Height Challenges in New Zealand

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Abstract. This paper discusses the main issues in the development of a national height system in New Zealand by Land Information New Zealand. New Zealand is an archipelago nation straddling an active tectonic plate boundary. Combining this with its rugged terrain, limited land gravity observations and no unified national height system, the approach to the development of a national height system is investigated.

New Zealand now has a geocentric datum that is based on ITRF96 and incorporates a horizontal velocity model to account for the effects of earth deformation. The existing height system is a collection of 13 primary vertical datum which have their origins based on independent pre-1950 tide gauge observations. With the increasing use of GPS for navigation and positioning New Zealand is faced with the task of providing a means to convert from ellipsoidal heights to orthometric (or practical) heights.

Prior to developing a consistent national height system New Zealand is assessing a number of issues and drivers which include:

- Accuracy and spatial density of survey marks used to realise the new system,
- Methodology to compute a high resolution national geoid model,
- Should any new gravity data be collected and if so via what method,
- Accounting for the effects of earthquakes and varying uplift and subsidence rates,
- Incorporating the effects of sea-level rise on the determination of mean sea-level,
- Determining the advantages and disadvantages of adjusting the independent levelling networks,
- Determining what are the international trends in establishing height systems,
- Assessing the requirements of hydrographers, topographers, surveyors and engineers.

Through addressing these issues and drivers in-light of the current scientific approaches this paper intends to try to answer one of the main questions facing Land Information New Zealand, "Do you put resources into unifying the 13 vertical datum, do you just provide an "accurate" geoid model to convert the ellipsoidal heights to an orthometric type height, or do you have to provide both?"

Keywords. Vertical datum, national geoid, heights

1 Introduction

Land Information New Zealand (LINZ) has a Strategic Business Plan for the geodetic system which sets out a number of goals (OSG, 1998). Two of these goals, which have a targeted completion date of 2008, are:

- support multiple vertical datums and provide transformations between these datums,
- provide transformation method/s between ellipsoidal and orthometric heights.

New Zealand does not currently have a national unified height system that takes into account the local gravity vector. Though with the establishment of the New Zealand Geodetic Datum 2000 (NZGD2000) there are ellipsoidal heights which are nationally unified in terms of ITRF96. NZGD2000 incorporates a horizontal velocity model to account for the effects of horizontal earth deformation, but the model does not contain vertical deformation rates, see Pearse (2000).

New Zealand has a collection of 13 primary independent levelling networks rather than a unique height system. Each of these networks have their own tide gauge observations as the origin for their heights. Though these independent levelling networks do have marks that are common to other networks, they have not been adjusted together.

Since the GPS technology became available in New Zealand it has been recognised that users need to be able to convert their GPS derived ellipsoidal coordinates into the independent levelling networks (e.g. Reilly, 1990). As well as trying to determine which is the best way to compute this transformation, there is also the question of whether New Zealand needs a truly national height system that takes into account the local gravity vector.

This paper presents some of the issues that face LINZ, the nations government department responsible for providing the national spatial reference network.

2 Physical Setting

New Zealand is an archipelago nation with most of the population living on two islands (North and South Islands). The nearest country to New Zealand is Australia, which is approximately 2000 km to the north-west. It is a sparsely populated nation that has a rugged terrain, as shown in Figure 1, with over 200 named peaks being higher than 2300 m (highest mountain is 3754 m). This rugged terrain is partly the result of the active tectonic plate boundary that the country straddles (Figure 2) and its associated back arc spreading, volcanoes and earthquakes.

Areas within the Taupo Volcanic Zone are subsiding up to 10 mm/yr (Blick and Otway, 1995). The Southern Alps are subjected to uplift rates due to the interaction of the Pacific and Australian plates along the alpine fault (Walcott, 1984). These subsidence and uplift rates have a slow but continuous affect on the height of stations. Earthquakes however often have the largest short term effect on heights, for example subsidence of up to 2 m resulted from the Edgecumbe earthquake of 1987 (Beanland et al., 1990).

