A national vertical datum independent of local mean sea level?

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Abstract. New Zealand currently does not have a single national orthometric height datum. It has 12 separate levelling networks based on individual tide gauges and a multitude of other less significant vertical datums. In August 1999, the New Zealand Geodetic Datum 2000 (NZGD 2000) was implemented. This is a three dimensional datum based on ITRF96 with ellipsoidal heights defined in terms of the GRS80 ellipsoid. No accurate geoid model currently exists for New Zealand.

New Zealand is now looking at options for development of a national vertical datum. Two main options are:

(1) To first unify the existing levelling networks and tidal data to generate a single orthometric height datum. This can then be used, together with NZGD 2000 ellipsoidal heights to help define a geoid model.
(2) To develop a geoid model using gravity and digital terrain model data and based on a recognised global geopotential model such as EGM96. Observed geoid height differences derived from GPS and spirit levelling may also be employed. This can then be used, together with NZGD 2000 ellipsoidal heights to define a national vertical datum. A model (possibly with time dependencies) for local mean sea level and transformations to historical vertical datums can then be derived.

The second option is currently the preferred one.

A further decision required is the choice of the orthometric datum zero. This could be set so that the orthometric height is zero at one specified tide gauge or that the mean height of a number of tide gauges is set to zero. Alternatively it would be possible to use the global geopotential model to define the equipotential surface corresponding to zero height. This would leave the national vertical datum independent of (but close to) the local mean sea surface, while providing alignment with the global mean sea surface inherent in the geopotential model.

The advantages and disadvantages of the options are assessed against desirable characteristics of a national vertical datum.

1. Introduction

1.1 Existing Vertical Datums

Pearse (2001) and Hannah (2001) describe the levelling networks and tidal datums in New Zealand. There are precise levelling networks on the two main islands used to define 12 separate regional vertical datums, each based on a different tide gauge. There is also a wide range of more localised vertical datums developed, for example, for engineering works such as hydroelectric power.

There has been no national adjustment of the levelling data and, as a result, some benchmarks are assigned multiple heights in terms of different datums. For example, Pearse (2001) reports a difference of 0.23m between two of these datums.

New Zealand lies across a tectonic plate boundary and significant vertical deformation occurs. Localised vertical deformation of up to 8.5m has been reported from the draw-off of geothermal energy (Walcott, 1984). Co-seismic vertical deformation of 2m (Beanland, et al, 1990) has been reported as well as on-gong uplift (Walcott, 1984) and, eleswhere, subsidence (Blick and Otway, 1995) of up to 10mm/yr.

1.2 New Zealand Geodetic Datum 2000

New Zealand Geodetic Datum 2000 – NZGD 2000 (Grant, et al, 1999, Pearse, 2000) is a three dimensional geocentric reference system, based on ITRF96 and incorporating the GRS80 ellipsoid. It is a "semi-dynamic" datum (Grant et al, 1999) and makes use of a horizontal velocity model to reference all coordinates to epoch 2000.0. A three dimensional velocity model for New Zealand has not yet been developed.

All GPS-observed geodetic control points have ellipsoidal heights in terms of NZGD 2000. The density of these is 1 to 5 km in urban areas and 20 to 50km in rural areas.

2. Fundamental Principles of Datum Definition

2.1 Horizontal Datums

Traditionally, the definition of a horizontal datum has been based on geodetic astronomical observations. The geodetic latitude (ϕ) and longitude (λ) of the datum origin were often set equal to the astronomic latitude (Φ) and longitude (Λ) of a point. Astronomic azimuths generally defined orientation.

The predecessor to NZGD 2000, New Zealand Geodetic Datum 1949 was defined in this manner (Lee, 1978). However, satellite geodesy has changed this practice. Modern geodetic datums are designed to be geocentric and are usually based on a realisation of the International Terrestrial Reference System (ITRS). The resulting geodetic coordinates (ϕ,λ) of points in terms of these datums remain close to the astronomic coordinates (Φ,Λ) but there is no explicit connection between them.

2.2 Vertical Datums

Just as, horizontal datums were traditionally defined by measurements in terms of the local gravity vector, the definition of vertical datums has been based on measurements related to the local gravitational potential – specifically, measurements of mean sea level.

More recently, it has become obvious that mean sea "level" departs from a level surface but this has not resulted in a significant shift in the method of defining vertical datums. Unlike horizontal or 3 dimensional datums, vertical datums tend to remain explicitly linked to their tide gauge origins.

The location and movement of the sea surface is a very important physical phenomenon. It would be useful to be able to model its behaviour with respect to an independent and accurate vertical reference system rather than allowing spatial and temporal variations in the sea surface to define and distort the vertical reference system. Therefore this paper questions whether the traditional approach to vertical datum definition is still desirable.

