations to be acquired on each line, however slowing the aircraft increases the survey cost more as more flight time required to cover a given area
- Height – a lower flying height is better because it makes the observation reductions easier, however the air is more turbulent at lower altitudes so there are more anomalous vertical accelerations that need to be removed from the observations
- Line Spacing – decreasing the distance between flight lines gives denser observations, however closer flight lines increases the survey cost as more lines are required to cover a given area

Airborne gravity surveys can provide observations sufficient to determine a geoid accurate to 5 cm over a few kilometres when combined with an accurate global model. This accuracy can be improved to the 2-3 cm level in areas where terrestrial observations are also available. In the New Zealand case, the existing terrestrial data holdings are probably of sufficient accuracy to enable this accuracy to be achieved. Coincidentally the observations are also located in developed areas, which is where the higher geoid accuracy is likely to be required.

Pros	**Cons**
Provides regularly spaced observations across all areas	Cost – a high-density airborne survey could be expensive
Fills data gaps in remote and marine areas	Full benefit from new data is not realised until geoid is computed – if collection is staged over too many years the geoid could take a long time to produce or several iterations will need to be done as more data is available
Collects data quickly	Resulting geoid resolution/accuracy limited by spacing of flight lines
Can provide 2-3 cm accuracy in areas where terrestrial data is also available	
Provides a world-class gravity dataset enabling an accurate geoid/vertical datum to be derived	

5.5 GPS-Levelling

GPS-levelling can be used to improve the published offsets between the NZGeoid2009 and the 13 LVDs (see section 4.2). The acquisition of additional points can enable a better determination of the offset. However, the offset accuracy it is still limited by the accuracy of NZGeoid2009 and the accuracy of the GPS-levelling itself. The main limitation to obtaining a better spatial coverage of GPS-levelling points is the locations of precise levelling bench marks being restricted to the sides of major roads.

Similarly, offsets to other local datums (i.e. datums other than the 13 LVDs) can also be defined if GNSS heights are determined at a sufficient number of marks with heights in terms of the local datum. This approach can be used to incorporate additional datums and thereby encourage the uptake of NZVD2009 and to enable the integration of disparate data, such as that obtained from the LINZ Data Service.

The accuracy of GPS-levelling data is a combination of the GNSS ellipsoidal and precisely levelled normal-orthometric heights. For example, the accuracy of the GPS-levelling points used to define the LVD offsets was approximately 15 cm.

Pros	**Cons**
Defining offsets to more datums encourages the uptake of the official datum by more people	Location of marks limited to roads where precise levelling has been undertaken, often poor spatial coverage
Quick to acquire if levelling already completed	Individual point accuracy ~15 cm
GPS-levelling is the most common method of estimating geoid reliability	

5.6 Recommendation

An improved national vertical datum with an accuracy of 2-3 cm in areas of development or intensive land use, and 5 cm elsewhere, can be obtained from a national airborne gravity survey augmented with sporadic terrestrial gravity and GPS-levelling observations. A national airborne gravity survey is the recommended option.

Because airborne gravity data has not been collected in NZ on the proposed scale before, it is also recommended that airborne observations are initially collected over a test area to verify the suitability of the technique and to assist with the cost-estimation for a national campaign.

Following the completion of the airborne gravity survey, an updated national geoid should be computed using the latest global model and computation techniques. The resulting geoid should then form the basis of an improved national vertical datum.

Offsets should be defined to additional local datums as GPS-levelling data becomes available. These points can either be acquired from the agency responsible for the datum (e.g. local council) or by LINZ survey as part of the annual geodetic programme.

6 Alignment to LINZ Strategic Direction

6.1 Project Goals

There are two key goals of this project:

Improve the accuracy of the vertical datum,

Improve the relationships between the official vertical datum and other vertical datums

The important reasons for doing it are:

- To enable the consistent representation and integration of geospatial data (through vertical datum and relationships)
- To enhance the geodetic system as a fundamental geospatial dataset
- To support other LINZ initiatives, such as all of Government imagery, hydro data integration, etc

6.2 Project Benefits

The successful implementation of this project is expected to realise the following benefits:

- **Gravity based heights from GNSS** – Customers will be able to use GNSS technology to measure heights that refer to the Earth's gravity field. These measurements will be quicker to acquire, more accurate, and therefore cost less than at present.
- **Geospatial data integration** – Customers will be able to reliably relate geospatial data held in terms of a greater range of vertical datums. The definition and refinement of relationships between local datums and NZVD2009 is essential to enable the efficient, reliable and repeatable transformation of data.
- **Rapid and coordinated response to disasters** – Response teams will be able to integrate disparate geospatial datasets so that informed and timely decisions can be made. As essential components of the geodetic infrastructure, NZVD2009 and its relationships to other datums enable informed decisions to be made to respond to and mitigate the effects of natural disasters.
- **Efficient establishment of height network** – An improved geoid will enable LINZ to efficiently establish NZVD2009 heights on marks with NZGD2000 ellipsoidal positions with little additional effort or cost. The annual geodetic programme currently emphasises establishment of NZGD2000 positions at the expense of gravity based heights. Because Contractors easily exceed the accuracy requirements in their surveys, gravity based heights will be able to be accurately determined from them.
- **Improved access to the official vertical datum** – Customers will be able to access NZVD2009 using GNSS rather than needing to locate and prove the reliability of an existing precise levelling bench mark.

- **Consistent heighted boundaries** – Cadastral boundaries established by GNSS surveying that include a height element will be able to be efficiently referenced to NZVD2009 within the accuracy requirement of the Rules for Cadastral Survey 2010.