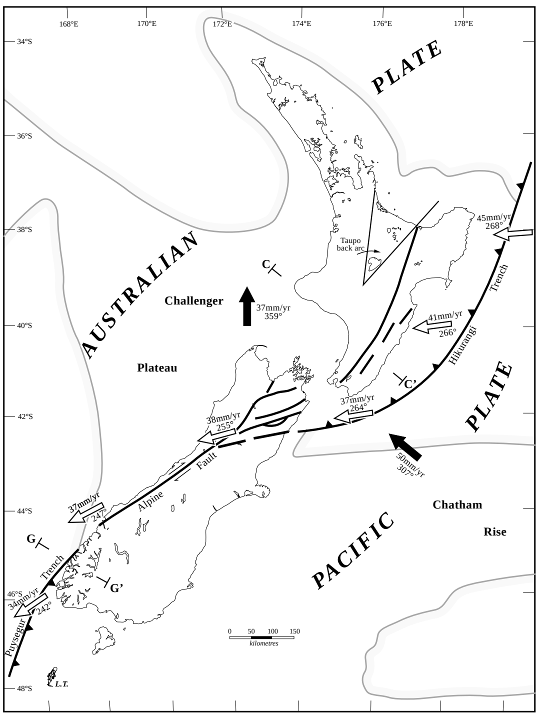

Fig. 2 Tectonic Setting of New Zealand (Pearse, 1998). Solid arrows represent the Nuvel1A absolute rates at Wellington for each plate. Open arrows represent the relative rates along the fault.

Fig. 1 Topography of New Zealand

3 Mean Sea Level Data

The history of New Zealand tidal data observations shows that there has been a spasmodic approach with very little national coordination.

An analysis of New Zealand mean sea level data from the period 1899-1988 by Hannah (1990) indicates that sea level is rising at 1.7 mm/yr along New Zealand's east coast. Despite this rate of sea level rise no levelling networks have had their heights adjusted to accommodate this change.

New Zealand tide gauges are often located in river mouths and harbours, not the open oceans, as they are primarily run by Port Authorities to assist in shipping and tidal predictions.

4 Levelling Network

New Zealand's existing height system is a collection of 13 primary vertical datum which have their origins based on independent pre-1963 tide gauge observations. As Gilliland (1987) reported, generally 3 years tidal data was used to define the primary tide gauge heights though the 3 year span taken varied from between 1909 through to 1963. Each of these 13 vertical datum have an associated network of sprit-levelling runs which have been internally adjusted. Even though these independent levelling networks do have marks that are common

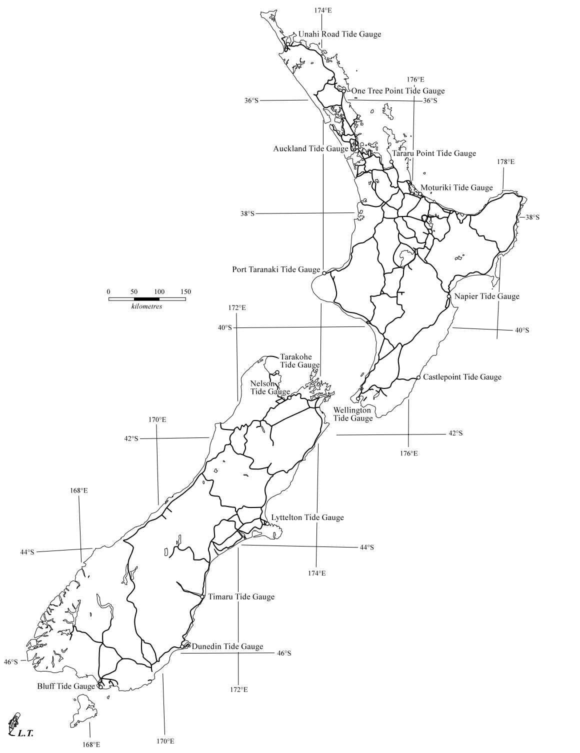

Fig. 3 New Zealand Precise Levelling network as at 1990 (Pearse, 1998)

to other networks, they have not been adjusted together.

Pearse (1998) reported that common first-order bench marks generally had height differences of less than 0.23 m. This agreement is acceptable when one remembers that each network is based on a different tide gauge determination of mean sea level and that sea surface topography computed from satellite altimetry data as reported by Hannah (2000) can vary by 50 cm from the north to south of New Zealand.

The spirit-levelling observations have been reduced using normal gravity and thus provide normal orthometric heights due to not using observed gravity values for the reduction. If one takes an extreme case in the North Island of a 200 mGal residual gravity error at the top of Mt Ruapehu (2800 m) there is approximately a 0.56 m difference in a normal orthometric and orthometric heights measured at sea level and at the top of Mt Ruapehu. However the levelling in the North Island does not go higher than approximately 950m and with a residual gravity error of 15 mGal in this area the difference in heights is only 0.015 m.

