AN ASSESSMENT OF NEW ZEALAND'S HEIGHT SYSTEMS AND OPTIONS FOR A FUTURE HEIGHT DATUM

Prepared for the Surveyor General
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by

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1. INTRODUCTION

For many years Mean Sea Level (MSL) was assumed to remain at a constant (equipotential) level relative to the stable parts of the earth's surface. The sea levels were monitored and recorded at a number of sites around the New Zealand coastline and the resulting data processed to produce a mean height at each of these sites. The stability of the tide poles against which these heights were measured, were not only monitored by spirit leveling from a near-by "tide-gauge" benchmark, but these benchmarks were in turn given a MSL height relative to their respective tide poles. These derived benchmark heights then became the foundation for local height systems (datums).

In New Zealand, over a period of years, at least seven major datums were formed and many more minor datums, each being used as a basis for either a local or a regional height system. Despite some early (but sparse) evidence to the contrary, these datums were assumed to be stable and thus capable of being linked via precise leveling so as, eventually, to form a national (or possibly a North Island and a South Island) height datum.

In recent years, however, evidence for the instability of these height datums has mounted. Not only has New Zealand been shown to be tectonically active, but the reality of sea-surface slope has been recognized (i.e., MSL at all points around our coastline does **not** form a single equipotential surface). Furthermore, it has become clear (e.g., Douglas, 1991), that global sea levels are rising at a rate of approximately 1.8 mm/yr. Thus, the hope of forming a theoretically consistent, national height datum based upon the sea level measurements made at a number of tide gauges, each linked by precise leveling, has slowly but inexorably been growing more remote with time.

However, at the same time as this traditional approach to the establishment of a national height datum has been growing in complexity, new technologies have been emerging that offer an alternative approach to the height datum problem. High precision, absolute gravimeters, capable of determining height changes to a few millimeters, have become small and portable such that they can easily be transported by road from one point to another. Satellite laser ranging (SLR) systems and Very Long Baseline Interferometry (VLBI) systems that offer the prospect of high precision reference frame determination have diminished in size so as to become transportable. Perhaps more importantly, the Global Positioning System (GPS) now offers a new and inexpensive means of establishing a national three-dimensional reference system that can be monitored in real-time.

This report not only examines the above technologies in greater detail but it also looks at current international practice with respect to height datum issues. It presents some wider user perspectives before looking more specifically at the physical characteristics of New Zealand and the particular problems that its faces. It also considers the investment already made in establishing New Zealand's regional height datums, and the technology now available for defining a new datum. Finally, it seeks to define a way forward for New Zealand with respect to its vertical datum problem.

2. THE CONCEPT OF HEIGHT

Contrary to the perception of the layperson, the concept of "height" is not simple. There are, for example, a number of different heights that can be defined, most of which are inextricably linked to the earth's gravitational potential. Furthermore, there are a variety of different reference surfaces to which a height may refer. These are the issues that will be discussed in this chapter.

For convenience, heights will be separated into two categories, i.e., those derived with respect to the local gravity vector, and those derived independently of this vector. While only brief details will be given here, more information can be found, for example, in Heiskanen and Moritz (1967).

2.1 Heights With Respect to the Local Gravity Vector

This category of heights includes all those made by systems that measure a height or height difference with respect to the earth's local gravity vector. While the focus of the following discussion will be on spirit leveling, being both the most accurate of such methods and the one used to determine New Zealand's highest order height networks, it need not be so restricted.

It is useful to begin by noting that spirit leveling around a closed circuit, in general, will not produce an algebraic sum of height differences that are rigourously zero. This is because of the non-parallelism of the level surfaces. Fundamentally, if one levels in a number of segments (setups), between two well separated points A and B, obtaining the height differences (h_1, h_2, h_3, ---, h_n), with corresponding values of gravity (g_1, g_2, g_3, ---, g_n), for each segment, then the potential difference between A and B is expressed as an integral (summation), and is given by:

$$W_B - W_A \;=\; - {}_{A}^{B}\; g_n \;\; h_n \qquad \text{-------------------------- (1)}$$

If the geoid is selected as the zero reference surface, then every point may be given a geopotential number (C_A, C_B, etc., etc.) with respect to this surface. This potential number is calculated from the integral

$$\mathrm{C} \;=\; {}_{0}^{H}\; \mathrm{g\, dH}\,, \qquad \text{--------------------------- (2)}$$

where g is the value of gravity along the curved plumb line and H is the corresponding orthometric height.

Thus, leveling combined with gravity measurements furnishes potential differences from which geopotential numbers are derived.

It is important to note here that in the same way that we use an ellipsoid as a simple approximation to the geoid, so we can use normal gravity at a point (i.e., gravity with respect to an ellipsoidal surface), as an approximation to the actual value of gravity. Normal gravity may be calculated either on the ellipsoid itself ($_0$), or at some (normal) height above the ellipsoid ($_h$). In the former case the computation is straightforward, whereas in the latter case an iterative process is necessary. When a geodetic datum is defined and a reference ellipsoid adopted, this ellipsoid should not only have a defining set of geometric parameters, but also a defining set of gravimetric parameters.

With these concepts in mind, it is possible to define three different types of height for any point.

1. The *dynamic height* given by: $H^{\mathrm{dyn}} = C/\quad_o$, where $\quad_o$ is normal gravity on the ellipsoid for an arbitrary standard latitude, usually 45°. Clearly, all points with the same geopotential number will have the same dynamic height, i.e., they will be on the same level surface.

2. The *orthometric height* given by: $H = C/g$, where g is the mean value of gravity along the plumb line between the geoid and the point in question.

3. The *normal height* given by: $H = C/\quad$, where $\quad$ is the mean value of normal gravity along the plumb line between the geoid and the point in question.

In practice, the dynamic heights and the orthometric heights are generally obtained from spirit leveling by applying dynamic or orthometric corrections to the observed height differences. When the orthometric correction is rigorously applied using actual gravity data it results in the computation of rigourously correct (Helmert) orthometric heights. When the orthometric correction is derived using the normal gravity formula as an approximation to actual gravity, it results in the calculation of normal orthometric heights. While the variation between the two in very small (less than 1 cm) in areas of flat, low lying terrain, it can reach some decimeters in size in mountainous regions such as the Rockies (or the Southern Alps)!

Each of the above heights has its advantages and disadvantages. The geopotential number, for example, has physical significance and is capable of rigourous interpretation. However, it is not a height in a geometrical or practical sense. The dynamic height, on the other hand, while having no geometrical meaning does indicate direction of fluid flow. Conversely, the orthometric height while having obvious geometrical and physical significance to the technically literate user (it is a height above the geoid), does not indicate direction of fluid flow. Because its zero point has traditionally been tied to MSL as a reference surface and because it closely approximates MSL over distances of some 100 – 200 km (at least, in general), it has wide user acceptance. However, its rigourous computation not only requires that gravity data be collected along a leveling route but that a careful reduction process is used, especially in mountainous areas.

The normal height, while important in modern theories of geodesy and easy to calculate rigourously, doesn’t have an obvious physical or geometric meaning, except to the scientific user.

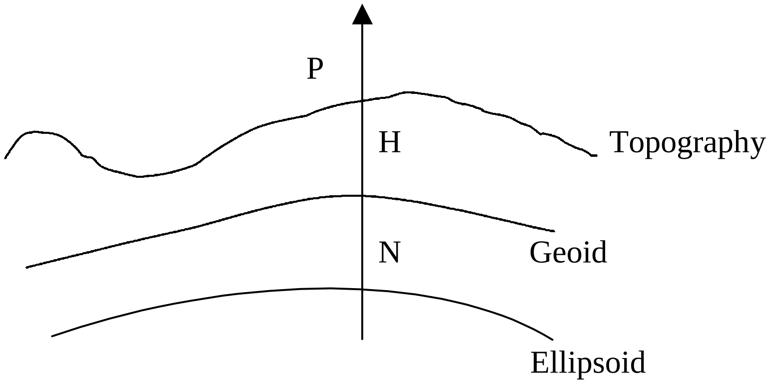
2.2 Heights Independent of the Local Gravity Vector

With the advent of Very Long Baseline Interferometry (VLBI), Lunar Laser Ranging (LLR) and satellite geodesy, it has become possible to determine three-dimensional positions of points on the earth’s surface with respect to an earth-centred reference frame. These positions can be defined as a set of X,Y,Z coordinates in three-dimensional space. In order to be linked to the gravity dependent heights noted earlier, a reference ellipsoid must be selected and appropriate transformation formulae used in order to convert these three-dimensional coordinates into a latitude, longitude and height. The height so derived is called the ellipsoidal height (denoted by h) and is the height of the point above (or below) the ellipsoid as measured along the ellipsoidal normal.

The diagram below illustrates the simple relationship between the orthometric height of a point P and its ellipsoidal height, namely that

$$h = H + N \quad \text{------------------------} \quad (3)$$

where *H* is the orthometric height and *N*, the geoidal undulation or geoidal height. Clearly, given any two of the above quantities, the third can be readily derived.



While the ellipsoidal height has a clear geometric meaning and is easy to derive, its practical use tends to be limited. It has no direct relationship to the earth's gravitational potential or sea level and thus has limited user acceptance. When combined with a known geoidal height, however, it can be transformed into the much more widely accepted orthometric height.

3. A GEOGRAPHICAL AND HISTORICAL PERSPECTIVE

Any future direction that New Zealand might choose to take with respect to its height systems, should first consider both a geographical and an historical perspective on its existing data. While it has yet to be seen, for example, if there will be a future use for New Zealand's extensive data sets of precise leveling, the fact that they exist, that they have been widely used, and that they represent a large financial investment, is sufficient cause to consider their possible future value.

3.1 Geographic Perspective.

Geographically, New Zealand sits astride one of the major structural elements on the earth's surface, i.e., the Australian and Pacific plate boundary. Its position across this active tectonic zone is primarily responsible for many of the physical features and physical events that influence the day-to-day life of its citizens. The mountainous topography is considered to reflect both the collision of these two massive plates and their ongoing uplift. The seismic events that are very much a part of national life are a reflection of some of the deep earth processes that occur in the plate boundary zone. Equally, the volcanic nature of much of the landscape is a typical feature of the back-arc spreading that is associated with a major boundary zone. In total, the country is situated in a dynamic environment in which physical change is the norm rather than the exception.

New Zealand is also a coastal nation. It has a long and narrow shape with a heavily indented coastline that is variously estimated to be between 11 000 and 15 000 km in length. It is a nation that is not only surrounded by ocean but it is one that historically has been greatly influenced by these oceans. It was upon the ships that sailed these oceans that the first settlers came to New Zealand and upon these same ships that New Zealand relied for its trading prosperity.