3. Desirable Characteristics of a Vertical Datum

The definition of an optimum national vertical datum is not primarily a scientific problem. A vertical datum serves a wide range of users with a broad range of expectations as well as varying levels of geodetic understanding. Some of the desirable characteristics of a vertical datum conflict with others. We need to be able to define the desirable characteristics and their relative impacts on human affairs before deciding on the best option. A number of desirable characteristics are considered below.

3.1 Unified (at least within a land mass) and Definitive

It is desirable there be a single widely recognised vertical datum so that benchmarks can be assigned a single definitive height in terms of a preferred national (or continental) vertical datum. This does not prevent the use of special-purpose vertical reference systems for specialised users.

3.2 Good Coverage

It is desirable for the vertical datum to be readily accessed from anywhere in the country – particularly in areas of existing or new development. Users should be able to generate heights for points relatively easily regardless of their location. Traditional vertical datums are only readily accessed at selected points along the coast or along major highways. This is due to the cost and limitations of precise levelling.

3.3 Based on an equipotential (level) surface

It seems self evident that a vertical datum should be based on heights above an equipotential surface. Mean Sea Level (MSL) has traditionally been used as a conveniently measurable surface which is close to being equipotential. However it is now widely accepted that MSL is measurably non-level.

3.4 Consistent with gravimetric geoid models

Increased use of GPS has resulted in a demand for geoid models to convert ellipsoidal heights to orthometric heights. The use of a gravimetric geoid for this purpose depends on the assumption that the vertical datum reference surface is essentially the same as the geoid.

3.5 Zero height close to sea level

Most users of height systems expect heights to be approximately equal to zero at sea level. However different users are interested in different sea surfaces. Hydrographers often reference heights to a low-water surface such as Lowest Astronomic Tide (LAT). Land title boundaries are more commonly related to a high-water surface such as Mean High Water Springs (MHWS). A high-water surface is more likely to be of interest to agencies managing storm water or river systems.

The main useful characteristic of MSL is that it is closer to being an equipotential surface than other definitions of the sea surface such as LAT or MHWS. MSL is also widely used for topographic mapping although the accuracy required is relatively coarse compared with engineering, scientific, or geodetic purposes.

3.6 Applicable to Islands (and Continental Shelf)

For a nation, like New Zealand, consisting of several main islands and many offshore islands, it would be desirable to have a vertical reference system that could be uniformly applied across broad stretches of ocean. Also, there is increasing integration of national spatial databases covering geodetic, cadastral, topographic, and hydrographic data across New Zealand's landmass and continental shelf.

3.7 Consistent with international standards and systems

The benefits of basing 3 dimensional or horizontal datums on international systems such as the ITRS are well known. In vertical positioning, there are many complex interactions and potential biases resulting from the use of inconsistent systems. For example, different sets of gravity data may have been reduced using inconsistent height datums.

3.8 Able to support sea level modelling

See Figure 1 below. It is desirable to be able to develop models to accurately predict (in time and space) instantaneous sea level with respect to positioning systems such as GPS. This depends on a height reference system which is not distorted by invalid assumptions. If the definition of a vertical datum depend on the assumption that Mean Sea Level and the geoid are coincident, or that variations in sea level are solely due to tidal influences, then the datum will have limited ability to act as a framework for accurate sea level modelling.

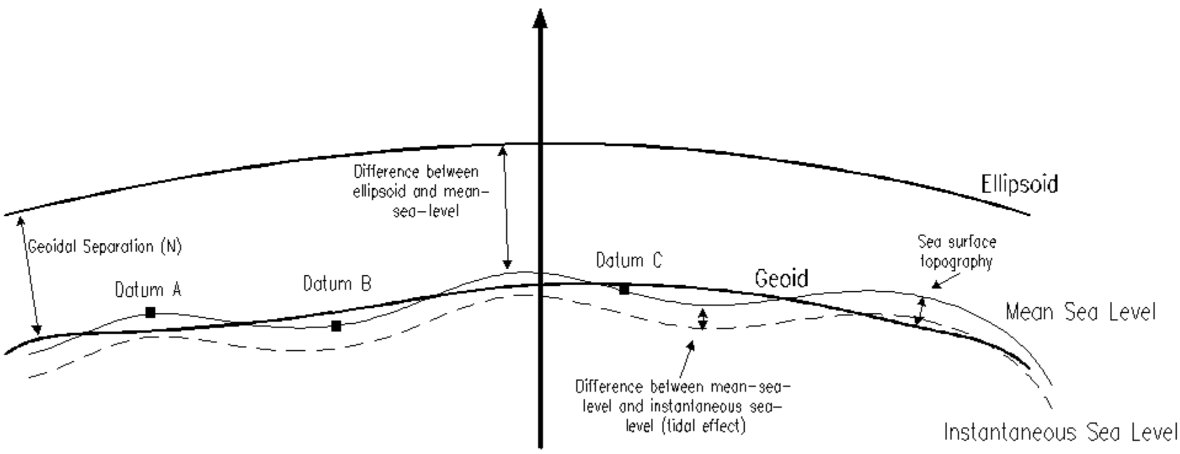

Figure 1. Relationship between ellipsoid, geoid (equipotential surface proposed for new datum), mean sea level (surface on which current datums are based), and instantaneous sea level.