Figure 3 shows the network of first order levelling that had been undertaken in New Zealand up until 1990. Since 1990 there has been no significant levelling data collected. When viewed together these first order levelling networks do form a reasonable coverage which would enable adjustment of the data together in each of the North and South Islands.

5 Gravity Data

A summary of the gravity data available in New Zealand is presented in this section. Some or all of these sources could be used in the computation of a national gravimetric geoid model.

5.1 Land Data

New Zealand's Department of Scientific and Industrial Research (DSIR) has collected land based free-air gravity observations in the past. The density of the observations as reported by Gilliland (1988) is 1 station per 7.5 km^2 nationally. As can be seen from Figure 4 the density does vary across the country with less data having been collected in areas of rugged terrain. One of the issues with the free-air anomalies is that the heights of the stations were often determined by barometric levelling.

The land gravity data, as far as the author is aware, has not been used to compute a national geoid model but it has been incorporated into the global geopotential model – EGM96 (Lemoine et al., 1998).

5.2 Sea Data

DSIR has also collected gravity observations in the past from ship based instruments. The density along the coastal fringe varies considerably but in

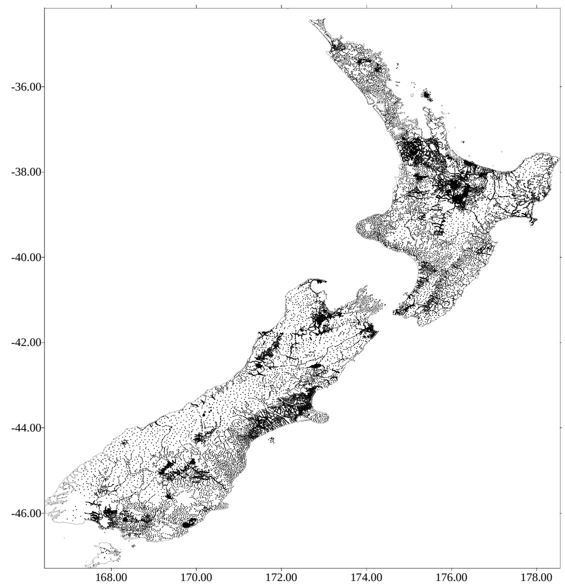

Fig. 4 Distribution of Land Gravity

general it reduces the further away from the main ports you are.

Satellite Altimetry data unfortunately is not collected up to the coastline but is does provide a uniform data set in open oceans.

Even when the sea data is combined there is a coastal strip around the country where there are very few gravity observations.

5.3 Absolute Data

The above land and sea data has been collected using relative gravity observations and were referenced to the International Gravity Standardisation Network 1971 (IGSN71).

In resent years the research work of Roger Bilham (University of Colorado, Boulder) has resulted in a network of 16 absolute gravity stations in the South Island. There has been no absolute gravity observed in the North Island as part of this research.

6 International Height System Examples

International experience is worth looking at to see what direction and definition problems other countries have needed to overcome in the development of their height systems. The following examples build on the work of Hannah (2000) and cover Australia, USA, Canada, Denmark, Finland, Norway and Sweden.

One thing that all of these countries have done is adjust together their levelling data to provide a national height system. Though these national adjustments may have technical imperfections they have served the vast number of users successfully. Some of the technical imperfections are that they did not take account of sea surface topography between the defining tide gauges and they used normal orthometric height corrections.

With perhaps the exception of Australia, all the countries face the effects of either tectonic deformation or post-glacial rebound. The Nordic countries have developed models for the rate of post-glacial rebound and scientific users apply this correction to their heights but it is often ignored by the non-scientific user.

The USA has recently completed the North American Vertical Datum 1988 (NAVD88) which superseded the National Geodetic Vertical Datum 1929. The new adjustment was constrained by one tide gauge benchmark and observed gravity data was used to compute orthometric heights (Zilkoski et al., 1992).

One of the benefits of a national levelling network which has been rigourously adjusted, e.g. NAVD88, is that it enables national high accuracy geoid models to be tested more efficiently. The need for geoid models is now being driven by non-technical users who are using GPS for positioning. They require a simple and accurate method to convert their ellipsoidal heights to orthometric heights.

7 National Height System

7.1 Reason for Review

As reported in OSG (1998), there are a number of drivers which necessitate a review of the current height systems in New Zealand. These include:

- establishment of NZGD2000,
- geodetic and cadastral automation,
- simplify digital spatial data management,
- reduce risk and cost to the Government,
- increase public usage of the core spatial infrastructure,
- facilitate the use of international systems, and
- anticipate future user requirements.