It is thus no great surprise that in the late 18th Century, at the same time as a major migration of peoples to New Zealand was occurring, tide-gauges were established at New Zealand's major ports. The data from these gauges were initially used for the essential task of predicting the tides and for the control of shipping. However, it was not long before other uses were suggested. In 1908, for example, the then Surveyor-General of the Department of Lands and Survey, Mr Theo Humphries, wrote the following in a memorandum to his Chief Surveyor in Christchurch:

> *"With a view of providing data for detecting and determining the degree of slow secular elevation or depression of different parts of the coast of New Zealand, at some later period, it is the intention, as a preliminary to a more comprehensive scheme to follow in a wider distribution of tidal observations and permanent reference marks on the shore line, to have the zero points of tide gauges in the various ports, and any others that there may be in the Dominion, connected by very careful leveling to permanent reference marks in secure positions on the adjacent shore.*
>
> *From evidence of early residents and my own experience of the differences in high water, or mean sea level on part of the West coast of the North Island in the fifties, and present day conditions, goes to show very conclusively that a considerable rise of that part of the coast has taken place during the period. The detection and measurement of earth movement of this character, in addition to its being of scientific interest and value, is an important factor in the designing of marine works."*

It is clear from this memorandum that even as early as 1908, one of the fundamental difficulties of establishing a consistent and unified sea level height datum in New Zealand had been identified, namely, the possibility of differing rates of elevation and depression along different segments of the coastline.

There are, however, other geographic elements of New Zealand's landscape that deserve mention. The existence of Cook Strait, for example, presents a difficulty to any attempt to devise a single, rigourously correct height datum – assuming of course, that such a datum might be considered necessary. While trigonometric heights have been observed between the North Island and the South Island, there has been no demand by the user community to undertake a rigourous unification of the height systems between the two islands. Furthermore, there has been no demand for the inclusion of other islands (e.g., Stewart Is and the Chatham Is), in a single integrated system.

Equally, the mountainous terrain of New Zealand has tended to encourage the establishment of smaller (regional) datums rather than a larger national datum. For many years, for example, it was considered far easier to adopt local datums in Nelson and Westport than to level over the various systems of ranges that stood between either location and the Canterbury Plains which in turn had heights referenced back to the primary tide gauge at Lyttelton. The same was true in Gisborne, and to a lesser extent, the Bay of Plenty.

3.2 Historical Perspective

3.2.1 MSL Data Following the penning of Mr Humphries memorandum, there was concerted activity by the then Department of Lands & Survey to check and calibrate tide gauges. It appears to have resulted in a systematic campaign to ensure that tide gauge data was both collected and recorded at many of the ports of the Dominion. While some of these data were subsequently used to assist in the reductions of the horizontal measurements used to define the NZ Geodetic Datum 1949, they were predominantly used both for tidal predictions and to define a number of local datums that were subsequently used by local port and city authorities.

As efforts began to be focused towards the establishment of a national geodetic datum, so some of these local datums began to gain greater importance. When the heights for the first order points in the 1949 Geodetic Datum were subsequently derived, they were referenced to MSL at principal ports throughout the North and South Island. These tide gauge MSLs were transferred to the primary geodetic network points by means of both precise leveling and trigonometric leveling. Although it is now difficult to be certain as to which tide gauges were used for this task, it seems likely that those listed in the first section of Table 1 were the primary reference sites.

It is important to understand, firstly, that heights were never considered to be part of the NZGD'49 and, secondly, that the heights that have been determined for geodetic points have, unlike their horizontal counterparts, never been considered to be absolutely fixed. As additional (local) MSL datums were added in data sparse areas (e.g., Moturiki and One Tree Point), and the precise leveling extended, so the heights on nearby NZGD'49 points have been upgraded. In addition, where two or more primary MSL datums have had common points, transformations from one to the other have been defined. Heights of points in the Dunedin Datum can be converted to equivalent heights on the Lyttelton Datum, for example, by the addition of 0.1786 ft.

Table 1 also shows a number of Secondary Ports where additional tide gauge data has been collected and where other MSL datums of much smaller extent have been defined.

Table 1. New Zealand's Most Significant MSL Height Datums

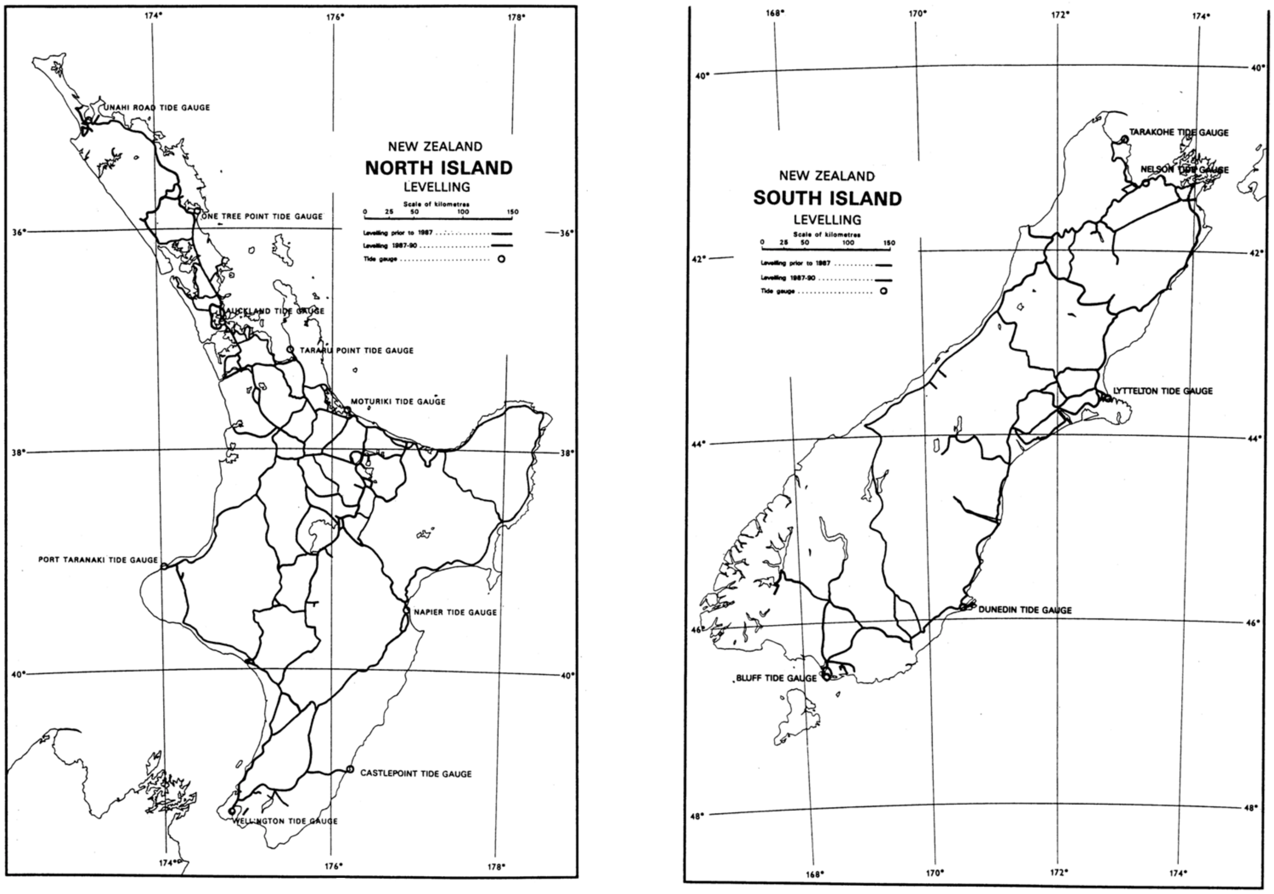
Datum Name	Location	Definition
Principal Ports		
Auckland (1946)	Auckland Harbour	MSL from TG data collected between 1909 -1923
Wellington (1953)	Wellington Harbour	MSL from TG data collected from 1909 - 1946
Lyttelton (1937)	Lyttelton Harbour	MSL from 9 years of TG data collected between 1918 - 1933
Dunedin (1958)	Dunedin Harbour	MSL from TG data collected between 1918 - 1937
Bluff (1955)	Invercargill harbour	MSL from 8 years of TG data collected between 1918 - 1934
Other Primary Datums		
One Tree Point (1964)	Whangarei Harbour	MSL from TG data collected between 1960 -1963
Moturiki (1953)	Moturiki Is	MSL from TG data collected between 7/2/49 - 15/12/52
Secondary Ports		
Tararu (1952)	Tararu Point	MSL from TG data collected between 1922 - 1923
Napier (1962)	Napier Harbour	No record of derivation
Taranaki (1970)	New Plymouth Hbr.	MSL from TG data collected between 1918 -1921
Gisborne (1926)	Gisborne Harbour	MSL from TG data collected throughout 1926
Nelson (1955)	Nelson Harbour	MSL from TG data collected from 1939 - 1942
Picton	Picton Harbour	MSL from TG data collected from 1942 - 1943
Westport	Westport Harbour	MSL from TG data collected from 1918 - 1922
Greymouth	Greymouth Hbr.	MSL from TG data collected from 1939 - 1943
Timaru	Timaru Harbour	MSL from TG data collected from 1935 - 1937
Other MSL Datums		
Chatham Island	Waitangi Harbour	MSL from TG data collected in 1959
Deep Cove (1960)	Deep Cove	MSL from TG data collected in April and May 1960.
Stewart Island (1977)	Stewart Island	MSL from 3-5 high and low tides at two different locations

Table 1 should not be construed to be a complete representation of all New Zealand's local height datums, for over the years many smaller and/or special purpose datums have also been defined. A significant number of these, e.g., Tekapo, Arapuni, Karapiro and Maraetai were defined with respect to some existing datum and were used to serve specific hydroelectric power projects. Others, e.g., Deep Cove, Chatham Island, Stewart Island and those around the Kaipara Harbour were defined from short periods of tidal data and used for local purposes only. Others again were introduced in a nominal sense so as to assign unique height values to stations that had been rigourously leveled as part of the national earth deformation study program.

Although New Zealand's primary MSL datums are now considered to be those as defined at the Principal Ports together with One Tree Point, Moturiki, and perhaps Nelson, the total situation is both convoluted and confusing to anyone but the technical specialist. When viewed from a national perspective, there is no overall consistency or coherency in New Zealand's height networks.

3.2.2 Precise Leveling Data. Into the above mix, one needs to add the very extensive runs of precise leveling (more than 16 000 km) that have been observed over a period of more than 40 years. The first order leveling standards used in New Zealand have always produced precise leveling data of the highest order of accuracy. While it is possible that some of this data may still be subject to the residual systematic errors that have been found to be part of historical leveling operations, the greater problem may well lie in either bench mark disturbance or in any earth deformation that may have occurred since its collection. The diagram below shows the extensive nature of the precise leveling that has been completed in New Zealand.

