University of Southern Queensland

Faculty of Engineering and Surveying

Localised Geoid Modelling using GPS and Precise Levelling Data

A dissertation submitted by

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towards the degree of

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Abstract

This project evaluates the accuracy of GPS heights derived using the current New Zealand Geoid model (NZGeoid05) as compared to an empirically based spirit level network over a small study area (55 km x 50 km) in the South Island of New Zealand. It analyses the current New Zealand Geoid model; NZGeoid05, and the history of levelling datums in New Zealand with specific focus on the Lyttelton 1937 datum. It then uses GPS observations to derive ellipsoid heights at known points that have precise level information, a calculation of geoid – ellipsoid separation values is performed and used to build a local geoid model. This is done mainly using the software package Grid Factory.

The results of this research show that while there is a measureable difference between GPS derived heights and precise levelling heights, the differences are mostly within the specified accuracy of NZGeoid05. As the two datums are independent interpretations of the equipotential surface, it is not surprising there are some differences.

Further investigation shows that the reliability of the Lyttelton 1937 datum in terms of accurately representing the equipotential surface is now questionable due to poor initial definition, tectonic deformation and sea level change. This is a problem that will worsen with time. Another disadvantage of the Lyttelton 1937 datum is that it is orientated towards conventional technology and techniques. With the increasing popularity of modern GPS surveying, vertical determination methods using geoid models are becoming more common.

The localised geoid model was successfully created. This proves that is it possible to build local geoid models. It was tested against NZGeoid05 and EGM08 to determine which produced height values that best correlated with the Lyttelton 1937 datum. The ProjectGeoid proved to provide the best solution. However, the evaluation of the model shows that it is not an independent interpretation of the equipotential surface but rather, it has given the Lyttelton interpretation a new expression. Because the Lyttelton interpretation of the equipotential surface is outdated and subject to continued degradation, this new interpretation will then not provide orthometic heights that truly represent actual MSL.

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ENG4111 Research Project Part 1 & ENG4112 Research Project Part 2

Limitations of Use

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Dean
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Candidates Certification

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in the dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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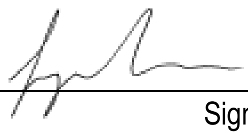

Signature

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Date

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Sam Cech and Maurice Perwick of Eliot Sinclair and Partners Ltd generously provided all the GPS data and assistance with reductions. Alan Witherington from Trimble NZ provided software and global geoid models. Matt Amos of LINZ provided research material. My employer The Timaru District Council has supported this project and been generous in allowing me time to ensure its completion.

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1. Introduction

Applications as varied as construction, aircraft navigation and climate change research all have a common requirement: an accurate, reliable datum that defines mean sea level. The definition and regular determination of this level is of paramount importance.

1.1 Project Outline

This research was prompted by observations that questioned the reliability of the current New Zealand geoid model (NZGeoid05) in determining mean sea level heights that agree with existing levelling datums. Therefore, the aim of this dissertation was to study NZGeoid05 and document its development, structure and accuracy as compared to heights from an empirically derived spirit level network. This comparison was performed over a localised study area which is roughly centred over Banks Peninsula, New Zealand (Figure 1.1).

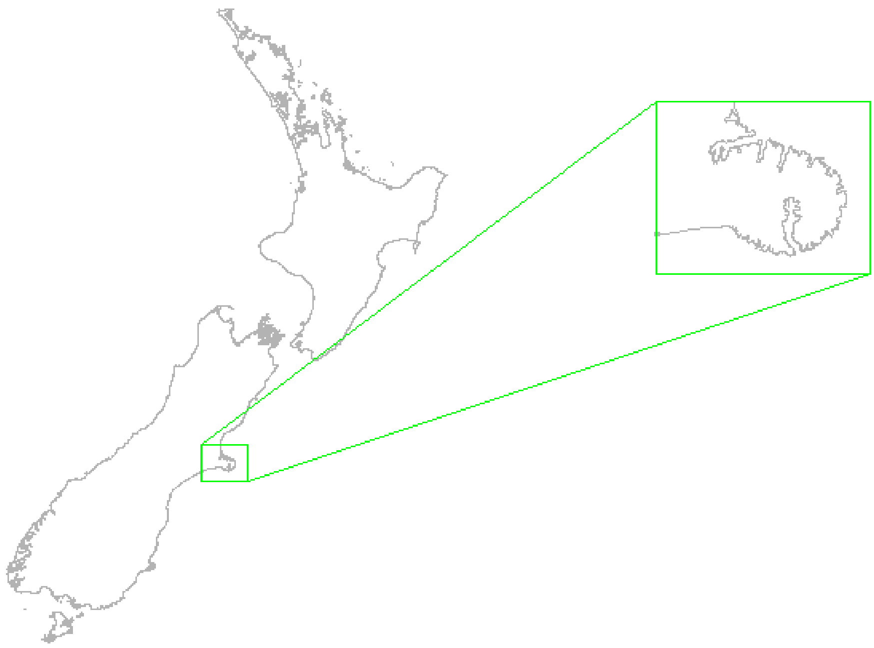


Figure 1.1 Study Area: Banks Peninsula, New Zealand

This research then attempted to use ellipsoid heights, as determined by GPS (Global Positional System) observations, and orthometric heights, as determined by the precise level network, to calculate a set of geoid – ellipsoid separation values and hence build a geoid model.

This model was then tested in order to compare it against NZGeoid05 and EGM08, a global geoid model, to determine whether it could produce orthometic heights that agreed more closely to the precise levelling network.

Finally the constructed geoid model was converted to a format that could be used by GPS data recorders and reduction software. This is commonly in the form of a *.ggf* file. This means that the model has a practical use and the methods contained within this research can be applied to other areas to produce similar working models.

1.2 Project Background

The need for this research arose from the work performed by Christchurch based survey firm Eliot Sinclair and Partners Ltd who have carried out extensive GPS surveys around the South Island of New Zealand (Perwick and Cech 2008). During the course of these surveys they have observed differences of upto 0.1m when making GPS observations to marks that have empirically derived precise levels, predominantly around the extinct volcano of Banks Peninsula. It is suspected that these errors are due to the current gravimetric geoid model (NZGeoid05) being too coarse to represent the changes in the geology and density of the underlying rocks.

1.3 Project Aims

This project aims include; to develop an understanding of, and document the structure of NZGeoid05; to document the difference between GPS heights and mean sea level heights around the area; to construct a geoid model for the study area of Banks Peninsula based on GPS observations to precisely levelled marks; to determine appropriate techniques to evaluate and test this model; and to develop a geoid model that can be incorporated into data recorders for field use.

1.3.1 Objective 1: Document the type and structure of the current New Zealand Geoid model (NZGeoid05).

It is essential to this research that NZGeoid05 is clearly defined so that its application, advantages and disadvantages can be understood.

1.3.2 Objective 2: Document the difference between GPS derived orthometric heights and heights based on a mean sea level derived datum around Banks Peninsula, Christchurch, New Zealand.

By using GPS observations to precisely levelled marks, any differences in the two height systems can be documented and investigated.

1.3.3 Objective 3: Use GPS observations and precise levelling data to construct a local geoid model or enhance the existing geoid model.

GPS observations can be used to determine the ellipsoid height at points that have precise levelling heights. The difference between the two will be the geoid – ellipsoid separation. If sufficiently distributed observations are collected, they can be combined to produce a geoid model.

1.3.4 Objective 4: Test and evaluate the model

The development of techniques to test the model is required to ensure that it is robust and accurately represents the difference between the ellipsoid and geoid.

1.3.5 Objective 5: Liaise with Alan Witherington from Trimble NZ to convert the model into a format that is useable.

Alan Witherington from Trimble NZ offered his technical help to assist in converting the model into a format that could be incorporated into a GPS controller, enabling real time correction of ellipsoid heights.

1.4 Summary

This research is expected to result in an increased understanding of the structure of NZGeoid05 and its accuracy relative to a precise levelling network over the study area. Using GPS derived ellipsoid heights and orthometirc heights, a localised geoid model will be constructed that can be applied in the field.

