University of Southern Queensland
Faculty of Engineering and Surveying

A Comparison of AUSGeoid09 and AUSGeoid98 In the Hawkesbury Valley

A dissertation by
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ABSTRACT

Horizontal coordinates in Australia are defined by the Geocentric Datum of Australia (GDA94) which is based on a global geodetic datum that has been established to facilitate the use of Global Navigational Satellite Systems (GNSS), however the Australian Height Datum (AHD), a mean sea level based datum has been retained to define vertical position. This is because the reference ellipsoid used by space based measurement systems cannot properly describe the flow of fluids as it is not related to gravity. A geoid model representing a surface of equal gravity is needed to transform GNSS heights onto the gravity based AHD. In March of 2011 Geoscience Australia released a new geoid model known as AUSGeoid09 to replace the existing AUSGeoid98. This model has been developed with the specific aim of giving GNSS users a more accurate means of determining AHD heights.

A study has been conducted to establish the accuracy of AHD heights generated using AUSGeoid09 and AUSGeoid98 within a test area of the Hawkesbury Valley NSW. Using published AHD heights as the standard for comparison, the accuracy of each model has been assessed to gauge the level of improvement if any, gained by the use of AUSGeoid09.

The results show a significantly better determination of AHD using AUSGeoid09 within the test site, using the equipment and methods adopted by this study. However the level of improvement is not consistent throughout the test area. It was found that AUSGeoid09 did not improve the accuracy of the AHD heights generated along the escarpment of the Great Dividing Range.

This research draws attention to the need for GNSS users to have an understanding of the performance and limitations of the geoid models they use in order to make sensible decisions regarding their use.

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Limitation of Use

Prof Frank Bullen
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Certification

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

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

Date

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ACCRONYMS

AGSO	Australian Geological Survey Organisation
AHD	Australian Height Datum
CQ	Coordinate Quality
GNSS	Global Navigational Satellite System
ICMS	Inter-governmental Committee on Surveying and Mapping
LPMA	Land and Property Management Authority

NRTK	Network Real Time Kinematic
PM	Permanent Mark
RL	Reduce Level
RMS	Root Mean Square
RTK	Real Time Kinematic
SCIMS	Survey Control Information Management System
SSM	State Survey Mark

CHAPTER 1

INTRODUCTION

1.1 Introduction

A level surface can be defined as a surface of which all points are at equal gravitational potential. The flow of unconstrained fluids is defined with reference to a level surface and as such they are of significance to engineering projects that involve the flow of fluids. So for a level system to be of any value to such projects it must be referenced to a level surface. This creates a problem when using a Global Navigational Satellite System (GNSS) to measure height.

Heights generated by a GNSS are referenced to an ellipsoid. This is an imaginary surface defined by the Earth's shape, rotation and gravitational forces, however it is not based on local gravity anomalies. As such it is not a level surface and cannot be used to describe the flow of water.

To convert an ellipsoidal height to a height referenced to a level surface a geoid model is used. A geoid, in its purest form, is an irregular surface of equal gravity, of which at any point the surface is perpendicular to gravity, and thus by definition is a level surface. The distance between the ellipsoid and the geoid model along the line normal to the ellipsoid is called the ellipsoid-geoid separation or N value. This N value is used to convert ellipsoidal heights to a height referenced to the geoid called an orthometric height. It will be shown later that heights generated this way are not strictly orthometric heights despite the conventional terminology.

The Australian Height Datum (AHD) is a spirit levelled representation of mean sea level across the continent. A geoid at mean sea level can be used to represent mean sea level across the continent and as such orthometric heights generated by such a geoid should closely represent the AHD. This was not case with AUSGeoid98 and the AHD. This was because errors in the data used to generate AUSGeoid98 and problems with the levelling data and generalisations of gravity and mean sea level used to create the AHD resulted in two surfaces that were not coincident. The end result was that any orthometric height derived using AUSGeoid98 was often significantly different when compared to the published height value of an established AHD benchmark.

While it has long been accepted that AUSGEoid98 did not produce accurate AHD heights when used in the absolute sense, this was not a significant problem in the past. With traditional differential GNSS surveys the geoid model was only used in a relative sense where the gradient of the geoid was used to transfer height. It is only with the increased popularity of continuously operating reference station (CORRs) systems that errors in the geoid model used to calculate AHD heights have become problematic. When using these systems the accuracy of the derived AHD height is directly dependant on the accuracy of the N value.