New Zealand's Precise Leveling Networks
(from NZNCGG, 1991)



Conventionally, height datums have been defined (c.f., Chapter 4), either by using precise leveling to carry MSL heights from one tide gauge to the next or by creating closed leveling loops. For many years the Department of Lands & Survey had a long-term goal of completing an accurate national height datum (or even possibly a North Island and a South Island datum), by connecting its precise leveling to a series of principal tide gauges. However, it was not until the late 1980s that the last major leveling run (down the West Coast of the South Island and through the Haast Pass) was completed. While closed loop leveling adjustments have been made in some regional areas (e.g., the Volcanic

Plateau, and the Bay of Plenty), no attempt has ever been made to undertake a single, integrated and rigorous adjustment of all leveling data.

Furthermore, the orthometric corrections were derived from the normal gravity formula via the following type of process.

In equation (2), Ch.2, we had $C = {}_{0}^{H} \; gdH$

Now an abbreviated form of the normal gravity formula is given by

$$= \quad {}_a(1 + \quad \mathrm{Sin}^2 \quad) - 2 \quad {}_aH/a$$

where ${}_a$, , and a are all constants associated with the reference ellipsoid and where   is the latitude of the point.

If this formula is substituted into the integral and the integration performed, we obtain

$$C \qquad {}_aH + \quad {}_a \quad \mathrm{Sin}^2 \quad H - \quad {}_aH^2/a$$

After differentiating, we obtain $dC = \quad {}_a dH + \quad {}_a \quad \mathrm{Sin}^2 \quad dH - 2 \quad {}_aHdH/a + 2 \quad {}_a \quad \mathrm{Sin} \quad \mathrm{Cos} \quad Hd$

On an equipotential surface such as the reference ellipsoid , however, dC = 0 and, therefore,

$$dH = -(H \quad \mathrm{Sin}2 \quad d \quad)/[1 + \quad \mathrm{Sin}^2 \quad -(2/a)/H]$$

$$\text{i.e.,} \qquad dH \qquad - \; H\,\mathrm{Sin}2 \quad d$$

The orthometric height of the point H_{i+1} can then be approximated by the expression

$$H_{i+1} = H_i + \quad h + dH$$

where   h is the observed height difference obtained by spirit leveling. In this expression, dH is the normal approximation to the orthometric correction and results in the computation of a normal orthometric height for each point. Mulder (1981) and Gilliland (1987) outline the way in which precise leveling was developed and undertaken in New Zealand.

Given sufficient gravity data, Helmert orthometric heights can still be calculated from the original leveling data with relative ease. The greater difficulty with New Zealand’s existing precise leveling networks is more likely to be found with either uplift or subsidence due to one or more of a variety of processes. On a local level, subsidence of as much as 8.5m has been reported as occurring in the Waireki area due to the draw-off of geothermal energy (Walcott, 1984). Furthermore, co seismic movements in the order of 2.5m are not uncommon (e.g., Boyes, 1970). On a broader scale, geophysicists have postulated that a general land uplift of as much as 10mm/yr may be occurring (c.f., Walcott, 1984), although it seems clear that these effects are not being seen in the coastal regions (e.g., Hannah, 1990). Existing scientific experiments, combined with the planned national GPS network, should help to isolate the extent of these problems.

3.2.3 Gravity Data. Over a period of many years, the Department of Industrial and Scientific Research (DSIR), collected and data based a considerable volume of onshore and offshore gravity data. These data holdings were reviewed by Gilliland (1990). At that time the data were reduced using the 1930 International Gravity Formula and were referenced to the New Zealand Potsdam Datum, 1959. This datum used an observed value of 980509.5 mGal at the national base station (48732A) in Christchurch. This remains the case (Woodward, 2000, private communication).

The onshore data file had approximately 35 000 records equating to an average station density of approximately one per 7.5 km^2. Gilliland, as part of his project, created new data files which were not only referenced to the International Gravity Standardisation Net (IGSN71) and the Geodetic Reference System 1980 but were also corrected for atmospheric effects and the terrain correction.

The offshore gravity data formed part of the DSIR Marine Data Base and contained over 800 000 records of which approximately 500 000 contained gravity information. Gilliland processed this data and created 460 000 records, referencing it to the IGSN and GRS80 but corrected for atmospheric effects only.

While these data are now resident with the Institute of Geological and Nuclear Sciences (IGNS), lack of funding has led to the database not being well maintained. Indeed, it is not clear to what extent additional data has been added over the last 10 years. Woodward (private communication), does report, however, that gravity measurements have been made along “many” of the precise leveling runs and that oceanographic satellite gravity data (at one minute intervals), has been added to the database. Beavan (private communication, 2000), indicates that a number of absolute gravity stations have recently been established as part of a scientific project, four in and near Christchurch, six across Arthur’s Pass, one at Mt John and five west of the main divide south of the Copeland Pass.

3.2.4 Other Data. New Zealand has other (generally lower order) data types that could contribute information to a vertical datum. These may be listed as follows.

- Vertical trigonometric observations across the entire network of stations that formed the backbone of the NZGD ’49 reference system.
- Geoidal undulations at a number of stations as derived from the old TRANSIT Doppler satellite system. These, however, are in reference systems that were not entirely stable and are of a relatively low order of accuracy.
- Very accurate deflections of the vertical that were calculated with respect to NZGD ’49 and that were derived from first order astronomy observations. These observations have potential value in that they enable the calculation of geoidal undulation differences between the respective observation points.
- Data on sea surface topography as derived from international satellite altimetry missions.
- An increasing volume of data derived from a wide variety of GPS geodetic control surveys. This data type, which is recent rather than historic, will be described in Section 5.3.

Before considering some of the methods that might be used to assist in the definition of a national height datum (given that such a datum is both beneficial and desirable), it may be of some value to consider overseas practice and experience. The next chapter deals with this issue.

4. INTERNATIONAL PRACTICE IN DATUM DEFINITION

In order to examine overseas practice, a number of different jurisdictions were considered, including: Australia, the United States, Canada, Taiwan and the Nordic countries. Each of these jurisdictions has different characteristics. Australia, for example, is a large but stable continent that is surrounded by ocean. The United States, whilst part of a large continent, not only has areas that are mountainous but also has the problem of an on-shore plate boundary. Canada while having similar physical characteristics to the United States must deal with high rates of glacio-isostatic rebound in its northern regions. Taiwan, is a small island nation situated at the boundary of the Eurasian Plate and the Philippine Sea Plate. Finally, all of the Nordic countries face the problem of high rates of glacio-isostatic rebound thus requiring the introduction of time as a additional dimension in the datum definition process.

4.1 Australia

Australia (Tasmania excepted) differs fundamentally from New Zealand in that it does have a single, unified height datum – the Australian Height Datum (AHD). AHD was formally defined in 1971 when 97 230 km of two-way leveling was simultaneously adjusted. This leveling was connected to 30 tide gauges that were positioned around the Australian coast and at which mean sea level for 1966 – 1968 was assigned the value of zero (ICSM, 1999). The resulting datum surface, with minor modifications in two metropolitan areas, has been termed the AHD.

The leveling network in Tasmania was adjusted in 1983 and is known as AHD (Tasmania). This network consists of 72 sections between 57 junction points and is based upon mean sea level for 1972 at the tide gauges at Hobart and Burnie. MSL at both Hobart and Burnie, as determined from this year of data were assigned the value of zero on the AHD (Tasmania).

Australian authorities recognize that AHD is an imperfect realization of an equipotential surface because some of the tide gauges are not well sited, MSL was determined over a limited period only, and sea surface topography has been ignored. They concede that discrepancies in the order of one metre may exist because of these difficulties (ICSM, 1999).

At this stage, Australia has no official plans to update its height datum although they do continue to test and evaluate it particularly with respect to its role in geoid determination. They are aware that user disenchantment may grow as GPS surveys reveal its inconsistencies but have not addressed any of the public policy type issues that may arise as a consequence of attempting to change to a newer, more consistent datum (Steed, private communication).

4.2 USA

The United States of America established a National Geodetic Vertical Datum in 1929 by holding MSL fixed at 26 tide gauge stations (five of which were in Canada) and undertaking an adjustment of 106 724 km of leveling data (31 565 km of which in Canada). This adjustment was the fourth in a series, the others being undertaken in 1903, 1907 and 1912 with each subsequent adjustment incorporating new data (c.f., Zilkoski et al, 1992). The NGVD 29 datum did not use observed gravity data in determining the orthometric corrections and thus the resulting heights were normal orthometric heights (see Section 2.1). Although Canadian data was included in the adjustment, the resulting “Sea Level Datum of 1929” was never adopted by Canada.

The next national adjustment to occur was undertaken 60 years later and resulted in the definition of a new vertical reference system, known as the North American Vertical Datum, 1988 (NAVD 88). This new datum included approximately 625 000 km of leveling that had been added to the US national network since 1929. It also included 81 500 km of re-leveling across the North American continent. The datum was realized by undertaking a minimum constraint adjustment of US, Mexican, and Canadian leveling data, holding fixed the primary tide gauge benchmark of Rimouski, located at the mouth of the St Lawrence River. The MSL tide gauge height used for Rimouski was the same as that used to define the new International Great Lakes Datum of 1985 (IGLD 85), thus ensuring that NAVD 88 and IGLD 85 were on the same reference system.

The NAVD 88 adjustment used observed gravity data to calculate the geopotential numbers, thus enabling Helmert orthometric heights to be computed for all points (see Section 2.2). Zilkoski et al (1992), note that the differences in orthometric height between NGVD 29 and NAVD 88 in the co-terminus United States range from –40 cm to +150 cm but that in most “stable” areas, relative height differences between adjacent benchmarks are less than 1 cm.

It is of interest to note the reasons for the development of NAVD 88. These are largely as outlined in Zilkoski et al (1992), and may be listed as follows.

- The 1929 datum was deficient in terms of its coverage of the United States.
- Many thousands of benchmarks had been destroyed, often as a result of post-World War II highway construction activities.
- Many of the existing benchmarks were affected by crustal motion, postglacial rebound, and subsidence due to the withdrawal of underground liquids.
- Network distortions (some of which were severe) were being created by forcing the new 625 000 km of leveling to fit the previously determined NAVD 29 heights.
- The National Geodetic Survey had just completed its new horizontal datum adjustment and had the staff available to work on the project.
- The potential to generate cost savings through the elimination of duplicate surveys and readjustments by a variety of federal, state and local agencies. NGS did not believe that it would continue to have the resources to maintain NGVD 29 as in the past.

Although NAVD 88 was formally implemented in 1991, those responsible for the project never saw it as the final solution to the vertical datum problem in the United States. **Rather, it was perceived to be a necessary step en route to the construction of a very accurate continental geoid**.