A review of literature for this research will provide some background theory about the shape of the earth and geoid models. It will investigate: the current Geoid model used in New Zealand; the nature of mean sea level in New Zealand; and the existing mean sea level datum used within the study area. The methodology used by others to construct localised geoid models will be investigated and selected methodologies shall be applied to a small data set over the study area with the aim of building a geoid model. The independent testing of this model will be carried out and a critical review of this given.

2. Literature Review

2.1 Introduction

The aim of this chapter is to outline the basic principles of geodesy as they apply to the shape of the Earth and geoid models. This explanation will provide a theoretical setting for this research and define the specific terminology. More specific detail will be given on the nature of the geoid and geoid models, with this knowledge applied to the regional geoid model currently used in New Zealand; NZGeoid05. The other height system used in this research is then analysed, that is orthometric heights derived from the determination of mean sea level (MSL). The vertical datum network in New Zealand is described and an analysis given to evaluate its durability in our dynamic environment and its ability to determine the equipotential surface.

A review of current research will reveal the methods being used to construct geoid models from GPS observations and precise levels. This will include the construction of new models as well as supplementing existing geoid models. The testing and verification of models will be briefly examined.

2.2 Shape of the Earth

2.2.1 Ellipsoids

The shape of the Earth is not a perfect sphere, the effects of rotation and variations in gravity combine to produce an irregular, non uniform shape. It was *Isaac Newton* (1643 – 1727) who first proposed using a rotational ellipsoid as a representative figure for the Earth (Torge 2001, p 8). Ellipsoids are commonly used to model the Earth because they approximate the shape of the Earth on a global scale and are relatively simple mathematically to describe. Just two variables are required to model an ellipsoid; a which is the length of the semi-major axis, and b which is the semi-minor axis. These are shown in figure 2.1.

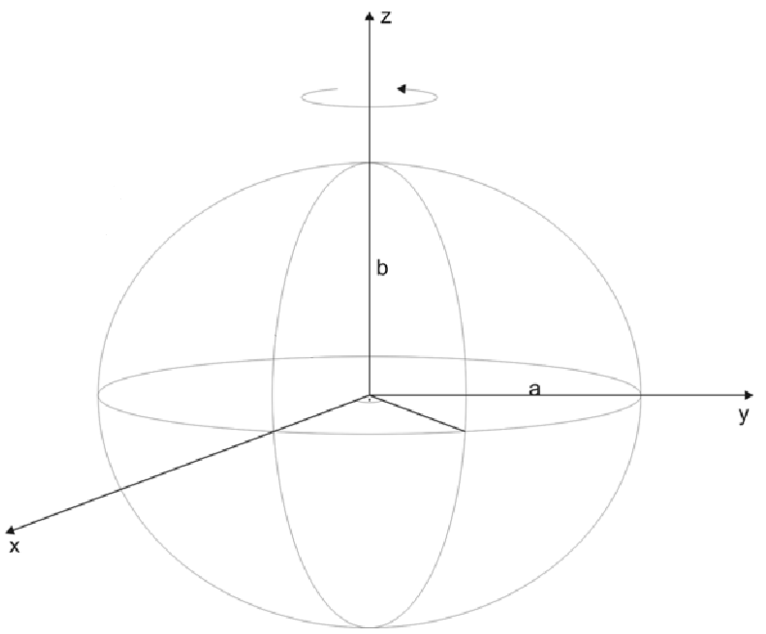


Figure 2.1 A Geocentric ellipsoid

The semi-major and semi-minor axis can be used to calculate *f,* which is the flattening ratio as shown in equation 2.1 as:

$$f = \frac{a-b}{a} \quad (2.1)$$

Several ellipsoid models have been developed through time. Two commonly used recent models include WGS84 (World Geodetic System 1984) and GRS80 (Geodetic Reference System 1980). WGS84 has major axis of 6,378,137.0m and a flattening of 1/298.257223563 (Leick, 1990), and GRS80 has major axis of 6,378,137.0m and a flattening of 1/298.257222101 (Torge 2001, pp 116 - 117).

Although ellipsoids are useful for representing a position in the horizontal plane, being a purely mathematical representation, they fail to accurately represent a meaningful vertical datum, such as mean sea level.

2.2.2 Geoids

A geoid is typically defined as an 'equipotential surface of the Earth's gravity field coinciding with the mean sea level of the oceans surfaces as regarded as extending under the continents (Torge, 2001 pp 76 - 77). It is a complex geometrical figure dependant on the gravity of the Earth and its motion.

A geoid is of importance to engineering and geosciences as a physically defined surface for determining orthometirc heights (Torge, 2001 p.45). Orthometric heights are of primary importance because they predict the flow of fluids. This is because the flow of fluids and the level of bodies of fluids such as the oceans are determined by the Earth's gravity field and are reflected in the gradient between orthometric heights. In comparison, ellipsoid heights do not represent the gravity field and hence the ellipsoid height gradient between two points could be opposite to the orthometic height gradient. This suggests that water could run uphill, which of course it cannot. Therefore it is orthometric heights which are of greatest concern.

Figure 2.2 below is a schematic representation of the relationship between the ellipsoid and geoid. It shows that while the two may occasionally coincide, more frequently there is a significant difference between them.

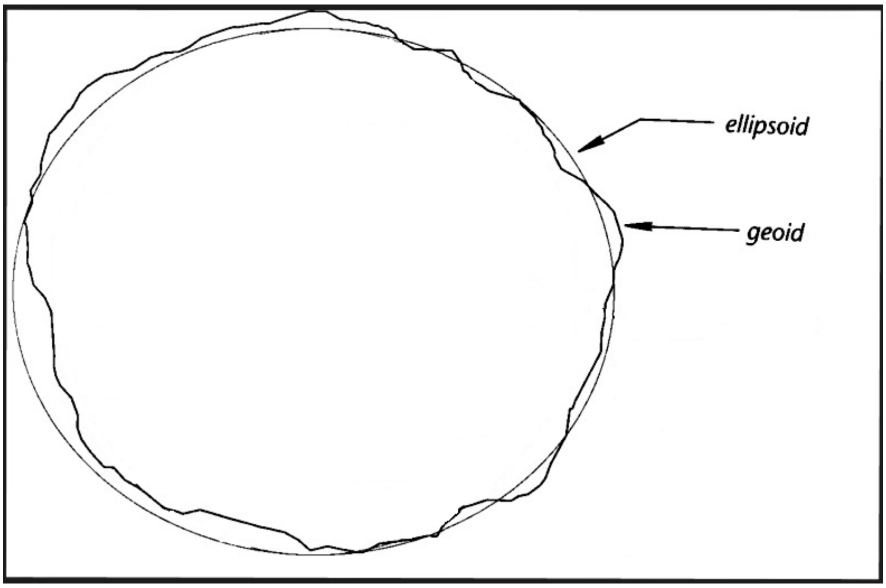


Figure 2.2 Relationship between ellipsoids and geoids

2.3 Height Systems and Vertical Datums

The terms in which a height system is defined is dependant on the way that the Earth's gravity field is observed or modelled. Given the range of terminology used to describe height, this section will define the terminology used in this research.

2.3.1 Orthometric Height

The orthometric height is defined as the distance along the curved plumbline between a surface point and the ellipsoid (Torge 2001, p 82). This definition corresponds to the common understanding of height above sea level. However, because of the curved nature of the plumbline and unknown variations in gravity down the plumbline, it is not possible to physically observe or compute a true orthometic height (Amos, 2007). The use of gravity field models does enable its relative determination.

2.3.2 Ellipsoid Height

The ellipsoid height is the distance along the normal to the ellipsoid to the Earth's surface. Unlike the previous definitions, it is independent of gravity and therefore does not correctly determine the flow of fluids (Amos, 2007). In some cases the gradient of ellipsoid heights can be in the opposite direction to orthometric heights.