4. Options for Datum Definition

4.1 Status Quo - a height datum for each tide gauge

This is the current system in New Zealand. Each of the datums may result in equipotential zero height surfaces but these surfaces are inconsistent with each other. This results in multiple heights for benchmarks where the datum coverage overlaps.

4.2 Height datum constrained to several tide gauges

The Australian Height Datum uses this model (ICSM 1999). It is accepted that slopes in sea level have distorted the height datum so that the surface of zero height is not a level or equipotential surface.

4.3 Height datum constrained to one tide gauge

This model is used for the North American Vertical Datum 1988 (Zilkoski, et al, 1992). It results in non-zero heights for MSL at other tide gauges. It results in an equipotential datum surface but whether this surface is "the geoid" is arguable. The arbitrary choice of tide gauge for the origin makes the datum definition itself somewhat arbitrary.

4.4 Height datum constrained to the mean of a set of tide gauges

This option results in non-zero heights for MSL at all tide gauges. It does result in an equipotential datum surface but this may be offset from both local and global definitions of "the geoid". The arbitrary choice of tide gauge for the origin is avoided although the datum definition depends on the set of tide gauges chosen.

4.5 Height datum aligned to global geoid model

Under this option, the datum definition is not explicitly linked to any tide gauges. It is relatively independent of local sea level although it would be expected, in practice, to be reasonably close to sea level. The global geoid model has an implicit definition of the mean height of the global sea surface. This would be used to define the datum surface for the national vertical datum.

5. Analysis of Options

Table 1 below provides an analysis of how the datum definition options in Section 4 match the desirable characteristics in Section 3. It can be seen that the status quo is unsatisfactory and that the option of a vertical datum fixed to many tide gauges (and thus not defining a level surface) is little better.

The remaining three options are very similar in effect although not in the principle applied. All result in a datum surface that will generally not be coincident with MSL across the country even though it may coincide at one or more points – either by design or by coincidence.

The option of a height datum based on a global geoid model has additional advantages of consistency with international systems and the ability to be applied to offshore islands across New Zealand's continental shelf. A potential disadvantage (of a magnitude unknown at this stage) is the extent to which the resulting datum lies acceptably close (at least within the normal tidal range) to the definition of MSL at tide gauges. If it is acceptably close, then this would seem to be the best model. However, if the resulting datum is unacceptably different from MSL, (e.g. if the surface of zero height lies outside the normal tidal range) then the disadvantages of this option may outweigh the advantages.

Table 1 Analysis of Desirable Characteristics for Datum Definition Options

	Datum Definition Options				
Desirable Characteristics	**Status Quo**	**Fixed to Many Tide Gauges**	**Fixed to One Tide Gauge**	**Mean of Many Tide Gauges**	**Global Model**
Unified / Definitive	No	Yes	Yes	Yes	Yes
Coverage	Limited	Limited	Good	Good	Good
Equipotential	No	No	Yes	Yes	Yes
Geoid Consistency	No	No	Yes	Yes	Yes
MSL Consistency	Yes (locally)	Yes (at fixed gauges)	Yes (at one gauge)	No (but best fit)	**?**
Applies to Islands	Yes	No	No	No	Yes
International System	No	No	No	No	Yes
Model Sea Surface	No	No	Yes	Yes	Yes

6. Conclusions

Three potentially acceptable models have been identified for definition of a vertical datum. These models would all involve definition of a level datum surface from available levelling, geoid, gravity and terrain model data but not constrained by tide gauges. The choice of datum origin would then be to set a zero height at:

1. MSL as defined by one tide gauge;
2. the mean MSL at a specified set of tide gauges; or
3. the mean geoid as defined by a global equipotential model such as EGM96.

It is proposed that investigations will proceed on the basis of the 3rd option with the possibility that an alternative will be required if the resulting vertical datum surface departs unacceptably from MSL at principal tide gauges.

Once we have decided that a national vertical datum should be based on a nationally consistent equipotential surface, and accepting this surface will depart to some extent from local MSL, the actual choice of specific equipotential surface is rather arbitrary from a practical perspective.

However the principle on which the choice is made, is not arbitrary. We propose that consistency with current and future international systems is a important principle that New Zealand should follow if possible. A global vertical datum will be defined and promulgated sooner or later. This may require New Zealand to make changes to its national vertical datum. However, those changes will be more easily made and applied if our new vertical datum is focussed on the principle of international consistency.

New Zealand's geodetic datum (NZGD 2000) is based on an international reference frame which is no longer fixed to the earth's surface or tied to the current mean spin axis of the earth. Similarly a future global vertical datum is likely to be based on a conventionally accepted equipotential surface that may have been derived from measurements of the global sea surface but which will no longer be fixed to it.

We recommend that datum definition decisions for New Zealand's national vertical datum should be based on the principles inherent in such a future global vertical datum.

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