In April 2000, NGS formally released its National Height Modernization Study (NOAA, 1998). This document presents a rationale for the need to modernize the vertical component of the National Spatial Reference System (NSRS). The primary argument advanced in support of this new NSRS focuses on the inability of the existing geodetic reference framework to support the use of GPS to make accurate orthometric height measurements, thus weakening the “substantial” benefits that can be accrued through the use of GPS heighting.

The essence of the height modernization proposal is one of a cooperative effort amongst private sector, state and Federal agencies, over a five-year period, aimed at establishing a network of

55 000 benchmarks with a nominal 10 km by 10 km spacing, Each of these benchmarks will have an accurate ellipsoidal height (obtained via GPS techniques), and an accurate orthometric height (obtained using precise leveling and gravity data), thus enabling the calculation of an accurate geoidal undulation at that point. This network will then be used to control all in-fill surveys. The decision to space benchmarks at a nominal 10 km by 10 km interval was not based on any firm scientific rationale but rather on a series of "warm and fuzzy feelings" (Zilkoski, private communication), held by the State authorities who would largely be responsible for funding the program. In the final analysis, however, it is recognized that decisions regarding spacing should be based upon factors such as the terrain, the population density, local user needs, and the accuracy of the geoid that is able to be determined when interpolating within the network of points. As a guiding policy, NGS has set an unofficial goal of obtaining a two centimetre geoid within the heavily populated regions of the United States.

NGS anticipates an expenditure on the project of $US 66 Million over a five year period, much of which will come from State governments and other Federal agencies. It is anticipated that the private sector would undertake the relevant surveys under the technical guidance and control of NGS.

4.3 Canada

Canada's official height datum is known as the Canadian Geodetic Vertical Datum 1928 (CGVD'28). It was established by precise leveling between the more than 80 000 stations that form part of the primary vertical control network. The MSL used in establishing CGVD'28 was determined in 1928, based upon data collected at six tide gauges. Two of these gauges are on the Pacific Ocean (Vancouver and Prince Rupert), one on the St Lawrence River (Pointe-au-Pere, near Rimouski, Quebec), two on the Atlantic Ocean (Halifax and Yarmouth) and the last at Rouses Point in southern Quebec.

The published CGVD'28 orthometric heights provide a standard vertical reference system that "*meets the needs of the majority of users in Canada*" (Mainville, et al, 1997). This system is known to be contaminated by systematic error due to the following:

- The use of normal orthometric corrections rather than Helmert corrections.
- Long term sea level change.
- Post-glacial rebound, particularly in the Hudson Bay region.
- The neglect of sea-surface topography.

Despite these deficiencies there has been no public or provincial pressure for any formal readjustment of the datum. Indeed, the provincial governments seem to be quite satisfied with the status quo. While the Geodetic Survey Division of Geomatics Canada believes that a new or revised datum is required to satisfy the increasing high accuracy requirements of modern space-based positioning, it will make no formal recommendation to this end until it has completed forming and analysing a precise geoid model for Canada (estimated to be 3-5 years away). It is using existing resources to investigate the systematic differences that occur between a gravimetric geoid of Canada and one that is determined by differencing the orthometric and ellipsoidal heights for the network of precise leveled benchmarks that stretch across Canada. By resolving these scientific problems now, it is preparing itself for an anticipated change in user expectations that will come about through the widespread use of GPS technology.

While Canada has undertaken comprehensive and rigorous minimum constraint readjustments of its vertical network in 1995 and 1998 (holding MSL at the Rimouski tide gauge fixed), these have been done for scientific purposes only. With the validation and data-basing of the historical leveling data completed as part of the NAVD'88 project, it has been a relatively easy matter to update and readjust the entire data set on an as needed basis.

Canada has undertaken almost no precise leveling in the last four years except for that needed to support small scientific missions. It believes that the costs of precise leveling are no longer warranted and accordingly, no longer has a budget for such activities.

Canada also supports the Great Lakes Datum which is formally readjusted every 20 – 30 years in order to compensate for differential uplift/tilting across the Great Lakes due to glacio-isostatic rebound. This, however, is a specific datum that is upgraded with specific practical and commercial objectives in mind.

4.4 Taiwan

Taiwan, is a small island nation (approx 400 km long by 130 km in width), situated at the common boundary of the Eurasian and Philippine Sea Plates. It not only experiences severe seismic activity, but it has on its eastern side a major oceanographic feature – the Kuroshio Current. This current in turn is responsible for major variations in the local Sea Surface Topography (SST).

Historically, Taiwan's vertical datum has been determined by traditional methods, i.e., by precise leveling linked to a tide gauge (Keelung) at which MSL (as determined from some years of tidal observations), has been adopted as the zero orthometric height. As with New Zealand, the ongoing (presumed gradual) effects of vertical crustal movements on benchmark heights have been ignored as have the effects of oceanographic phenomena on tide gauge determinations of MSL (Hwang, 1997).

It is not clear if Taiwan presently has any formal plans to redefine its vertical datum. However, Hwang (1997), has suggested that if it do so, it not only use conventional precise leveling data but that it link this leveling to six tide gauge sites where MSL has been determined. He further suggests that SST be determined at each of these sites by using both oceanographic and GPS data and that these SSTs be introduced into the network adjustment in the form of weighted constraints. The datum would thus be referenced not to MSL, but to the zero reference surface (theoretically equipotential), from which SST has been determined. Hwang also alludes to the possibility of integrating a vertical velocity model into the network. He gives no attention to any public policy or user issues.

4.5 The Nordic Countries

Because of their long history of settlement and the significant influence of glacio-isostatic uplift on most Nordic countries, more relevelings and vertical datum re-adjustments have been undertaken in this region than in almost any other part of the world. This section will discuss the vertical positioning strategies of four countries, i.e., Denmark, Finland, Norway and Sweden. Much of the descriptive material in this section can be found in Cross et al (1987).

4.5.1 Denmark. Denmark has seen a number of precise leveling campaigns. The first covered the Jutland Peninsula and the Danish Islands, with data being collected from 1885-1894 and 1896-1904 respectively. The second precise leveling of the Danish Islands was made between 1938 and 1944 being followed by a releveling of the Jutland Peninsula between 1943-1953. In recent years a further complete releveling has been undertaken.

As a result of these various levelings, three different height systems have been created. The first (known as the DNN - GM system) used the data from the initial leveling campaign and referenced it to a fundamental bench-mark in the Cathedral of Arhus. This bench mark was given a fixed elevation such that the average of the MSLs at 10 Danish tide gauges (sea level data collected between 1888 and 1900), was close to zero.

A second height system that used the second set of precise leveling data only was calculated for the Danish Islands and became known as the DNN – GI system. It was defined by holding the height of the fundamental benchmark in the Cathedral of Arhus to its original value. In 1974 a second system was then defined for the Jutland Peninsula by using both the original 1885-1894 data and the 1943-1953 data in a simultaneous adjustment. The adjustment gave two sets of elevations (one each for the epochs 1890.5 and 1950.5), and the land uplift numbers for each benchmark common to the two levellings. The elevation of the fundamental benchmark was fixed at its original value despite evidence that it had been subsiding at a rate of 0.55mm/yr relative to local MSL. The new system, which is known as the DNN – GM, 1950.5 system, has both the heights and the land-uplift numbers published in terms of their geopotential units.

A further adjustment was undertaken in the early 1990s using both the most recent leveling data and a new elevation for the fundamental benchmark (Makinen, personal communication). Each benchmark now has new geopotential numbers as well as a velocity.

Makinen (personal communication), reports that there has been widespread dissatisfaction with the most recent system by a user community who have not appreciated having to deal with a further set of new elevations and velocities for their benchmarks.

4.5.2 Finland. Finland’s initial leveling, which was undertaken between 1892-1910 in the Southern part of the country, was adjusted and referenced (subsequently found to be erroneously so by 109 mm), to the zero of the tide gauge at Helsinki. Land uplift was not taken into account in the leveling or adjustment process. This was known as the NN-system.

The second leveling of Finland, which covered the whole country, was begun in 1935 and completed in 1955. The first loop, when completed, was adjusted into the NN-system system by holding the height on the junction benchmark at its old NN value. Each subsequent loop was fitted to the earlier ones without correction for land uplift. The temporary height system thus created was known as the N-43 system. Coincidentally, by 1943.0 the zero of the NN-system had risen with land uplift such that it now coincided with MSL at Helsinki.

Once the second leveling was completed, height differences, divided by the time epoch difference (1900.0 to 1944.0) were calculated at all common points thus yielding crude land uplift rates. These were adjusted in order to arrive at land uplift estimates that were in turn used to time-homogenise the observations resulting from the two levelings (i.e., to eliminate differential uplift which would have occurred over the period of 18-20 years that it took to complete each leveling). Each leveling was then adjusted separately for its own epoch thus giving elevation differences in the epochs 1900.0 and 1944.0. The comparison of the elevation differences for these two epochs yielded a new set of land uplift values which were then amended by a constant term to fit the tide gauge data. The estimate for eustatic sea level rise of 0.8mm/yr was included in the tide gauge values. The elevation of the MSL at Helsinki was redetermined using data collected between 1935-1954.

The benchmark heights were then extrapolated forward from 1944.0 to 1960.0 using the land uplift numbers, and the resulting system published as the N60-system. A land uplift number is attached to each benchmark but is ordinarily **not** used to update heights. The heights as published are thus considered invariant. All new leveling is reduced back to the N60 system by using the estimated land uplift rates.

Interestingly enough, Cross et al (1987) report that most land surveyors consider the creation of the temporary N-43 system to have been a mistake and that the new bench marks of the second leveling should have been included in the old NN-system. They note that there is a clear view that the extra work caused by multiple systems has far outweighed any advantages offered by more “realistic heights”. Although recent new leveling has been undertaken, there is, for the same reason, an equally clear view that the introduction of any additional new height system should be postponed as long as possible.

4.5.3 Norway. Although the topography of Norway presents a host of problems for precise leveling, three different datums have been defined over the last 100 years.

The first was based upon 887 km of leveling in Southern Norway that was undertaken from 1890-1909. The datum was defined by meaning two years of sea level observations that had been collected at Oslo. This was known as the NN network of elevations.

In 1916, modern precise leveling was begun and continued through to 1953 by which time 8468 km of leveling had been completed. This work was adjusted in 1954 with the effects of land uplift being ignored. A new datum was defined by using MSL data from seven tide gauges (with record lengths that varied between 17 and 67 years) in Southern Norway. At five of these gauges a linear regression line for sea level was computed and the derived regression parameters, used to compute an adjusted value of MSL for 1952. At the remaining two gauges a simple arithmetic mean was used for the 1952 value of sea level. These gauges were then compared through the adjusted leveling network and their average chosen as the zero reference point for the new datum. The network became known as the NN 1954 system.