2.3.3 Mean Sea level (MSL)

Because of the assumption that MSL and the geoid coincide in the open oceans, it is possible to relate MSL to the geoid using tide gauge measurements and therefore define a vertical datum. In order to accurately define MSL, it is necessary to take regular measurements of MSL over a period sufficient to cancel out the effects of features such as long term tidal cycles and sea surface topography variations. A continuous record of at least 19 years is recommended for this purpose (Amos, 2007).

2.4 Geoid Models

A geoid model is a model of the separation values between an ellipsoid and the geoid for a given area, be it global, regional or local. It is used to convert ellipsoid heights to an orthometirc height, such as mean sea level. The relationship between the different height systems is described by the following equation:

$$H = h - N \qquad (2.2)$$

where: H = Orthometric height

h = Height above Ellipsoid

N = Geoid – Ellipsoid separation value

Therefore the orthometric height (H) can be determined by subtracting the geoid - ellipsoid separation value from the ellipsoid height. Note that if the geoid is above the ellipsoid, the N value is positive, if it is below the ellipsoid, the N value is negative. This relationship is shown in Figure 2.3 below.

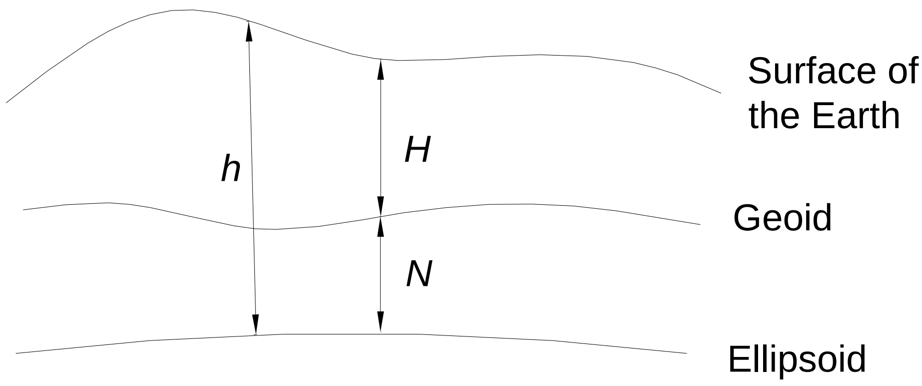


Figure 2.3. Relationship between Ellipsoid, Geoid and Orthometric Heights.

As gravity is a function of the density of the Earth's mass, which is not evenly distributed, the shape of the geoid is not regular, nor can it be represented by a regular mathematical expression. As a result, geoid models are often tabulated files containing grid parameters and corresponding geoid values, with intermediate values being interpolated. Alternatively, spherical harmonic equations can be used to determine geoid heights (Amos et al 2003c)

Geoid models have particular application to GPS (Global Positioning System) surveying as GPS instruments measure their position relative to a chosen ellipsoid. Therefore the height measured will be the ellipsoid height. With the increased use of GPS equipment in surveying, the need for an accurate geoid model has become evident. This is particularly the case when GPS equipment is being used in preference to traditional spirit levelling, which in mountainous terrain is labour intensive and slow.

2.4.1 Geoid Model Development

There are two main methods that are used to compute a geoid model: gravimetric methods and geometric methods (Office of the Surveyor-General 2005). Gravimetric methods use gravity observations from satellite, land and ship based sources to map the Earth's gravity field. The advantages of this technique are that it is relatively easy to collect data over a large area such as the entire Earth.

An example of a global gravimetric model is EGM08 (Earth Gravitational Model 2008). It was released by the National Geospatial Intelligence Agency EGM Development Team. It is a 2.5 minute grid of geoid ellipsoid separation values based on satellite observations (National Geospatial Intelligence Agency).

A geometric geoid model is developed from GPS observations to points that have precisely known orthometric heights. The difference between the ellipsoid height derived from the GPS and orthometric height is the geoid-ellipsoid separation value. It can be argued that this approach does not strictly determine a geoid, rather it computes a transformation surface between the ellipsoid and the local levelling system (Office of the Surveyor-General 2005). The disadvantage of this approach is that it requires a network of levelling points, this can often be difficult due to terrain and access issues.

2.4.2 Effects of Local Gravity Variations

An inherent feature of gravimetric geoid models is their need to comprise of sufficiently dense gravimetric readings so as to accurately represent localised variations in the gravity field. Several case studies (Nelson 2008 and Featherstone 2000) have documented instances where differences in GPS observed orthometric heights and precisely levelled observations have been attributed to localised changes in geology that cause changes in the gravity field.

The Nelson 2008 study is of particular relevance as it studies the Otago Peninsula which is a similar geological structure to Banks Peninsula. That is, they are both an intrusion of dense volcanic rock surrounded by less dense sedimentary deposits (Nelson et al 2008).

2.4.3 Geoid Model Application

There are several methods of incorporating a geoid model into a data set to convert ellipsoid heights to orthometric heights.

If the NZGD200 coordinates and ellipsoid height are known, then the ellipsoid – geoid separation value can be calculated using the LINZ online facility (http://www.linz.govt.nz/geodetic/conversion-coordinates/online-conversion-service/converter/index.aspx?advanced=1). The offset (*o*) for the relevant regional datum is also applied as shown in equation 2.2:

$$H = h - N + o \qquad (2.3)$$

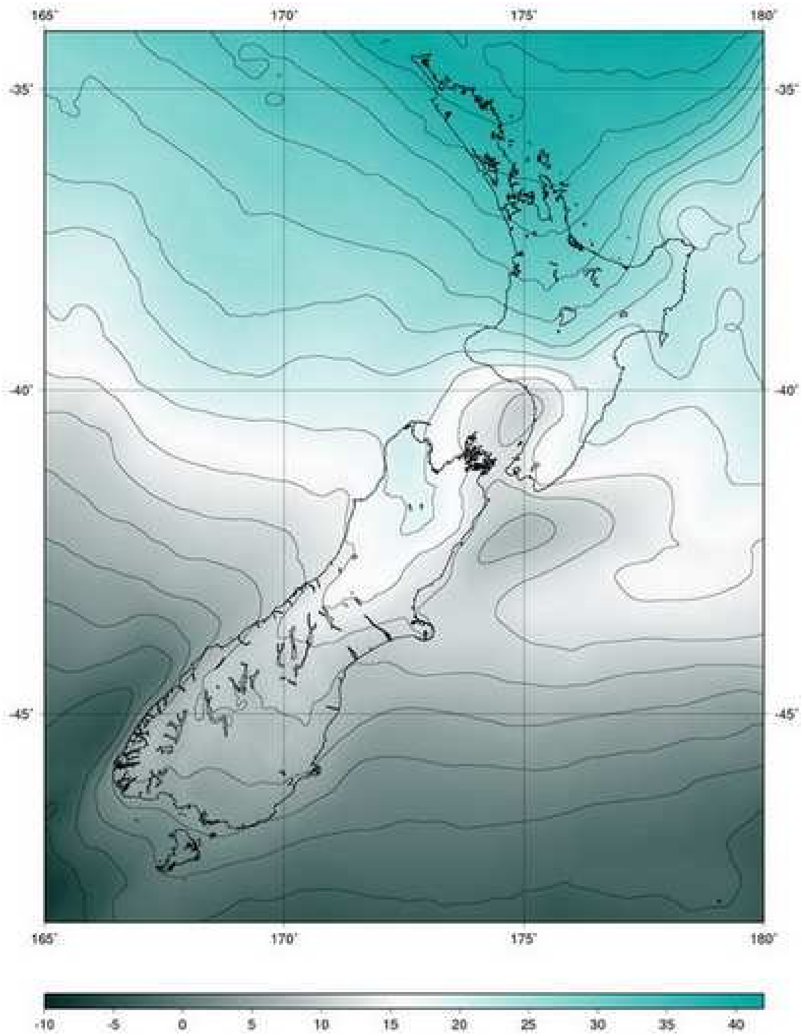
Alternatively software, such as Trimble Geomatics Office (TGO), can incorporate geoid models into the data reduction process. Most software comes with current geoid models preloaded, or they can be downloaded from various websites such as LINZ.