- **National gravity coverage** – Regularly spaced, airborne gravity observations will be acquired across all of New Zealand. The current gravity observations are primarily located along roads, tracks or watercourses with notable gaps over water bodies, areas of rough topography and the coastal margin.

- **Reliable gravity data** – Gravity observations with a known accuracy will be consistently acquired together with reliable heights and positions of the measurement locations. The current gravity data was observed in the 1960s and 70s over a number of campaigns and contains positions and heights of variable accuracy.

- **Accurate regional geoid** – A geoid computed from recent, accurate, gravity data will provide a reference surface that can be used to determine future changes as a result of climatic or geophysical phenomena. This surface needs to be based on observations acquired over a short time period to enable changes to be reliably determined.

- **Resilient vertical datum** – An accurate geoid-based vertical datum will enable heighted marks to be rapidly reinstated following deformation events such as earthquakes. The existence of heighted marks prior to and following events is critical to enable the magnitude of changes to be determined and to facilitate recovery activities.

- **Scientific studies** – A national gravity dataset will be useful in future scientific research, in particular geological and geophysical studies. There is also potential for this data to be used for large-scale mineral exploration, thereby potentially improving the use of NZ's natural resources.

6.3 Statement of Intent

The LINZ Statement of Intent 2011-2014 includes as outcome two:

Increasing the productive use of geospatial information

This outcome seeks to deliver the following impacts:

Increase the productive contribution made by New Zealand government geospatial information

Increase the productive contribution made by LINZ's datasets

The impacts will be achieved through the following key initiative:

Delivering available, accessible, and usable geospatial information and infrastructure to New Zealanders

An improved definition of NZVD2009 and better defined relationships to a greater number of local datums will generate efficiencies for customers transforming and integrating geospatial data held in terms of those datums. This benefits LINZ because our datasets will be provided in terms of a well defined reference system. Customers will benefit because they will be able to uniquely describe heights within their own geospatial data and effectively integrate it with data from LINZ and other government agencies.

Improvement of the official vertical datum and the definition of offsets to an increased number of unofficial datums are essential to enable several other LINZ initiatives to occur. These are:

- Provides accurate vertical height information for the New Zealand Spatial Data Infrastructure (NZSDI)
- Provides accuracy, and supports, the transformation of data to the Hydrographic Data Infrastructure (HDI)
- Provides accuracy, and supports, the transformation of data within the proposed National Elevation Data and Imagery Framework

A national gravity dataset will form a fundamental geospatial dataset in its own right. While this information is critical to the development of a national geoid, it may also be useful in a geological and geophysical studies and potentially mineral exploration.

6.4 Geodetic Strategy

The draft 2011 Geodetic Strategy includes the following goal:

To develop, maintain and enhance a national vertical datum that provides an accurate and consistent reference surface across the land and sea

This project relates directly to the fulfilment of this goal. The major outcome will be an improved national vertical datum that facilitates the integration of disparate datasets that include a height component. The national vertical datum has coverage across the New Zealand continental shelf so can relate datasets from mainland New Zealand, the offshore islands and the marine areas between them.

6.5 Regulatory Outcomes

This project directly assists with achieving the following regulatory sub-objectives for geodesy:

Unique and reproducible heights above a level surface can be determined throughout New Zealand in terms of a vertical (gravimetric) datum

Geospatial data can be transformed between historic and official New Zealand datums and projections without significant loss of accuracy

The fact that both of the key outcomes from the project directly relate to these sub-objectives indicates the tight alignment of the project to addressing a regulatory need.

7 Summary

This report has investigated whether the NZVD2009 has sufficient accuracy to meet the current and short-term future requirements of geodetic customers. While the most demanding scientific accuracy requirements can not be met by a national datum, the needs of cadastral survey and local government customers can be satisfied by a 0.03 m datum accuracy.

In addition to the accuracy, customers are also requesting better access to the datum so that they can relate their existing datasets to the official datum. This can be achieved by improving the quality of the offsets between the national datum and the 13 LVDs and by publishing offsets to other locally used datums.

NZVD2009 has an accuracy of 0.08 m over NZ. The accuracy ranges between 0.02 and 0.15 m across the 13 LVDs. Because this accuracy is only evaluated at GPS-levelling points located along roads, it is less certain whether these accuracies are maintained throughout the datum. While NZVD2009 has been a significant improvement on the situation before it was implemented, it is not sufficiently accurate to meet the needs of its customers.

The NZ height situation could be improved by the acquisition of a national gravity dataset that can be used as the basis of a new national geoid and vertical datum. The most efficient and industry-accepted method of acquiring gravity data at this scale is by using an airborne gravimeter.

In parallel to the airborne survey, additional GPS-levelling points should be acquired to enhance the quality of the 13 LVD offsets and to connect additional local datums. This will increase the uptake of the national datum by users and facilitate easier integration of datasets, such as those derived from the LINZ Data Service, and also enable the development of the NZ Spatial Data Infrastructure (NZSDI). In conjunction with improving the GPS-levelling data, investigations should also be carried out into alternative approaches for modelling the differences between datums, including inclined planes and polynomial surfaces.

The successful completion of this project will provide NZ with a world-class vertical datum that will meet customer needs for the medium-term. The current accuracy of 0.08 m will be improved to better than 0.03 m with the new vertical datum. It will also assist LINZ to continue demonstrating leadership in the geospatial arena within NZ and internationally.