In 1957 a new (and separate) datum, known as the NNN 1957 system, was defined for Northern Norway. The fact that it was a separate datum was not forced by land uplift, by rather by the physical difficulties in connecting the northern network to the southern network. The NNN 1957 system was referenced to two tide gauges in North Norway with their sea level observations being collected between 1948-1956 and 1945-1956 respectively.

These networks have been densified and extended since the time of their original definition. NN 1954 was finally joined to NNN 1957 in 1974, showing a difference of only 28 mm. Although a releveling of 13 000 km was planned to start in 1986 it is only now just coming to a conclusion. It appears that no decisions have yet been made as to when or even how a new height system for Norway should be defined.

4.5.4 Sweden. The first high-precision leveling of Sweden was undertaken between 1886 and 1905. The network was comprised of 12 loops and had a total length of 4857 km. The elevation of the fundamental benchmark at Stockholm was fixed such that the average MSLs at a number of Swedish tide-gauges had a zero elevation at epoch 1900.0. This is now known as the RH 00 system.

The second precise leveling of Sweden was carried out between 1951 and 1967. It comprised 27 loops with a total length of 10 389 km. Before the final adjustment, land uplift data were obtained both from tide gauge records and from a comparison of heights obtained after a preliminary adjustment of the new data, with heights in the RH 00 system. The uplift values were then used to reduce the second leveling to a 1960.0 reference epoch for its final adjustment. The datum for this new system is based upon the elevation of a junction benchmark between Sweden and Denmark that was transferred to a junction in the new net and then reduced to the 1960.0 epoch.

After adjustment, the elevations were all extrapolated to the epoch 1970.0 using the final land uplift values, the result being known as the Height System 1970 (RH 70). Cross et al (1987) note that the older (RH 00) system continues to be used in many municipalities.

A third precise leveling was begun in 1979 and has recently been completed. Again it appears that decisions have yet to be made about when or how a new height system might be defined.

4.6 Summary

After reviewing the above information, the following salient points can be made.

(a) While New Zealand is one of a number of countries encountered in this study that lacks a rigourously correct vertical datum, it is the only country that has never had its precise leveling comprehensively adjusted. Common datum deficiencies in other countries include the use of normal orthometric corrections rather than Helmert corrections, the neglect of sea surface topography on tide gauge MSLs and the neglect of eustatic sea-level change.

(b) With the exception of Australia, all the countries included in this study face problems either with post-glacial rebound or with tectonic instability. Because post-glacial rebound is an ongoing systematic effect it is relatively easy to both derive and to describe the associated vertical velocity field. Insofar as earth deformation is characterized by a long-term, ongoing systematic uplift or subsidence, it too can be easily described. Episodic deformation, such as is associated with seismic events and is found in the Western United States and New Zealand, creates far greater problems.

(c) There is no evidence of any concerted user demand in any of the countries studied, for a change from an older vertical datum to a modern, rigourously correct datum. Indeed, in many cases, the introduction of new datums seems to create more consternation and confusion amongst the non-scientific users than goodwill. Put another way, users need to see compelling reasons for a new datum if they are to embrace it happily. This issue is discussed more fully in Chapter 6.

(d) In general, the Nordic countries are more advanced than others in terms of the way in which time dependency is being handled in their networks. Denmark, Finland, and Sweden all have published land uplift rates for their bench marks that, in principle, allow the elevations to be reduced to any epoch. In general, however, these uplift rates are only used for scientific purposes or by those involved in network maintenance. In "ordinary work" (c.f., Cross et al, 1987), they are not used. Ordinary users are predominantly interested in relative accuracies between points rather than absolute accuracies.

(e) Over the course of the 20th Century the Nordic countries have invested a great deal of time and energy in determining land uplift from repeated precise levelings. Given the advances in both GPS and absolute gravity measurement technology, it is unlikely that any further relevelings will now occur. This is certainly true in Canada.

(f) The height modernization program recently approved by the United States government is clearly the most ambitious encountered in this study. It looks forward to a significant, GPS driven, change in user needs. Furthermore, it attempts to substantiate the long-term benefits of this change with a cost benefit analysis that overwhelmingly supports the investment required. It is strongly recommended that a detailed economic analysis be undertaken of these figures to assess their relevance to New Zealand.

(g) A rigourously adjusted precise leveling network is seen in most countries as an essential tool in the development of a national, high accuracy geoidal model. The motivation for finally adjusting New Zealand's precise leveling is unlikely to come from a user community disgruntled with the existing system, but rather from a need to build a geoidal model able to meet the needs of the wide segment of the (non-technical) community that has embraced GPS technology. The National Geodetic Survey now finds that 60% of the users of their CORS GPS network have no specific surveying affiliation. They expect this number to rise dramatically in the near future (c.f., Chapter 6).

5. POSSIBLE APPROACHES TO THE DATUM DEFINITION PROBLEM

This chapter considers a range of technologies or information types that may be used in providing some form of absolute frame of reference for a height datum. It is directed specifically towards some of the issues that would be faced should a particular data type be used in New Zealand. The advantages and disadvantages to each are discussed.

5.1 Sea Level Data. Traditionally, this is the data type that has been used for vertical datum definition. Such data have normally been collected over a period of years and averaged so as to provide a defined Mean Sea Level (MSL) reference surface. In the absence of other factors, the optimum data collection period is one complete lunar cycle of 18.6 years. In many cases, as has happened in New Zealand, datums have been defined from a much lesser length of data.

Historically, MSL has been determined at a number of tide gauge sites around a nation's coast with these sites have being linked by precise leveling. Then, by assigning a value of 0.00 m to the MSL reference surface at a single tide gauge site, or by using the MSLs obtained at a number of sites, the precise leveling stations have been given MSL values and a reference datum defined. This practice has had the clear benefit of providing a datum that has been of practical use to users, has gained wide acceptance, and has apparently met user needs despite its technical deficiencies.

Unfortunately, while New Zealand has some excellent long-term sea level records (greater than 90 years), this type of data when used on its own for datum definition purposes is subject to the following problems.

a) It reflects a fixed value of MSL that has been defined over a specific time interval. Unfortunately, for at least three reasons, MSL is an unstable surface. Firstly, and as pointed out by Douglas (1991), global MSL is rising at a rate of about 1.8 ± 0.3 mm/yr. Hannah (1990) has demonstrated a similar rate of sea level rise around the New Zealand coastline. Indeed, in the absence of any other problem most New Zealand MSL datums would now be in error by approximately 10 cm due to this cause alone. If climate change occurs in the future, and sea levels respond as predicted by having rates of sea level rise that are three to five times larger than the current rate (c.f., Warwick et al, 1995), further datum compromise will occur. While there is currently no evidence of an acceleration in sea level rise over the last 100–150 years (Baltuck et al, 1996), the future (near-term) possibility of such an acceleration cannot be discounted.

Secondly, any systematic land uplift or subsidence that might occur at a site will also invalidate the MSL reference figure over a prolonged period of time.

Finally, due to the inverse barometer effect, any systemic change in climate (pressure) systems also has the potential to systematically alter MSL at a specific location.

b). It reflects a fixed value of MSL at one location only. As was pointed out in Section 3, New Zealand is positioned in a region that is seismically, tectonically and volcanically active. While there is as yet little clear evidence to suggest differing rates of uplift (or subsidence) at differing locations on the New Zealand coastline (at least in a non-geological time-scale), it would be dangerous to assume that these influences might be either the same or negligible at all tide-gauge sites. Any derived value of MSL at a given tide gauge site must thus be considered as specific to that site only.

As a further difficulty, the tide gauge sites used are few (i.e., they have low spatial density), and are all in harbour locations. Their maintenance, in some cases, has been poor and their records possibly contaminated by the (generally small) aliasing effects that are found in these harbour environments. A recent initiative by the National Institute of Water and Atmospheric Research (NIWA) to install a network of high accuracy gauges in open coast locations has the potential to overcome these particular problems.

c). MSL is itself not an equipotential surface. Apart from the difficulties that can occur due to the inadequate length of a tidal record (30 year records, for example, can show decimeter level inconsistencies, e.g., Douglas, 1991), the sea surface has a characteristic topography.
This topography, which is very much a reflection of large-scale ocean circulation, can vary by as much as 2 meters on a global basis. Best current estimates from satellite altimetry data suggest a 40 cm range from the far north to the far south of New Zealand.

When sea level measurements by satellite altimetric techniques are combined with tide gauge measurements, some of the above problems are negated. Satellite altimetry data, for example, are of a high spatial density and are unaffected by seismic or tectonic motion. They also enable variations in sea surface topography to be well determined. As yet, however, the results are not as reliable in a coastal environment as they are over the deep ocean.

5.2 Absolute Gravity Data. Gravity data can be collected in either relative form (i.e., as a difference between two points) or in absolute form (i.e., instruments that measure *g* directly). In the former case it is used in combination with precise leveling data, to determine the potential differences from which orthometric heights are calculated (c.f., Section 2.1). In the latter case, it can be used for geophysical research, for earth deformation purposes and as a means for defining the unique position of a point along its gravity vector. Note that absolute gravity data collected over a period of time at a given point, will give height changes at that point (and thus a datum variation), but will not yield a height in any absolute sense.

In the latter part of the 20th Century, there was a rapid improvement in the portability and accuracy of absolute gravimeters. Using fundamental standards of length and time, and a free-fall technique based on the Michelson interferometer, laser interferometric absolute gravimeters were shown to be able to achieve a precision of ±5 Gal in a single-drop at a quiet site. With multiple drops a precision of ±1 Gal can be obtained (Niebauer et al, 1995; Murakami et al, 1996). A (possibly) conservative error budget published by CIRES (1993) suggests that the 75 cm tall FG5 gravimeter has an RMS accuracy of 1.7 Gal. Note that 1 Gal is equivalent to 3 mm in height displacement on the earth's surface

However, a new rise and fall gravimeter (chamber height of 35cm) and one fifth the volume of the FG5 has recently been developed. Initial tests suggest that it can deliver a single drop precision of ±7 Gal or better and an overall precision over multiple drops that closely matches the FG5 (Brown et al, 1999). The Geodetic Survey of Canada have recently purchased this gravimeter (known as the A10) for a total cost of approximately $US 150 000 and are excited about its potential for contributing to their geodetic/geophysical programs. It is understood that the Australian Geological Survey has also purchased a similar instrument.

Note: The purchase of the new gravimeter in Canada was justified on the basis of the cost savings generated from two primary sources. Firstly, a portable, high accuracy absolute-g gravimeter that measures quickly, eliminates the need for any of the measurements which are typically required to tie a point to an existing gravity network. Secondly, relative measurement gravimeters require calibration twice annually at a cost of approximately $C 7000 per calibration. If relative measuring gravimeters are no longer used and 10 are thereby made redundant, then significant levels of annual savings can be achieved.