Finally, a geoid model can be loaded onto a GPS controller unit. This enables real time corrections of ellipsoid heights.

2.5 New Zealand Geoid05 (NZGeoid05)

The New Zealand Geoid05 is a regional gravimetric geoid model covering an area from 160°E to 170°W and 25°S to 60°S. It was developed by Land Information New Zealand (LINZ) and implemented in 2005 to support the New Zealand Geodetic Datum 2000 (NZGD2000). It was calculated by using a combination of the GGM02S and EGM96 global geopotential models as a reference model (Office of the Surveyor-General 2005). A global geopotential model (GGM) comprises of a set of spherical harmonic coefficients that describe the long wave length characteristics of the Earth's gravity field (Amos et al. 2003a).

These models were enhanced with 40,737 terrestrial gravity observations recomputed with a 56 metre digital terrain model to determine terrain corrections, and 1,300,266 ship-track gravity observations (Amos et al 2003a). All terrestrial and marine anomalies were averaged onto a two arc-minute grid, this equates to a spatial resolution of approximately 3.7km. Figure 2.4 shows the model over the New Zealand land mass.



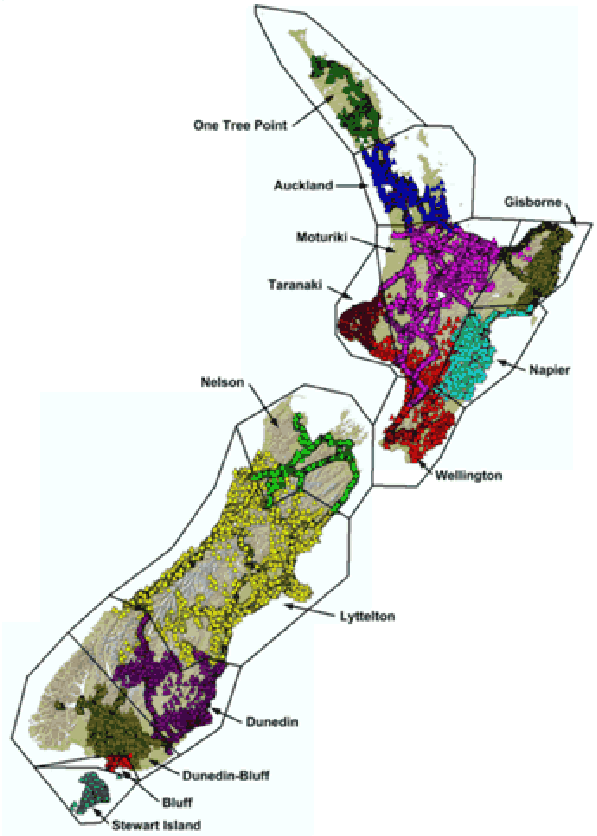
Source: www.linz.govt.nz

Figure 2.4. NZGeoid05

The target precision of orthometic heights derived using NZGeoid05 in relation to existing levelling datums is ±0.1m at the 95% confidence interval (Amos et al. 2003a). The development of NZGeoid05 has meant that a new vertical datum, New Zealand Vertical Datum 2005 (NZVD05) has been realised. NZVD05 is designed to support NZGD2000 which expresses its heights in relation to the ellipsoid GRS80.

2.6 Mean Sea Level in New Zealand

Previous to NZVD05, New Zealand did not have a single national vertical datum. Figure 2.5 below shows the spatial distribution of New Zealand's 13 major levelling datums. Each datum is based on a determination of MSL at a different tide gauge over a varying period of time. Because of: regional differences in sea surface topography; long term tides; and harbours and river flows; the MSL determinations for each datum does not lie on the same equipotential surface and can be offset from neighbouring datums by up to 0.3m (Office of the Surveyor-General 2005). Consequently each datum also has a different offset to NZVD05 (Amos 2007).



Source: www.linz.govt.nz

Figure 2.5. Major levelling datum's in New Zealand

First order precise levelling (±2mm$\sqrt{k}$) was then used to transfer the levels to surrounding areas (Amos 2007). Due to the dramatic topography in New Zealand, these networks have irregular coverage and are mainly limited to major roads.

2.6.1 Lyttelton 1937 Datum

The study area of this research is contained within the one datum; Lyttelton 1937 datum. It was defined by tide gauge records observed from 1918 to 1933 (Office of the Surveyor-General 2009). Its offset from NZVD05 is 0.47m (Office of the Surveyor-General 2009). As stated earlier, a continuous observation period of 19 years is recommended in order to take into account long term tidal cycles and variations in sea surface topography. The Lyttelton datum observation period falls short of this recommended observation period.

Other factors which affect the integrity of the Lyttelton datum being, an accurate representation of MSL and hence of the equipotential surface, are tectonic deformation and sea level rise. Because New Zealand straddles the Australian and the Pacific Plate, it is extremely tectonically active. The horizontal deformation that this causes is well documented and modelled in a horizontal deformation model as part of NZGD200 (Blick 2003). However the vertical deformation is not as well understood or modelled. Research (Bevin et al 1984) has shown that tectonic uplift along the Southern Alps that are directly above the plate boundary is in the order of 10mm/yr. Further from the plate boundaries, recent analysis (Amos 2007) of continuous GPS stations has shown average uplift of 2mm/yr. This includes observations from within the Lyttelton datum area.

Hannah (2004) analysed sea level observations at the Lyttelton tide gauge and found that sea level has risen by 0.279m since its definition in 1937. With the prospect of accelerated sea level rise with climate change a genuine possibility, this difference is likely to increase at a faster rate.

Because of the short observation time used to initially define the Lyttelton datum, tectonic deformation and sea level rise, it is highly questionable how representative it is of the current MSL and the equipotential surface.

2.7 Methods and Techniques for Computation

Using GPS and precise levelling data to improve or build geoid models has been done using a variety of techniques.

Featherstone (2000) tests the difference between using a least-squares collocation (LSC) and continuous splines in tension to combine GPS, AHD and AUSGeoid98 data over a local region. He concludes that the LSC technique is statistically better suited to account for the observed differences between AUSGeoid98 and AHD.

You (2006) also uses the LSC technique in the development of a combined geoid model for Taiwan, finding an improvement in separation values as determined from the national datum.

Featherstone (2001) uses bi-cubic and bi-linear methods to interpolate geoid heights from pre computed grids. Suggesting that these methods of interpolation are commonly used and can be applied generically.

Smith (1996) used polynomial fitting and interpolation with a data set of GPS observations to marks with known precise levels. He found that over a small area, linear interpolation was most reliable.

It is recognised that GPS and precise levelling data contain errors and are subject to inaccuracies. It could be argued whether or not using GPS observations and precise levelling data to test a gravimetric geoid model is a valid technique (Sideris et al 1992). However, considering the fact that one of the more common uses of gravimetric geoid is for the use of GPS derived orthometric heights, it should provide a reasonable indication of suitability (Featherstone 2001).

2.8 Testing and Verification

To independently test and verify the accuracy of a geoid model is extremely difficult. This is due to the fact that the equipotential surface is a theoretical surface and cannot be physically reached or directly measured to (Amos 2007). The use of GPS observations to marks with known precise levels has been used as a means of verifying the accuracy of gravimetric models such as NZGeoid05 (Denhan et al 2005, Amos 2007). This technique is independent in the sense that GPS and precise levelling data is not used in the construction of a gravimetric geoid model so provides a second interpretation of the equipotential surface.

Absolute verification is the accuracy and precision of the geoid with respect to the geocentric ellipsoid. Relative verification uses GPS derived ellipsoid height differences and precise levelled heights to estimate the accuracy and precision of the geoid gradients (Featherstone 2001). Given the fact that the geoid models researched in this project are of a small scale, the relative verification is more relevant (Gibbings et al 2005).

2.9 Conclusion

This chapter has described the relationship between the shape of the earth, ellipsoids and geoids. It has detailed the construction of geoid models, including NZGeoid05, and shown the need for geoid models in GPS surveying. The history of the various New Zealand vertical datums with specific details on the Lyttelton datum has shown that these datums may no longer provide an accurate representation of MSL and therefore the equipotential surface. A review of recent research has shown that geoid models can be built from GPS observations and precise levelling datum. Some of these techniques have supplemented existing geoid models while others have constructed entirely new models.