7.2 User Expectations

There has yet to be a formal consultation process undertaken to determine what type of height system and accuracy the New Zealand users require on a national scale. The following ideas on user expectations are based on the types of users of the geodetic system identified in OSG (1998).

- Cadastral Surveys: generally do not require heights other than for defining strata titles and coastal boundaries (0.25 m or better),
- Hydrographic Surveys: heights in shallow water have the most demanding requirements, with published charts showing heights to 0.5 m or better),
- Topographic Surveys: for 1:50000 scale maps spot heights are accurate to approximately 4 m,
- Engineering Surveys: the most demanding projects, e.g. structure deformation monitoring, can require millimetre accuracy where as other projects may require only metre accuracy,
- Scientific Studies: as with Engineering surveys they can vary from millimetre to metre, and
- Navigation Applications: for ships docking and planes landing centimetre accuracy could be required.

Along with the accuracy requirement different users will require heights in terms of equipotential surfaces while others may be able to use ellipsoidal height differences.

One of the difficulties of discussing height expectations with users is trying to determine what knowledge they have of how heights are computed (e.g. do they know about sea surface topography). Many users may still believe that once the height of a station has been computed it will never change.

7.3 Legal Requirements

In New Zealand there are at least 15 different height terms used in over 40 different pieces of legislation (Blick et al. 1997). In general the basis of these height terms are for cadastral boundary definitions, e.g. Mean High Water. The Surveyor-General and LINZ have, as stated in the 1996 Amendment to the Surveyors Act 1986, the responsibility to provide a vertical datum and the relationship between it and sea level to support these Acts.

The legislation often does not state the accuracy to which these different height surfaces need to be computable to. This leaves LINZ with some uncertainty as to the accuracy required from the vertical datum.

7.4 Height System Options

New Zealand has a nationally consistent height system through the ellipsoidal heights defined in terms of NZGD2000. These ellipsoidal heights do not take into account the effect of the local gravity vector.

7.4.1 *Difference Model*

The main user demand for heights in New Zealand currently is to have a method to convert their ellipsoidal heights into heights compatible with the levelling networks. LINZ could provide a grid of height differences between each levelling network and NZGD2000. Probably users would be satisfied with this approach as most work within only one or two levelling networks. This difference model approach would not provide a nationally consistent height system that incorporated the effect of the local gravity vector.

7.4.2 *Geoid Model*

A geoid model could be adopted for the country. This geoid model could be a global model, such as EGM96, or a national model computed from the current gravity data sets. A nationally consistent height system which accounts for the local gravity vector could then be defined on the basis of the geoid model adopted and the NZGD2000 ellipsoidal heights. This approach would not provide a means of converting between the geoid model derived heights and the levelling networks.

7.4.3 *Island Based Levelling Adjustment*

An Island based adjustment of the spirit levelling data would be able to provide a consistent height system for each island. If this adjustment takes into account the local gravity vector in the reduction process then each island would have an internally consistent orthometric height system. This approach would not result in a nationally consistent height system nor would the relationship to NZGD2000 ellipsoidal heights be known.

7.4.4 *Combined Approach*

If a national geoid model is computed and levelling data for each island adjusted, the differences between these two height systems could be computed. This would allow users to convert their ellipsoidal heights to a nationally consistent system via the geoid model, and convert the newly adjusted levelling network heights to the same nationally consistent system via the difference model. This approach would still leave the differences between each levelling network and the consistent island based adjustments to be determined.

7.5 Technical Challenges

Ellipsoid height differences derived from static GPS observations over long lines (e.g. 200 km) are probably more precise than orthometric height differences derived from spirit levelling over the same distance. Though the error on geoid height differences used to convert ellipsoid height differences to orthometric height differences are larger than either the GPS or levelling differences. This raises the issue and challenge of what data (gravity or other, e.g. DEM) is needed to compute a suitably accurate geoid model. Do you need to have data along the coastal fringe? Does one geoid computation approach better suit the data sets available in New Zealand?

To answer the question of what data is needed for the geoid model one needs to know what accuracy does the national height system need to provide to users.

Once you have established the accuracy required from the national height system then to be able to test the combined ellipsoidal and geoid model heights you need a nationally consistent orthometric network.

If one tries to use the existing levelling data and re-adjust the different runs together there is the issue of how to connect the data on different islands. Can you simultaneously observe sea level on the two islands and then try to correct the observations for the effects of sea surface topography during the period of observation? How will one determine what accuracy this connection has been made to?