It must be understood, however, that the determination of *g* is not without complexity. In addition to instrumental noise, and even if a site is stable, there are a number of environmental noise sources. Table 2 below (from CIRES, 1993), gives an assessment of the uncertainties in these noise sources for the FG5 gravimeter.

Table 2. Environmental Noise Sources When Measuring *g*

Noise Source	**Typical Size** (Gal)	**Uncertainty in correction**
Tides	300	0.2 – 0.5 Gal
Periodic ocean loading	20 (coastal sites only)	0.2 Gal
Non-periodic ocean loading	10	2 Gal
Atmospheric effects	8	1 Gal
Water table	0 – 100 site dependent	0 – 10 Gal
Microseisms	7 – 100, but 25 is typical	0.5 Gal
Temperature	10 Gal transient in 1 hour	0 – 1 Gal

While instrumental accuracies are currently in the order of 2 Gal, and site repeatability equal or better than 1 Gal, the environmental effects are more problematical. If these are ignored or inadequately modeled, substantial errors may be incurred. CIRES (1993) suggests that if accurate modeling is undertaken then absolute–*g*, VLBI, and GPS will have somewhat similar vertical measurement uncertainties for almost all baselines. At the very least, they will provide strong, independent measurement techniques. Under a worst-case scenario, there may be an overall uncertainty in the determination of absolute-*g* of perhaps 15 Gal. This in turn corresponds to a height uncertainty of 45mm.

Canada has established more than 50 absolute gravity stations in recent years and now uses some of these data to confirm the rates of uplift (approximately 1 cm/yr), that are being experienced in the Hudson's Bay region. Canada has attempted to co-locate permanent GPS tracking stations with some of its absolute gravity stations, thus obtaining two independent estimates of the ongoing crustal uplift. They see these two technologies as providing a very powerful, four-dimensional spatial reference system (Liard and Gibb, 1998).

5.3 **GPS Data.** The costs of obtaining GPS receivers, the overall usefulness of the system and its operational characteristics are all well known and do not require repetition here. The fact that LINZ has made the commitment to use high precision GPS techniques to monitor and maintain its horizontal datum suggests that it be considered as a data source for defining or monitoring a vertical datum. Furthermore, the proliferation of dual frequency GPS receivers and the current initiative to develop of national network of continuously monitoring receivers (CGPS) on permanent sites can only but strengthen the importance of this potential source of data.

The key issues to be considered are the long-term stability of the reference frames with respect to which the GPS measurements are made, the accuracies achievable and the nature of the heights themselves.

(a) Stability of global reference frames. The use of a multiplicity of high precision data sources (VLBI, SLR and GPS), the co-location of these differing measurement techniques at certain sites, the global nature of the monitoring networks, improved geophysical models of plate motion, and the refinement of computation models have all served to support the development of highly stable reference frames. IERS (1997) reports with respect to the International Terrestrial Reference System (ITRS), that its origin is at the center of mass of the earth (including oceans and atmosphere), its orientation remains consistent with the BIH System at 1984.0 within +/- 3 milliarcseconds and that it shows no residual rotation relative to the earth's crust. It is realized by a set of coordinates and velocities of a set of observing stations. ITRF96, for example, used 4 VLBI solutions, 2 SLR, 8 GPS and 3 DORIS in its establishment [c.f, IERS (1997)]. The global nature of the observing stations used in these solutions, the accuracy of the various observational techniques, their independence of each other, and the longevity of the available data sets, offer reasonable assurance of long term reference frame stability - at least to a level sufficient for datum monitoring (2 - 5 cm).

(b) Achievable Accuracies. For the past five years, NGS has processed consecutive GPS data sets from a global tracking network in independent 24 hr data blocks and obtained a sequence of solutions (i.e., 365 each year) that show root mean square errors of 0.003m in the Northings, 0.006m in the Eastings and 0.010m in the vertical direction (Snay, private communication). The long-term stability of these solutions and their consistency, are at a level that is certainly more than adequate for any vertical datum monitoring that might be contemplated in New Zealand.

(c) The Heights Obtained. The single major difficulty with GPS data rests in the fact that the derived heights are ellipsoidal rather than orthometric (c.f., Section 2.2). While it is altogether possible to define a datum based upon an ellipsoidal height system, the real question is whether or not such a datum would be acceptable to the user community. Alternative options include determining an accurate geoidal undulation at key GPS reference points, thus allowing their conversion to an orthometric height, and/or using the GPS reference points to monitor the stability of the ellipsoidal heights collected.

5.4 **Other Data Types.** A number of other data types may be used to contribute to the definition of a vertical datum. A brief description of each is given below.

- **Very Long Baseline Interferometry (VLBI):** In principle, VLBI involves the observation of extragalactic radio sources such as quasars. By measuring the time delay in arrival of the same radio signal at different locations on the earth's surface, it is possible to determine the three-dimensional baseline between the two receiving radio telescopes. It is thus a relative measuring technique rather than an absolute technique. Although VLBI measurements provide exceedingly accurate earth rotation data and the (X, Y, Z) baseline components to within a few millimeters, as a data collection technique it requires expensive equipment and highly trained operators. While there are now a few mobile VLBI observatories, they are costly to move and support. New Zealand, however, has direct GPS ties to key Australian VLBI sites (and thus secondary connections to the international VLBI network). These could prove useful, as a secondary source of information, to any adopted datum solution that was independent of the earth's potential field.

- **Satellite Laser Ranging (SLR):** By measuring the time delay for the pulse of light from a ground based laser to be reflected from a satellite and returned to its source, the range to the satellite can be calculated. After appropriate processing, very accurate (in the order of some millimeters), three-dimensional, center of mass coordinates can be calculated for the laser ranging station. As with VLBI, while mobile stations have been developed, the equipment is expensive and still requires specialist operators. While NASA has announced its intention to build an automatic SLR instrument suitable for unmanned operation, the cost and availability of such an installation is as yet unknown. As with VLBI, New Zealand does have secondary connections to the international SLR network through GPS ties to Australia that could prove useful under some datum definition scenarios.

- **DORIS:** This positioning technique uses a satellite-borne receiver to measure the spacecraft's velocity relative to a global network of transmitting beacons. Each beacon transmits on two stable frequencies, 2.1 GHz and 0.4 GHz. The space-based receiver processes one beacon at a time, measuring the Doppler shift relative to that beacon every 10 seconds. These data are transmitted twice daily to a ground-based site and are then forwarded to Toulouse (France) for processing. The system is inexpensive and delivers accuracies approaching those achievable from GPS. The principal disadvantages of the DORIS system are found both in the closed nature of the system (i.e., all data is processed by a central agency over which the user has no control), and in the fact that it does not have the same level of international support and commitment that the GPS has attracted. For a number of years, however, New Zealand has had an operational DORIS station on the Chatham Islands.

- **Satellite Altimetry:** Sea surface heights, measured by altimeter missions such as TOPEX/Poseidon, ERS-1/ERS-2, can be used both to derive changes in sea level and to determine the sea surface topography. However, one of the limitations of such altimeters is that they exhibit an on-board drift rate that must be determined. In order to enable the calculation of the drift rate, an optimum set of tide gauge locations, coupled with GPS measurements of the land motion, should be used. Furthermore, altimeters fail to operate well in the coastal regions of either major continents or long island arcs (such as New Zealand). Altimetry data, whilst being able to contribute to datum definition, do not represent a comprehensive solution.

5.5 Summary

Clearly there are many different data types that can be used to assist in the realization of a height reference surface. Sea level data as collected at tide gauges, for example, while having a relatively poor spatial density, are certainly common compared to VLBI, SLR and DORIS data points. Assuming that the LINZ CGPS Project is implemented, then the spatial density of continuously monitoring GPS receivers should at least match that of any tide gauge network.

From a cost point of view, the most attractive option in terms of datum realization, is to piggy-back off existing programmes, supplementing these with additional information if and when an opportunity might present itself. This type of strategy suggests that sea level data and GPS data be the logical choices for defining any future datum – perhaps supplemented with other data forms when the opportunity presents itself. If, for example, a mobile SLR or a mobile VLBI station were to come to New Zealand en route to a further destination, it would certainly be helpful, in terms of New Zealand’s connection to a global reference frame, to have some observations collected whilst the opportunity existed. It would also be helpful to be able to add absolute gravity data at a number of reference points.

6. A USER PERSPECTIVE ON CHANGE

Although a formal user analysis has not been part of this study, it has been possible to construct a coherent series of arguments both for and against change. These arguments are advanced below.

6.1 A Rationale for Maintaining the Status Quo.

1. Change creates unwanted confusion. It is clear from the study of international practice in datum definition, that the majority of the existing height system users do not like ambiguity. The modern (and multiple) reference systems found in some of the Nordic countries appear not to have been popular. While many benchmarks have uplift rates attached to them (a very helpful practical and theoretical advance), Cross et al (1987) and Makinen (private communication) make it clear that local users largely ignore them in favour of using the older 'fixed' datums.

2. Traditional users are not demanding change. In Canada, for example, the provincial governments appear to have no interest at present in seeing CGVD 28 updated, despite its known inconsistencies. Likewise, in the United States there was little or no user demand for the implementation of NAVD 88. Indeed, it seems that its implementation had far more to do with both the higher level interests of the scientific community and with a determination by the National Geodetic Survey (NGS) to fulfill its mission, than with any demands generated by the broader range of users (Zilkoski, private communication).

3. Traditional MSL datums have wide user acceptance. From an historical perspective, surveying, mapping and engineering users have been comfortable with datums that have been referenced to mean sea level. Storm water drainage systems in coastal communities, for example, may reference MSL or Mean High Water Mark. The heights shown on topographic maps are referenced to MSL. Nautical charting is generally referenced to the Lowest Astronomical Tide. All of New Zealand's coastal jurisdictional boundaries, as used in legislation, refer to some tidal reference surface. Higgins (1995), captures this well when he says that, *"users want relationship to MSL and preferably to as local a MSL as possible"*.

   It must be added here, that while widely used, some of the problems associated with a sea level reference surface (c.f., Section 5.1) are not widely known or appreciated by the user community.

6.2 A Rationale for Change

It is important to note at the outset that while non-orthometric sea level related systems of height have long been available, it has only been in the last three decades that some have become realizable. Until the advent of satellite geodesy there was insufficient data to contemplate calculating a detailed global geoidal model. In addition, it has only been in the last two decades that global reference systems have been able to be defined and monitored to accuracies of a few centimeters and only in the last decade that GPS usage has driven the user community towards the widespread use of ellipsoidal heights (and height differences). Given changes of this nature, it is perhaps dangerous to use past user requirements as a clear indication of likely future needs.

With the above in mind, the following is presented as a rationale for change.