This chapter therefore set the basis for this research, it provides the theory of geodesy and its application in the New Zealand context.

3. Methodology

3.1 Introduction

This chapter covers the description of the GPS and precise levelling data set used in this research. It details the resources in terms of software that was required and how it was applied. It then provides a detailed methodology of the process that was employed to analyse NZGeoid05, and to build a localised geoid model and finally to test the model.

3.2 Data Collection

3.2.1 GPS Observations – The Canterbury Wide Project

All GPS field observations were collected by Eliot Sinclair and Partners Ltd as part of various projects grouped under the Canterbury Calibration Project. This project covered most of the Canterbury region, however only the points within the study area were selected. These observations were a combination of static and fast static, with raw data logged and corrections post processed from locally deployed base stations, LINZ Rinex files or Eliot Sinclair's own reference receiver that is part of the iBase system (Perwick and Cech 2008).

The easting and northing are in terms of NZGD2000, Mt Pleasant 2000 Circuit. The ellipsoid heights are in relation to the GRS80 ellipsoid.

3.2.2 Height Order of Control Marks

The precise level information for each relevant point was sourced from the LINZ website (Land Information New Zealand 2009) and recent Christchurch City Council precise levelling runs. They are all in terms of the Lyttelton 1937 Vertical Datum.

LINZ published heights are given an Order of 1 – 5 according to the way in which they were observed. First and Second Order or Order 1 heights are carried out to full precise level specification, with a maximum closure error of ±2mm$\sqrt{k}$. Third Order or Order 2 heights are spirit levelled with a maximum closure of ±7mm$\sqrt{k}$ (Land Information New Zealand 2009). Only points with First and Second Order heights where used in this research.

3.3 Resources

3.3.1 Software

Given that all GPS observations were supplied by an external party and the precise levels were sourced from government agencies, the most important resource in this research is the access to software. The specific software used included Microsoft Excel, CivilCad, Trimble Geomatics Office and Grid Factory. Trimble's Geomatics Office (TGO) was used to reduce all raw GPS observations from ellipsoid heights to orthometic heights. Microsoft Excel was used to process all tabulated data. CivilCad was used to produce the contour model of the separation values and to extrapolate the grid values from the contour model. Grid Factory is part of the Trimble GPS software suit. It is capable of taking data in the form of a tabulated grid of separation values and converting it to a .ggf file of geoid – ellipsoid values. It is also used to open existing geoid models such as NZGeoid05 and EGM08. These models can then be visualised by the addition of colour fill models and cropped so they only cover a specific area.

3.4 Data Analysis

3.4.1 Analysis of NZGeoid05

A subset of the Canterbury wide data set was processed in TGO using NZGeoid05 to reduce ellipsoid heights to orthometric heights. These GPS derived orthometric heights were exported in tablular form and compared to the published precise levelling height at the relevant point to evaluate the difference.

3.4.2 Geoid – Ellipsoid Separation Values

The Geoid – Ellipsoid separation values (N) were calculated from the raw GPS observations and precise levelling data by rearranging equation (2.3) to give:

$$N = h - H + o \tag{3.1}$$

where: N = Geoid – Ellipsoid separation value

H = Height above Geoid or Orthometric height

h = Height above Ellipsoid

o = Regional Datum offset (0.349m)

The data was tabulated and processed in Microsoft Excel. It could then be exported to a text file in the form of xyz values where x was the Mt Pleasant 2000 Circuit easting, y the northing and z the separation value (N).

This data was then imported into CivilCad and used to produce contour plots which firstly provided a useful tool to visualise the basic shape of the geoid model, and secondly was used to extrapolate a contour model value at any given location. In order to build a regular grid of N values, a grid of approximately 2.5km by 2.5km was constructed and overlayed above the contour model. A value from the contour model was then extrapolated using a CivilCad function for each grid square. These grid values could then be exported as an ASCII file.

3.4.3 Grid Factory

The Project Geoid was created in Grid Factory. It is an out of licence Trimble application that is capable of converting tabulated geoid – ellipsoid separation values into a functional .ggf file. In order for the tabulated ASCII grid data from section 3.4.2 to be imported into the software, it was necessary to first create a format file that tells the software the structure and content of the input file. This is done from within the software. The specific settings and parameters of the format file are shown below.

Table 3.1. Grid Factory Format File

Point	Value	Setting
1	Name	ProjectGeoid
2	Basis	WGS84
3	Method	Bilinear
4	Input file type	ASCII
5	Data length	1
6	Missing data value	9999
7	Axis orientation	Longitude
8	Rows are Latitudes	
9	Latitude of 1st value	-43.472972
10	Latitude of last value	-43.812139
11	Latitude value grid interval	0.022611
12	Rows are Longitudes	
13	Longitude of 1st value	172.475694
14	Longitude of last value	172.977361
15	Longitude value grid interval	0.031389
16	Grid file type	Geoid seperations

There are several important points to note:

- Although the measurement datum, NZGD2000 is based on the ellipsoid GRS80, Grid Factory does not have the capacity to accommodate this. Fortunately, GRS80 and WGS84 are generally considered interchangeable.
- Grid Factory allows several different methods of interpolation. These being bilinear, biquadratic and bispline. This determines the method used to calculate the value of points between grid values.
- All latitudes and longitudes are in decimal degrees.
- It can be seen that the grid interval or resolution of the model is 0°01’20” latitude and 0°01’50” longitude.

The tabulated ASCII grid data can then be imported using the above format file to ensure that the values are properly geo-referenced. A full copy of the input file is reproduced in Appendix 2. It can be seen that it contains a header that defines the limits of the geoid model area in terms of WGS84 latitudes and longitudes, the size of each grid and a value (*N*) for each grid.

Once that data is successfully imported into Grid Factory, it can be visualised with a colour fill representation such as Figure 4.5, cropped and saved as a .ggf file which is compatible with GPS reduction software such as TGO and can be uploaded to field data recorders.

3.5 Testing

Ideally to test a geometric model such as the one that is proposed in the methodology, independent testing would be performed by means such as terrestrial gravity observation. However, due to the difficulty in access to such equipment, this was not possible.

Therefore, testing was performed by re-reducing the raw GPS observations in TGO using: ProjectGeoid; NZGeoid05; and EGM08. The reduced heights were then exported in tabular form to Microsoft Excel where they were compared to the published precise levels. Excel was also used to calculate the mean and standard deviation of the differences. This means the testing of the ProjectGeoid is relative rather than absolute. That is, it will be tested against other geoid models and orthometric height datums as opposed to being tested against the true position of the equipotential surface.

3.6 Conclusion

A description of the data used and method applied has been described. The process of data analysis has been detailed and the form and structure of the data explained. It has been shown that the method of testing the ProjectGeoid is relative as absolute testing is beyond the resources of this research. This methodology enables the interpretation of results to be better understood.

4. Results

4.1 Introduction

This chapter documents the results in terms of the specific objectives outlined in the Project Aim (1.3). These are: the documentation of the type and structure of NZGeoid05; documenting the difference between GPS heights and Lyttelton MSL Heights; the construction of a local geoid model; and the testing of the model.

4.2 Documentation of Type and Structure of NZGeoid05

A detailed analysis was given of NZGeoid05 in section 2.5. In summary it is a regional gravimetric geoid model developed specifically for New Zealand. The target precision of orthometric heights derived using NZGeoid05 in relation to existing levelling datums is ±0.1m at the 95% confidence interval (Amos et al. 2003a). Figure 4.1 below shows a colour fill representation of NZGeoid05 over the study area.