Once you have overcome the above challenges you are then faced with maintaining the system. How do you account for the effects of vertical deformation rates and sea level rise? What role does absolute gravity data play?

8 Conclusions and Recommendations

As Earth is a dynamic environment we need to acknowledge that heights, and coordinates, change over time. It is therefore important for users to be aware that heights change and that databases and systems need to be designed to allow for these changes.

Any new height system needs to be easy to use and represent the basic notation that water will flow from the point with the highest height to that with the lower height.

The next step for Land Information New Zealand is to determine what accuracy the new nationally consistent height system needs to achieve to meet user expectations and their statutory responsibility. One could speculate that a relative accuracy of the order of centimetres will be required. Based on this it appears almost certain that a national high resolution geoid model needs to be developed. Along with the geoid model the levelling data will probably need to be adjusted to form a unified orthometric height system.

At that stage New Zealand would have the three components to allow the checking of each of them via the simple relationship of $h = H + N$. For New Zealand that is the NZGD2000 ellipsoidal heights equal the unified orthometric heights plus the national geoid model heights.

With a national geoid model and a unified height system in place LINZ will be better placed to achieve by 2008 two goals stated in the New Zealand Geodetic Strategic Business Plan of:

- support multiple vertical datums and provide transformations between these datums, and
- provide transformation method/s between ellipsoidal and orthometric heights.

References

Beanland, S., G.H. Blick and D.J. Darby (1990). Normal Faulting in a Back-arc Basin: Geological and Geodetic Characteristics of the 1987 Edgecumbe Earthquake, New Zealand. *Journal of Geophysical Research*, vol. 95, pp. 4693-4707.

Blick, G., D. Mole, M. Pearse and B. Wallen (1997). Land Information NZ Role in and Needs for Sea Level Data. *SG Immediate Report 97/17*, Office of the Surveyor-General, Land Information New Zealand, Wellington, New Zealand.

Gilliland, J.R. (1987). A Review of the Levelling Networks of N.Z. *New Zealand Surveyor*, vol. XXXII, no. 271, August 1987, pp. 7-15.

Gilliland, J.R. (1988). *Unpublished Project Report for Research Contract R87/496*. School of Surveying, South Australian Institute of Technology, Adelaide, Australia.

Hannah, J. (1990). Analysis of Mean Sea Level Data from New Zealand for the Period 1899-1988. *Journal of Geophysical Research*, vol. 95, no. B8, August 10 1990, pp. 12399-12405.

Hannah, J. (2000). An assessment of New Zealand's Height Systems and Options for a Future Height Datum. Interim Report prepared for Land Information New Zealand, Wellington, New Zealand.

Lemoine, F.G., S.C. Kenyon, J.K. Factor, R.G. Trimmer, N.K. Pavlis, D.S. Chinn, C.M. Cox, S.M. Klosko, S.B. Luthcke, M.H. Torrence, Y. M. Wang, R.G. Williamson, E.C. Pavlis, R.H. Rapp and T.R. Olson (1998). The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96.

OSG (1998). New Zealand Geodetic Strategic Business Plan. *OSG Technical Report 3*, Office of the Surveyor-General, Land Information New Zealand, Wellington, New Zealand. http://www.linz.govt.nz/services/surveysystem/osgpublications/osg_tr3.pdf

Pearse, M.B. (1998). A Modern Geodetic Reference System for New Zealand. *UNISURV S-52*, School of Geomatic Engineering, University of New South Wales, Sydney, Australia.

Pearse, M.B. (2000). Realisation of the New Zealand Geodetic Datum 2000. *OSG Technical Report 5*, Office of the Surveyor-General, Land Information New Zealand, Wellington, New Zealand. http://www.linz.govt.nz/services/surveysystem/osgpublications/osg_tr5v1_0.pdf

Reilly, W.I. (1990). The Geoid and the needs of the GPS User. *New Zealand Surveyor*, vol. XXXIII, no. 277, August 1990, pp. 35-41.

Walcott, R.I. (1984). The Kinematics of the Plate Boundary Zone through New Zealand: a comparison of short- and long-term deformations. *Geophysical Journal of the Royal Astronomical Society*, vol. 79, pp. 613-633.

Zilkoski, D.B., J.H. Richards and G.M. Young (1992). Results of the General Adjustment of the North American Vertical Datum of 1988. *Surveying and Land Information Systems*, vol. 52, no. 3, pp.133-149. http://www.ngs.noaa.gov/PUBS_LIB/NAVD88/navd88report.htm