1. To support the use of new technologies. This is seen in three primary areas:

(a) In the development of a new range of GPS based positioning applications. The independent economic analysis undertaken as part of the proposed GPS based, NGS Height Modernisation Study (NOAA, 1998), revealed in excess of $12 billion in benefits versus costs of $66 million!! Many of these benefits can only be achieved if very accurate (local) geoid models are available that enable ellipsoidal height differences to be converted to accurate orthometric height differences. Even allowing for a number of loose assumptions in the NOAA analysis, the cost/benefit ratio revealed by this study is still nothing short of remarkable.

(b) As a foundational part of any future National Spatial Data Infrastructure (NSDI). Rather than expound at length on this issue, it is sufficient to note here that an NDSI facilitates data sharing by organising and providing a structure for the relationships between the producers and users of spatial data. The clearer the rules and the more consistent the data sets, the lower the risk of unnecessary data devaluation, and the easier it is to share data in a beneficial manner.

(c) In supporting the integration of new global data sets. Global references frames (e.g., ITRF 96) are now stable, are internally consistent (to a level of a few millimeters), easy to access, and are maintained by international agencies. These are the frames that are used by global mapping, remote sensing, and positioning systems. If New Zealand is to integrate easily existing data sets into these new data sets, then its own data will either need to be both internally consistent and compatible with the external data or be able to be transformed such that it is compatible.

2. User needs are changing. NGS, in the Height Modernisation Study referred to above, conducted a number of user forums. As a result of these forums they identified a need for users to have improved access to the national height system by:
    - having a network of points with a nominal 10 km by 10 km spacing.
    - densification of the GPS Continuously Operating Reference Station (CORS) network.
    - improvements to geoid models.
    - improved infrastructure support for real-time GPS positioning.

   It is instructive to note that all four of these points relate to the anticipated impact of the GPS upon the user community. They are thus closely related to point 1(a) above.

3. The user community is changing. GPS usage is becoming increasingly widespread amongst the non-surveying community, i.e., amongst those who are unlikely to either know or fully understand the technical nature of different height systems. NGS now estimates that fully 60% of the users of its CORS network fall into this category. This new user community is bringing with it a set of expectations with regard to data needs that have not previously been present. If this percentage continues to rise (as is expected), then it will be necessary to find some means of ensuring that users have ready access to heights that they can use and understand. Could ellipsoidal heights be used for such a purpose? One suspects not! Gilliland (1990) shows that the geoidal heights change by 40m from the north to the south of New Zealand. If one were to adopt an ellipsoidal datum anchored at the mid-point in this range, then a user in the far north or far south of New Zealand could expect to find a 20m discrepancy between his/her 0.0m ellipsoidal height contour and sea-level – a circumstance that must inevitably create confusion. If this argument is accepted, then there is clearly a need to give these users accurate geoidal undulations (and possibly other data), so as to allow them to obtain a height that has at least some degree of physical intuitiveness.

4. To support the development of a high precision geoid. If New Zealand is to have an accurate geoidal model (i.e., to the few centimetre level), then rigorously computed Helmert heights for the existing benchmarks will become a valuable source of information. One of the primary reasons why the Geodetic Survey of Canada has continued to undertake its ongoing series of scientific readjustments has been for the purpose of creating an accurate geoidal map of Canada.

5. It would benefit the science community. New Zealand is an ideal laboratory for both geological and climate change studies. A new and consistent height datum would be of significant benefit to those studying crustal deformation, geophysical modeling, climate change and sea surface type issues.

It may be useful to conclude this section by noting the various arguments that NGS has advanced for its various datum and height modernization programs. As part of its efforts to "sell" the idea of a new NAVD 88 datum to users, NGS listed the following as benefits (c.f., Zilkoski, 1986):

- A single datum for North America
- Improved set of heights for North America
- Replacement of destroyed benchmarks and extension of the existing leveling network.
- A better quality network through the use of improved techniques.
- An easy to access, fully validated, comprehensive, national height database
- The opportunity for improved geoid modeling.
- An improved base for from which to transition into satellite and gravity-derived orthometric height differences.
- The research outputs that would flow as a result of NAVD 88 activities.

In its most recent Height Modernization initiatives, NGS as part of its user forums NOAA (c.f., NOAA, 1998) listed the following as common themes with regard to unmet needs and requirements for height information.

1. The need for a reliable, cost-effective, standardized, legally established national vertical reference datum and infrastructure.

2. The need to easily inter-relate the "many" vertical datums in existence.

3. The need for national technical standards and guidelines for using GPS to determine heights.

Given that the first two of these unmet needs were also NAVD 88 goals, one might be excused for wondering if the NAVD 88 project was as successful as anticipated. In personal discussions with NGS staff it became apparent that **the NAVD 88 was never seen as a final solution to North America's height datum problems. Rather, it was seen as an interim step to the development of a high accuracy geoid that would support a future GPS positioning infrastructure.** In this regard, NGS must be commended for its foresight.

7. DATUM DEFINITION OPTIONS FOR NEW ZEALAND

New Zealand's somewhat unique geographical environment (a coastal nation of two major islands, both of which are mountainous and both on a plate boundary), presents a challenge to the problem of defining an accurate national height datum. This challenge has been sufficiently great that the past approach has been piecemeal (and pragmatic) rather than theoretically correct and holistic. There is no evidence to suggest that this past approach has failed to meet the vast majority of user needs.

Before proceeding with this chapter, it must be understood that there are many possible approaches to the datum definition issue. As can be seen from prior chapters, apart from the type of height system desired, there are a number of variations in the realization of some of these systems. In order to provide sensible limits for the discussions in this chapter the material presented thus far will be drawn together in an attempt to eliminate options that are clearly not worth pursuing further. In order to help in this process, the following points are relevant.

1. From a user viewpoint, an orthometric height system linked, in some manner to MSL, has clear advantages over all other systems. Not only is it the system of choice (or an immediate derivative of the system of choice) in every country that was examined as part of this project, but MSL heights are ingrained in user thinking, in mapping and in legislation. If some alternative system were now introduced for all users, it would create a level of disruption that seems entirely unwarranted.

2. While ellipsoidal heights (or height differences) have the advantage of being an output of any form of GPS positioning, and thus may be convenient for some tasks (e.g., network monitoring), they bear no relation to the potential differences (i.e., to the fluid flow and level surface issues) that tend to be at the heart of the concerns of the wider user community. Given not only this situation but also the increasingly widespread use of GPS technology for positioning and the continuing use of orthometric heights in some form, it is clear that in the absence of an ellipsoidal height system, the development of a detailed geoidal model for New Zealand should become a matter of priority for LINZ.

3. It is clear that the development of a detailed geoidal model for New Zealand will not only be closely linked to its future height system, but will probably depend upon it. In both the United States and Canada, the orthometric heights that are part of the existing leveling networks have been a critical part of the development of their national geoidal models.

4. Given that the dynamic, orthometric, and normal height of a point are all produced from the same potential number (see Section 2.1), it makes a great deal of sense to define potential numbers for all points in a future height system. If both potential numbers and orthometric heights were published for each point, it would then become a very quick mathematical procedure for any sophisticated user to produce a normal height or a dynamic height if he/she had a particular use for such information. Indeed, any future LINZ database could be populated with all the relevant information to produce any of these quantities **once** the requisite potential numbers had been determined.

5. Given the dynamic nature of the New Zealand landmass, its ongoing distortion due to plate movement, and its seismic hazard, it is clear that some form of ongoing height network monitoring would be advisable. While this task could be linked to the definition of a new datum, it is also a

task that could be undertaken in concert with the existing effort to monitor deformation in the horizontal datum. There is no compelling reason why a national vertical deformation model could not be produced to match the horizontal model.

6. Over many decades, New Zealand has made a major investment in precise leveling. Provided that there has been no differential land (or bench mark) motion in the interim, then the leveling data itself should have retained its integrity. It seems foolish to ignore such a rich data source. It is thus assumed that in any new datum option, precise leveling data, if it is required, will largely be drawn from existing records.

7. Some attention needs to be given to the geographical fact that New Zealand has both a North Island and a South Island and that the distance between the two is sufficiently far to prohibit an accurate orthometric height transfer between them – at least by conventional measurement techniques. In terms of defining internally consistent datums for each island, these can (and should) be treated as separate entities. If the same height system definition procedures are used for each island, then the issue of a developing a fully consistent, New Zealand wide datum, merely becomes one of a datum transfer between the two islands.

With the above in mind, the following are suggested as possible approaches to the New Zealand's height datum problem.

7.1 The Status Quo Option

In practice this is the "do very little" option. The existing multiplicity of height datums are left unchanged apart from periodic maintenance work needed to replace destroyed marks or to rectify problems that might be incurred following a major earthquake. While work on a national geoidal model could proceed, it would need to be recognized that such a model would be limited by the underlying accuracy of the existing leveling network. The errors in the existing height network occasioned by the use of normal orthometric corrections, the neglect of sea level change, and the network propagation errors would not only remain but would contaminate any national geoidal model. Such contamination may in turn limit the extent to which the GPS can be used for orthometric height determination in the future, particularly when it comes to network maintenance.
The planned CGPS network, could be used to enable work to proceed on a national vertical deformation model.

This option has the advantage of requiring little immediate effort and expenditure and for the time being avoids any problems with users who do not want ambiguity and change. The greatest weakness in this option is its failure to look to the future. While it may well suffice for some years, some issues (e.g., sea level change, increasing demands from GPS positioning, etc), will eventually become problems. If precise leveling (rather than GPS positioning), continues to be used for network maintenance in any form (e.g., after a major earthquake), then maintenance costs will be commensurately increased.

7.2 Developing a New Orthometric Height System

Clearly, the only reasonable alternative to the status quo option, whether in the short term or long term, is to develop a new orthometric height system. The arguments for such a change are almost exactly the reverse of those noted in the previous section and thus will not be repeated here. Because of the options that exist in the realization of such a system, it may be best to approach the problem by looking at the optimum use of each data type.

7.2.1 Leveling Data. In the absence of an accurate geoidal model, it is the existing leveling data combined with gravity data, which will provide the detailed structure for any orthometric height network. Equally, if an accurate and detailed geoidal model is desired, then the leveling data is likely to be an essential element in its derivation. In any new height system, two things seem obvious:

(a) Unless clearly compromised, the existing leveling data should be used. Note that the fundamental leveling observable is a height difference and that the first order benchmark spacing a matter of a few kilometers at most. Unless there is differential (localized) uplift between benchmarks or some localized benchmark disturbance, the original height difference data should still be valid. When used in conjunction with new gravity data and GPS observations, it has the potential to provide a wealth of short wavelength geoidal undulation data.

(b) There is value in adjusting the existing first order leveling loops such that the data is fully validated and shown to be internally consistent.