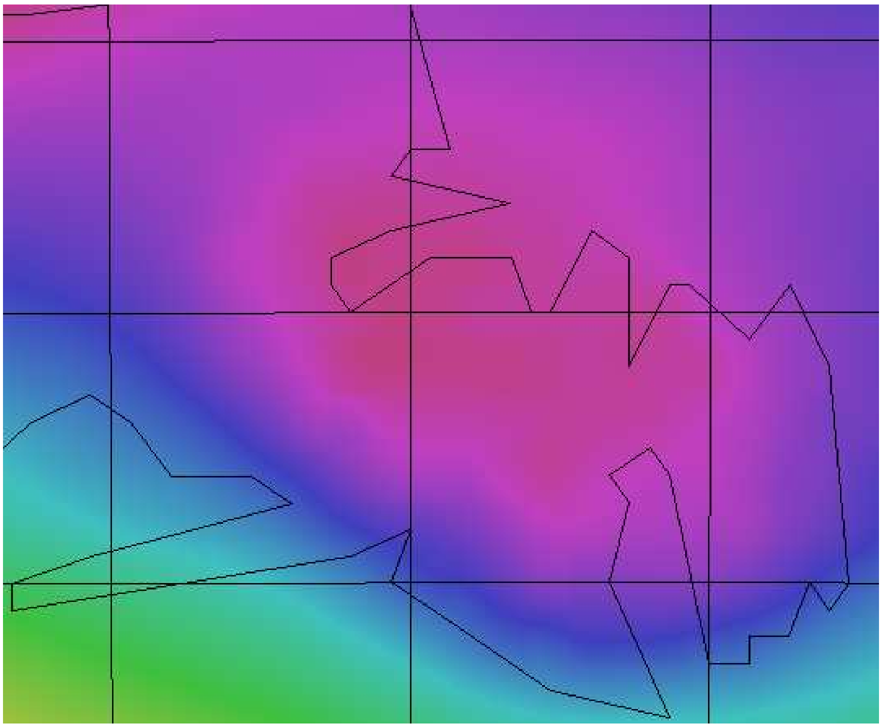


Figure 4.1. Colour fill representation of NZGeoid05 over the study area.

4.3 Documenting the difference between GPS heights and Lyttelton MSL Heights

4.3.1 Spatial Distribution of Observations

Figure 4.2 below shows the spatial distribution of the differences between NZGeoid05 GPS derived orthometric heights and Lyttelton 1937 datum orthometric heights. This plot does not quantify the difference clearly. But it is extremely useful for illustrating the poor distribution of observations that made up the data set. The contour plot shows that there is no distinct geometric pattern to the differences.

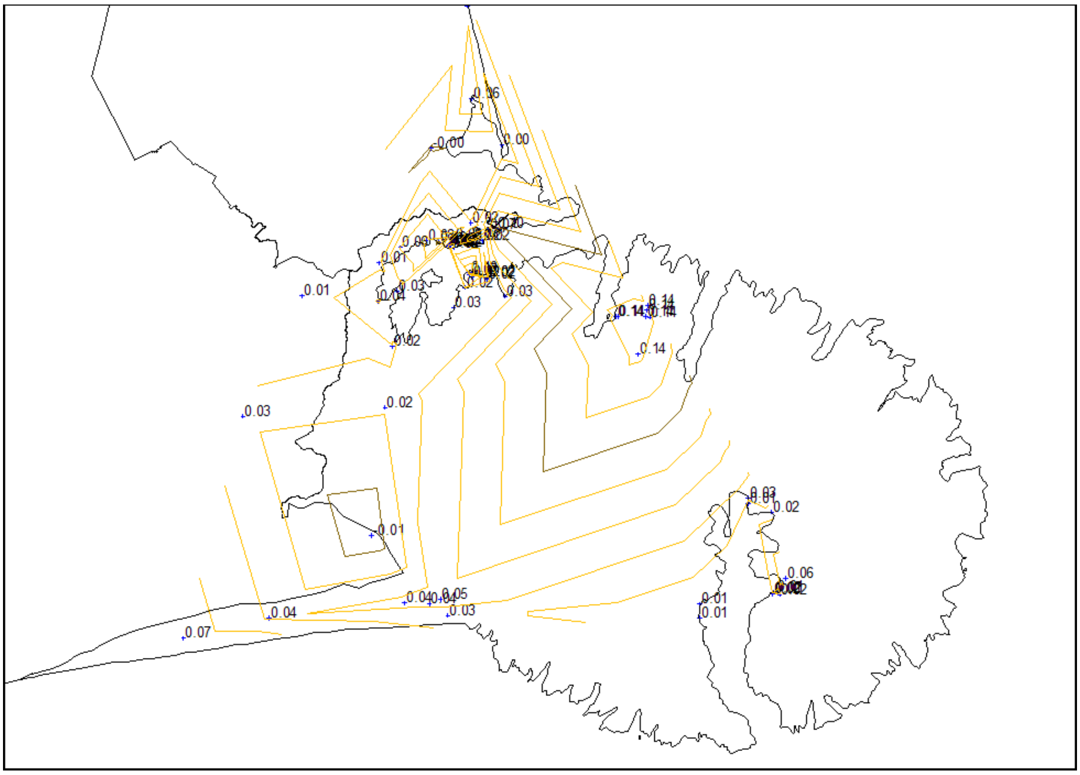


Figure 4.2. Spatial distribution of observed differences.

4.3.2 Cumulative Analysis

A cumulative analysis was performed on the differences to quantify the data. The results are shown in Figure 4.3 below. It shows that the majority of observations have a difference of less then 0.100m. There is a noticeable group of outliers in the 0.141 – 0.160m range. Note the size of the data set was 59 observations.

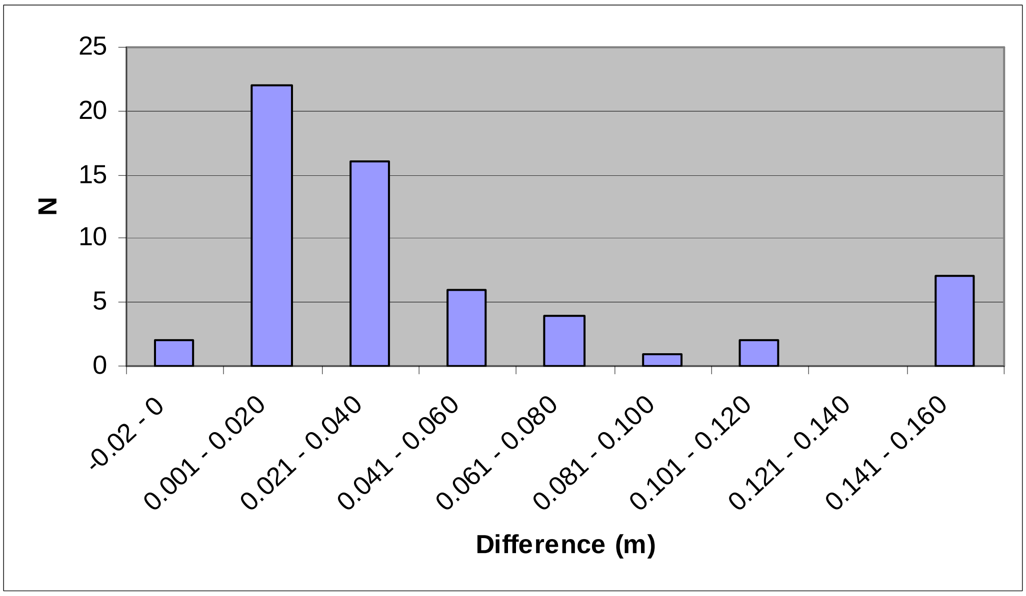


Figure 4.3. Cumulative analysis of differences.

4.4 Construction of a Local Geoid Model (ProjectGeoid)

Figure 4.4 below shows the spatial distribution of geoid – ellipsoid separation values (*N*) overlaid by the contour model. The contour model shows a general sloping surface toward the south with the dense collection of points around Lyttelton Harbour creating a mound.