7.2.2 Gravity Data. Given that the primary output of any non-ellipsoidal height network should be potential numbers, then gravity data will assume an important role in the process. In particular, it will be necessary to ensure that gravity data has been collected along all precise leveling runs thus facilitating the computation of Helmert orthometric corrections and thus rigourously correct orthometric heights. It is clear that some work will be required, firstly, to locate Gilliland's (1990) data files and, secondly, to ensure that all the gravity data collected since then is both correctly reduced and consistently referenced to IGSN 71.

In terms of datum maintenance, there is a very strong argument for using the existing (or planned) CGPS stations that are part of the horizontal datum maintenance programme, for the additional purpose of monitoring vertical network deformation. It is suggested that as opportunity permits, a small subgroup of these stations be considered as possible sites for observing absolute gravity. This would then provide a set of observations that are not only completely independent of the ITRF reference frame, but are also independent of any long term changes in sea level.

7.2.3 Sea Level Data. It seems clear that both existing and future users of the any height system will continue to require a linkage with MSL. Given that the idea of two internally consistent datums (one for the North Island and one for the South Island) is acceptable, then a number of issues require consideration.

(a) The definition of the zero potential reference surface. A number of options present themselves. Firstly, one could follow Hwang (1997) and use both satellite altimetry data and oceanographic data to arrive at a model for sea surface topography. This could be applied to the tide gauge data. Secondly, one could follow the example of the United States and Canada and adopt the value of MSL at a given location as a reference surface. Thirdly, one could perform a rigorous internal adjustment of the precise leveling network on each island and then use this adjusted network to link tide gauge sites together, adopting some weighted mean of MSL at these gauges.

If the goal is to provide a height datum that is rigourous, that is internally consistent, and that provides the entire user community with a reference system linked as closely as possible to MSL, then the third option best achieves this goal. It is simple to implement and, in theory, would provide a MSL reference surface for each island that averages out the effects of sea surface topography around the island. If MSLs continue to rise uniformly, then it also enables any necessary, subsequent datum adjustments due to this cause to be implemented with ease.

(b) The time period over which MSL is defined. A minimum period of 18.6 years (a complete lunar cycle), of continuous data is desirable, with the epoch of datum definition in the middle of that period (thus averaging out the effects of long-term sea level change over the 18.6 yrs). While a shorter period of say 9 yrs of data may have some justification [c.f., Hannah (1990) who notes that the 18.6 yr lunar tide is "small and ill-defined" with amplitude 6 mm], other systematic factors such as anomalous annual temperature and pressure regimes (due to *El Nino* or *La Nina* effects, for example), become much more problematical.

7.2.4 Global Geopotential Models.

A high-resolution global geopotential model (e.g., EGM 96) is an additional data source that may be used in the datum definition process. In principle, one could use such a model, in conjunction with local gravity data and local terrain data, to determine the geoidal undulations at specific tide gauge stations. By determining the ellipsoidal heights at these stations using GPS data, and then by using equation (3), the orthometric height at each point can then be calculated, and held fixed if desired. The fact that these datum points are all tide-gauge stations enables a direct determination of MSL to be made. In the absence of error, the difference between the MSL height of the point and its orthometric height is an estimate of for the local value of sea surface topography. To the extent to which the local gravity data used in the geoidal undulation computations is both dense and complete, such a procedure has the advantage of allowing the datum to be linked to a zero equipotential surface that is global in nature. It is thus not only more likely to be compatible with any future international height datum, but it is a methodology that would allow the height datums for all islands within New Zealand to be referenced to a single system.

There are three principal difficulties associated with this approach. Firstly, the geoidal undulations that are derived from GPS ellipsoidal heights combined with leveling and gravity data, in general, differ systematically from geoidal undulations derived from global geopotential models and local gravity data. Kotsakis and Sideris (1999) suggest that these systematic differences, which in Canada are in the order of 1.4m (c.f., Mainville et al, 1997), arise from the following sources:

- Random noise in the values of h, N, and H [see equation (3)].
- Datum inconsistencies and systematic distortions (due, for example, to incomplete or sparse local gravity data), in all three height data sets.
- Various geodynamic effects.

- Theoretical approximations in the computation of either *H* or *N*.

Secondly, in order to derive accurate geoidal undulations using the combined geopotential model/local gravity data approach, it is necessary to have a good knowledge of the gravity field in a 2° spherical cap around the point of determination. Given that these points are tide gauge stations, this implies a good knowledge of the local marine gravity field – an area in which New Zealand appears to have some deficiencies.

Thirdly, the reference equipotential surface (and thus the datum surface) will be subject to change as new higher resolution gravity models are developed.

7.2.5 Other Possible Sources of Data.

Of the other possible data sources discussed in Chapter 5, GPS data offers by far the greatest benefits for the least cost. As noted earlier, it is suggested that the CGPS stations used to monitor the horizontal datum also be used to monitor vertical deformation. If this were done, then it should be relatively easy, over a period of years, to develop a vertical model for New Zealand’s crustal deformation. Given the fact that small ellipsoidal height differences at any point essentially map into the correspondingly small orthometric height differences at the same point, the CGPS network has the ability to provide all the macro-scale information necessary to either assist in the definition of datum uplift model.

7.3 Implementation Issues

In presenting the second of the above options, no attempt has been made to address implementation issues. A new datum, for example, could be considered to be a longer-term project for which preparations are made but implementation is delayed until an appropriate time (as in the Canadian model). Alternatively, if the economic rationale for a new datum is sufficiently compelling, then it is a task that should obviously proceed sooner rather than later. Clearly there are obvious initial steps that can be taken. Precise leveling data files can be prepared, gravity data collected and prepared and MSLs at appropriate sites calculated.

8. RECOMMENDATIONS AND CONCLUSIONS

Prior to concluding this report, it is useful to note two issues that appear to the author to be crucial to any decisions that are made with respect to New Zealand's future height datums.

Firstly, while LINZ has clearly decided that it is responsible for providing a geoidal model for New Zealand (and rightly so), there is a crucial issue as to the level of accuracy that such a model should have. If, for example, a 10cm geoid were the goal for the developed parts of the country (a factor of 5 lower than the NGS goal for the continental United States), then there is no doubt that a rigourously adjusted precise leveling network will be necessary to provide the fine level of detail that such a geoid would require. If, however, the goal were a 25cm geoid for populated regions, then it may well be possible to achieve this using the existing height system.

Secondly, LINZ must decide if it will move forward on the height datum issue only after there is a vociferous user demand for change to its height systems, or if it will attempt to anticipate change. Clearly NGS and the Geodetic Survey of Canada have taken the latter position. Indeed, NGS not only sees its mandate as being one of anticipating user demand, but also that of assisting the use of new positioning techniques such that the US economy can become more efficient and competitive.

With these thoughts in mind, the following specific recommendations are made.

1. The cost/benefit analysis undertaken by NGS as part of its height modernization program ($US 66 million in costs versus benefits of $US 12+ billion) is so striking as to clearly warrant assessment from a New Zealand viewpoint. It is recommended strongly that this be done as soon as possible. It is altogether possible that such a study could provide an overwhelming series of economic arguments that would support the derivation of a very precise geoid model for New Zealand. Such a study may well influence the rigour with which a new datum was computed and implemented.

2. Irrespective of the answers given to the two issues noted earlier, it is suggested strongly that the role of the existing, continuously tracking GPS network be extended so as to monitor both horizontal and vertical geodetic network distortions. Such a monitoring programme would be one immediate means by which long-term, systematic patterns of land uplift could be detected. The additional processing costs would be minimal but the potential benefits significant.

3. Any new future height system should be adjusted and derived in terms of geopotential numbers but published in terms of orthometric heights. Geopotential numbers for each point give the greatest flexibility to the user who might wish to compute either dynamic or normal heights.

4. While a formal user analysis was not a part of this study, it is clear that MSL is a well recognized reference surface both at a local authority level and in national mapping operations. While the detailed variations in sea level are probably not well understood, there is an ease of use of the term and a broad public recognition that suggests that any future height system be explicitly linked to MSL as closely as is possible. To this end, it is recommended that a framework of tide gauges on each if the North and South Islands with good quality tidal records (including new NIWA open coast gauges), be identified as those that would form the MSL reference points for any future datum.

5. If New Zealand is to have a new height system (a situation that would certainly seemed justified to the author of this report), then it is recommended that internally consistent datums be developed for each island by using the existing precise leveling data (in conjunction with new or existing gravity data), and adjusting it so as to form an internally consistent set of geopotential numbers. This network should then be linked to key tide gauges. Rather than holding the MSL height at one gauge fixed, it is suggested that an averaging or weighting process be used such that the effects of sea surface topography be averaged out around each island. Oceanographic studies indicate that the broad-scale variation in SST around the South Island is in the order of 10 cm and around the North Island 15 – 20 cm.

   In making this recommendation, the author recognizes that an alternative approach to the datum definition has been outlined in Sec. 7.2.4. The lack of a fully comprehensive on-shore and off-shore gravity database, plus the existence of the type of systematic biases described in Kotsakis and Sideris (1999) are genuine concerns in such an approach. Nevertheless, because of its global interoperability, it is an approach that should not be dismissed without investigation. It is thus recommended that the necessary investigations into the quality of the New Zealand data, and the possible biases therein, proceed at the earliest possible time. If this alternative approach was found to be able to provide a consistent and accurate datum throughout New Zealand, then it should be considered to be a serious datum definition candidate.

6. If a new datum is implemented, then it is also recommended that a sub-group of the CGPS stations (perhaps five) be designated as absolute gravity sites. Such sites must be exceedingly stable, either not be markedly affected by water tables or have known water table parameters, and preferably have a strong leveling tie to a local tide gauge. The aim here is to have a back-up datum measuring monitoring technique that is as independent as possible from other measurement techniques that might be used. Both the relatively low cost and the portability of the new A10 gravimeter suggest this as being the obvious back-up measurement technique.

7. There is an obvious need for an up-to-date assessment as to the status of the New Zealand gravity database. In particular, it would be helpful to know not only what data might have been added in the 10 years since Gilliland's original assessment but also the location of Gilliland's final data files. It would also be helpful to know which precise leveled benchmarks lack gravity data and then to arrange for necessary additional data to be collected.

8. At this stage it is not recommended that a new datum formerly have time dependency terms associated with each point. There are three reasons for this. Firstly, there is, as yet, insufficient GPS data to construct an uplift model for New Zealand. Secondly, the eustatic sea level changes that have occurred since the definition of the original datums would be caught up in the definition of a new datum. Thirdly, Scandanavian experience seems to indicate that such refinements are not appreciated by the wider user community. In the future, however, and as there is an improvement in knowledge as to the dynamics of both New Zealand's land and associated ocean masses, there is no theoretical reason why such a time dependency could not be introduced at some higher user level.

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