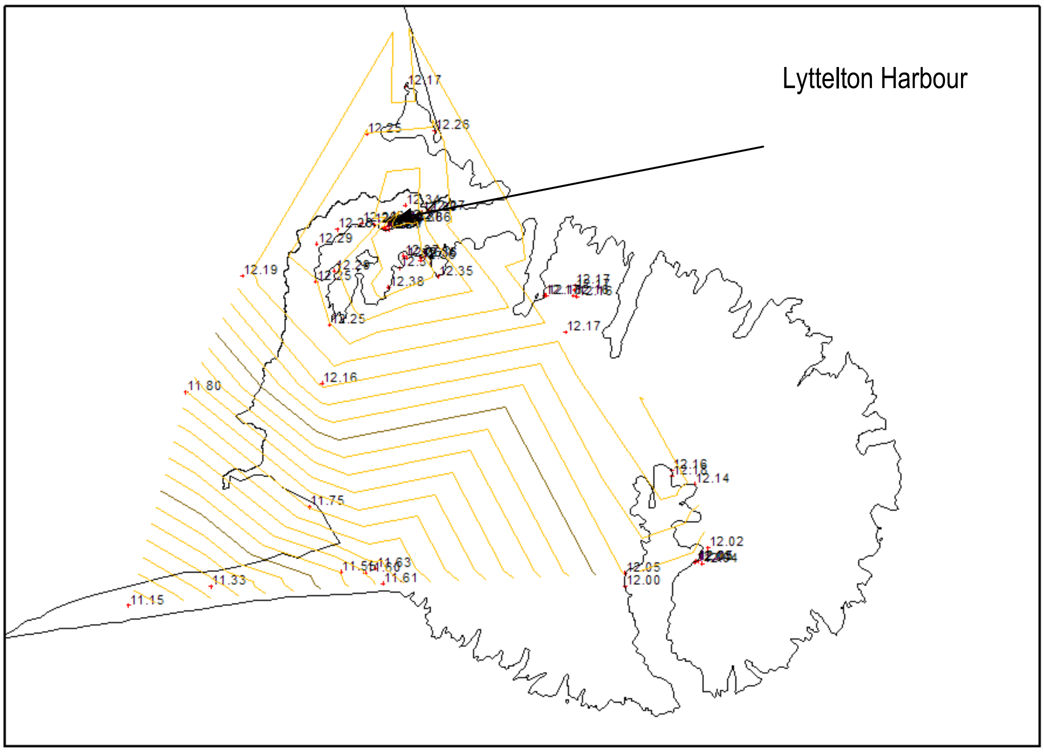


Figure 4.4. Spatial distribution of separation values (*N*).

The results from importing the data into Grid Factory are shown in figure 4.5 below. It is a colour fill representation of ProjectGeoid. Its shape mirrors the contour model in Figure 4.4.

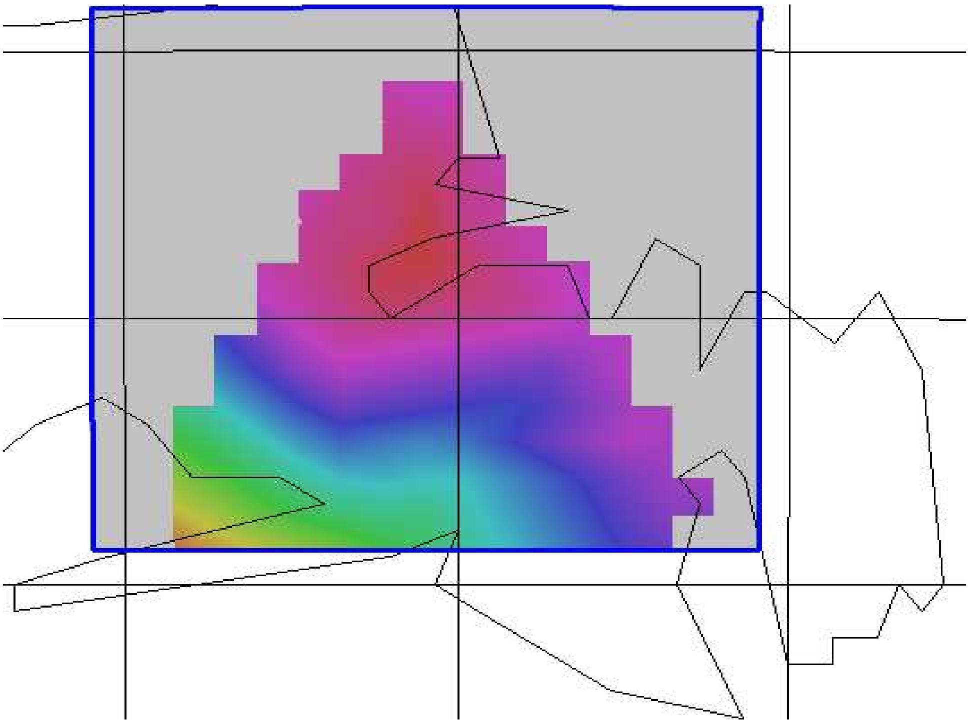


Figure 4.5. Colour fill of ProjectGeoid.

4.4.1 Conversion to a Useable Format

This process proved to be considerably easier to achieve than initially thought. Once the data was correctly loaded into Grid Factory, it could simply be saved as a .ggf file.

4.5 Testing and Evaluation of ProjectGeoid

Table 4.1 below shows the mean differences between the GPS height derived using the various geoid models and the Lyttelton precise levelling data.

Table 4.1. GPS heights compared to precise level heights

	ProjectGeoid	NZGeoid05	EGM08
mean difference (m)	0.005	0.033	-0.634
standard deviation (m)	0.049	0.045	0.057

4.6 Conclusion

The result for each research objective has been presented. It can be seen that each objective has been successfully achieved, these results must now be analysed.

5. Analysis

5.1 Introduction

This analysis chapter will follow a similar structure to the previous chapter. That is, each specific objective outlined in the Project Aim will be covered separately. An analysis on the need for a regional geoid model such as NZGeoid05 will be given. Specific analysis will then evaluate how well each objective has been achieved. An aspect of this research has been not only the results but more importantly the development of the process of building a local geoid model and a critical evaluation of this process.

5.2 Documentation of Type and Structure of NZGeoid05

The type and structure of NZGeoid05 has been fully documented in section 2.5. This analysis will focus on the need for a geoid model designed for the New Zealand environment. As discussed (2.4) GPS surveying is becoming more and more common. With instrumentation advancement, the launching of new satellites and additional frequencies, GPS surveying is set to become more and more applicable. The demand for a current geoid model will grow with this expansion in GPS use. Therefore, as New Zealand did not previously have a regional geoid model, the need for NZGeoid05 is clear.

In addition, it has been shown that New Zealand is an extremely dynamic environment, (2.6.1) in terms of tectonic deformation. By using a geoid model, the need to rely on a physical infrastructure of bench marks is significantly reduced.

5.3 Documenting the difference between GPS heights and Lyttelton MSL Heights

By documenting the difference between GPS heights and Lyttelton MSL heights, the application of NZGeoid05 to and compatibility with one of New Zealand's existing 13 vertical datums is evaluated.

5.3.1 Spatial Distribution of Observations

The poor spatial distribution of points shown in Figure 4.2 reduces the representative ability of GPS observations to precise levels to clearly document any pattern of differences. This is partly caused by having obtained the data from a third party who did not collect the data with geoid mapping in mind. However, the major restricting factor is the availability of bench marks that have precise levels. This is because precise level networks are usually restricted to main road networks. This is an inherent disadvantage with levelling networks. This aspect highlights the advantages that GPS levelling has over traditional spirit levelling, that is, it does not require the connection to a bench mark which in some cases may be a significant distance from the job. The mountainous nature of Banks Peninsula and much of New Zealand further reduces the availability of suitable bench marks.

5.3.2 Cumulative Analysis

A direct point to point comparison is shown in Figure 4.3. Given the target precision of NZGeoid05 is ±0.1m at the 95% confidence interval it can be concluded that this set of observations is within this target. The existence of a group of outliers in the 0.141 – 0.160m range is potentially a reflection of the fact that this data set was not primarily collected to check GPS heights. It is possible that a systematic field error is responsible for this group of outliers.

These findings show that NZGeoid05 is compatible with the Lyttelton datum to within the models target accuracies. They also show that to ideally perform such testing it is best to have a purposely designed GPS survey.

5.4 Construction of a Local Geoid Model (ProjectGeoid)

The poor spatial distribution of points noted is of greater concern when developing a model that represents the equipotential surface. This could be compared to a basic stock pile survey. Ideally to accurately represent the physical shape of the stock pile, a grid of points would be measured as well as points at changes of grade. In the case of geoid modelling, a grid of points would be the best representation. It can be seen in Figure 4.2 and 4.4 that the actual spatial distribution of points was not evenly distributed in a grid pattern.

Regardless of this fact, the primary aim of this research was developing the methodology and techniques required to create a functional geoid model. This was successfully achieved by creating an input data set (Appendix 2) for Grid Factory that could then be saved as a .ggf file. Therefore a functional localised geoid model was developed.

5.5 Testing and Evaluation of ProjectGeoid

The method used to test ProjectGeoid was to re-reduce the raw GPS observations using ProjectGeoid, NZGeoid05 and EGM08 and then compare the levels with against the published precise levels. Ideally it would be tested using independent gravity observations. An alternative option would have been to selectively or randomly remove observations from the data set used to build the geoid model, but then include these observations when ProjectGeoid was used to reduce the observations to orthometic heights. However given the small data set and the similarity of values where the data was clumped, it was considered that this would not give significant insight into the performance of the model or the process of constructing it.

The results shown in Table 4.1 show an improvement in the mean differences between the GPS height and the Lyttelton precise level when using ProjectGeoid as opposed to NZGeoid05. The results for EGM08 are significantly different, this is due to it being a global geoid model that only models the long wavelength features of the gravity field (Amos 2007), it does not include local gravity observations or local terrain corrections. In additional it does not include the 0.349m offset to the Lyttelton datum. Table 4.1 also shows that the standard deviations are high. This is because of the small data set.

The most important finding, that ProjectGeoid produced smaller differences than NZGeoid05 ,is an indication that the process of building a geoid model to predict heights in terms of the Lyttelton datum has worked. Given the testing of the process has be successful, the process now needs to be evaluated to determine if it is valid.

As discussed in section 2.6.1, the relevance and accuracy of the Lyttelton datum has been seriously degraded by dated and poor initial definition, sea level change and tectonic deformation. This suggests that the Lyttelton MSL, as an interpretation of the equipotential surface, is no longer valid. The process that this research project developed to build a local geoid model has used the Lyttelton interpretation of the equipotential surface to calculate geoid – ellipsoid separation values. As such this research project has not developed a new independent interpretation of the equipotential surface, but rather it has given an old inaccurate interpretation a new modern expression in the form of a geoid model. This means that the geoid model will produce orthometric heights that compare well with Lyttelton MSL heights, but will not produce orthometric heights that are accurate relative to the equipotential surface or actual MSL.

5.6 Conclusion

The advantages of a geoid model for GPS surveying have been described. This reinforces the need for a regional geoid model for New Zealand. An analysis of the spatial distribution of the data set used in this research shows that the data may not have been ideal at representing the shape of the geoid over the study area. Regardless of this, the process proposed in the methods chapter was successfully applied to produce a functional geoid model. An evaluation of this process showed that using an outdated interpretation of the equipotential surface will result in a geoid that inaccurately determines true orthometic MSL heights.

6. Conclusion

6.1 Introduction

The previous chapters have defined the aims of this research and described the study area. The theory behind the shape of the earth and the role of geoid models was explained. This has included a discussion of various height systems and geoid models. An assessment of MSL Lyttelton was also given. The methods and results of the research were outlined and a detailed analysis provided.

The following sections provide final conclusions regarding the specific objectives of this research. These conclusions were drawn from the analysis conducted in relation to the evaluation of the theory and process.

6.2 Documenting the difference between GPS heights and Lyttelton MSL Heights

This research showed that there is a difference between GPS orthomethic heights and Lyttelton MSL heights. The fact that these differences were within the target precision of NZGeoid05 do not hide the flaws in the Lyttelton datum. That is, it was initially poorly defined and has been further compromised by sea level rise. Also its physical network of bench marks has been subject to disturbance from tectonic deformation. This suggests that the target precision of NZGeoid05 of ±0.1m is not due to geoid model inaccuracies but rather inaccuracies in the Lyttelton datum.

6.3 Construction of a Local Geoid Model (ProjectGeoid)

The process used to construct the geoid model proved effective. However it revealed an area of weakness in this data set. That is, there needed to be an even spread of observations over the study area. A grid pattern of observations would have provided a better sampling pattern. However this is not always possible due to the constraining factor being the location of existing bench marks with precise levels.

6.4 Testing and Evaluation of ProjectGeoid

The testing of the ProjectGeoid proved that it determined heights in terms of the Lyttelton datum more accurately than NZGeoid05 or EGM08. However, the evaluation of the model shows that it is not an independent interpretation of the equipotential surface but rather, it has given the Lyttelton interpretation a new expression. Because the Lyttelton interpretation of the equipotential surface is outdated and subject to continued degradation, this new interpretation will then not provide orthometric heights that truly represent actual MSL.

6.5 Future Work

This research was prompted by concerns that NZGeoid05 was not determining accurate heights in terms of MSL which was assumed to be represented by the Lyttelton datum. What has been found is infact the opposite. That is, the Lyttelton datum is no longer representative of MSL or the equipotential surface. Without means to test the NZGeoid05, in absolute or relative terms, it is difficult to fully evaluate its accuracy. This is a possible area of future research.

What has been determined with respect to NZGeoid05 is that it is a modern solution that is perfectly suited to today's GPS technology and dynamic environment. It is more likely that our future vertical datum needs will be met by NZGeoid05 and NZVD05 rather than the Lyttelton datum or any other levelling network.

This leads to the issue of what to do with the physical infrastructure of the Lyttelton network and the sentimental attachment that many have to it. Just as changing from the empirical to metric system, or from the pound to the dollar was a difficult, potentially confusing and expensive exercise, the long term benefits far outweighed the short term disruption. The same applies to changing to NZGeoid05 and NZVD05. We need a future proof vertical datum.

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8. Appendices

Appendix A – Project Specification

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG4111/4112 Research Project: PROJECT SPECIFICATION 2009

FOR:	Frazer Munro
TOPIC:	Localised Geoid modeling using GPS and precise leveling data.
SUPERVISOR:	Albert Chong
PROJECT AIM:	To construct a workable geoid model for the study area that can be incorporated into data recorders for field use.

PROGRAMME (Issue A, 27/02/2009):

1. Document the structure and type of the current New Zealand Geoid model (NZGeoid05).
2. Document the effect of localised geological variations on the geoid model around Banks Penninsula, Christchurch, New Zealand.
3. Use GPS observations and precise leveling data to construct a local geoid model or enhance existing geoid model.
4. Evaluate and test the model.

As time permits:

1. Liaise with Alan Withington from Trimble NZ to convert model into a format that is useable.
2. Prepare presentation for 2009 NZIS conference.

AGREED

________________(student) ________________(supervisor)

27 / 04 2009 27 / 04 2009

Examiner/Co-examiner:__________________.

Appendix B – Grid Factory Input File

```
Min north: -43.472972  Max north: -43.812139  Min east: 172.475694  Max east:
172.977361  North step: 0.022611  East step: 0.031389  IUTM: 0  Iell: 0  Izone: 0
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12.182
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12.229
12.277
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12.165
12.146
12.126
12.105
12.085
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12.122
12.174
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11.802
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12.023
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11.982
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12.088
12.145
12.165
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11.698
11.781
11.875
11.944
11.92
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11.923
11.988
12.053
12.116
12.159
12.142
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11.678
11.76
11.824
11.838
11.818
11.823
11.888

11.954
12.019
12.084
12.13
12.152
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11.493
11.575
11.644
11.701
11.735
11.724
11.789
11.854
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11.984
12.05
12.101
12.092
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11.326
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11.452
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11.754
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