To overcome this problem, AUSGeoid09 has been developed to allow GNSS users a more accurate means of generating AHD levels. The following statements have been made about the accuracy of AUSGeoid09:

> *Applying AUSGeoid09 to AUSPOS derived GDA98 ellipsoidal heights rather than AUSGeoid98 resulted in an improvement of 270%, independent of the GNSS observation length, the overall accuracy was better than 70mm*

(Janssen, Watson & McElroy 2011)

Referring to AUSGeoid09

> *After this least square collocation surface fitting, the standard deviation of the fit reduced to +/-30mm, one third of which is attributable to the uncertainty in the GNSS ellipsoidal height*

(Featherstone 2011)

> *In most cases the AUSGeoid09 derived height results fall within the expected +/-0.05m accuracy stated by Geoscience Australia*
>
> (Janssen & Watson 2011)

The above statements are all strong testimony to the improved AHD determination possible using AUSGeoid09. The question is, how does a surveyor, or any other of the growing number of GNSS users, relate this information to their routine GNSS based tasks.

While numerous large scale tests of AUSGeoid09 have been undertaken, there is a need for individual users to verify the performance of AUSGeoid09 within the orbit of their own activity. Geoscience Australia recognises that the model is not perfect, and states in the version control text for version V1.01 of AUSGeoid09 that it would encourage users to provide them with their own accuracy assessment so that Geoscience Australia can identify areas of improvement.

Surveyors rarely rely solely on the AHD heights generated by a GNSS as a survey is usually connected to nearby established benchmarks. An understanding of the performance of AUSGeoid09 can be used to make informed decisions on how best to connect the surveys and to assess the accuracy of AHD heights obtained when the absolute AHD height generated by the GNSS is used.

1.2 Research Aim

The aim of this study is to assess the accuracy of AUSGeoid09 and AUSGeoid98 when used to generate AHD heights in a specific test area within the Hawkesbury Valley of NSW to gain an understanding of their performance and limitations.

1.3 Justification

While surveying instruments are generally no more accurate now than they were a decade or two ago, they have radically automated many survey tasks. With advances in equipment and technology comes a separation of the operator from the fundamental principles of the task being performed. Modern theodolites automatically sight targets, lasers measure distances, and digital levels read staves. It could be said that the more advanced the equipment becomes, the less understanding the surveyor has of the methods used by the equipment to perform its task. This is certainly the case with GNSS technology. Continuously operating reference station GNSS systems offer a fast, inexpensive and relatively accurate means of performing many surveying tasks, however operators often have a limited understanding of the complex mathematical theories being employed by the equipment they use. While it is unreasonable to demand that surveyors have a rigorous understanding of these vastly complex technologies, it is reasonable to expect they have an understanding of the accuracy and limitations of the equipment they use. Similarly it would be unreasonable to expect a surveyor to have a thorough understanding of the exact data and processing used to generate a geoid, however the prudent surveyor should understand the limitations of all the tools used, of which the geoid is no exception. This study seeks to improve understanding of the accuracy and limitations of AUSGeoid09 when used with GNSS systems to determine AHD heights.

As already mentioned, surveyors rarely rely solely on the absolute AHD values derived from GNSS measurements. Surveys are usually connected to nearby marks with established coordinates so a correction can be calculated. Often, as is the case where this study has been conducted, these marks are a considerable distance from the survey with varying terrain between the two. An understanding of how well the model performs over distance and areas of large local terrain variations will help surveyors make informed decisions on how best to connect the survey to existing established marks and assist in estimating the accuracy of the AHD heights produced by these surveys.

1.4 Scope of the Project

Four major tasks were undertaken to complete the research project:

a. Research literature relating to GNSS height determination. This was undertaken to establish the relationship between the AHD height system and GNSS derived orthometric heights and to gain an understanding the current problems associated with the generation of orthometric heights using a GNSS and AUSGeoid98. Finally the production and current testing of AUSGoid09 will be investigated. Within this context specific areas are discussed as follows:
    i. Geodesy and GNSS heights
    ii. Height Datums
    iii. Production and problems of AUSGeoid98
    iv. Production of AUSGeoid09
    v. CORSnet NSW and single rover real time kinematic (RTK) operation
    vi. Previous testing of AUSGeoid09

b. Validation of the equipment used in the study
c. Field Measurements
d. Analysis of the results and validation of any conclusions drawn from the analysis

The study was conducted within a small area that was considered representative of the type of terrain commonly encountered. The flood plains of the Hawkesbury River and the escarpment of the Great Dividing Range were two distinct topographical features within the wider region that were considered most likely to have an effect on the accuracy of AUSGeoid09 and AUSGeoid98. The test area was designed to represent a cross section of these features so that the results could be considered a generalisation of the wider region.

The conclusions drawn from the results of this study are limited by the accuracy of the RTK GNSS measurements used to compare the two geoid models.

1.5 Conclusion

This project aimed to research the theory of geodetic levelling and how it relates to GNSS heighting and the use of a geoid model to derive AHD heights. The research demonstrated that current testing of the geoid model is primarily large scale in nature and not entirely independent. Next the research sought to define a method to test the accuracy of AUSGeoid09 and AUSGeoid98 when used in typical survey conditions employed by a small survey company. Finally it is expected that the results will reveal the level of improvement, if any, brought about by the new model. From the research and testing the performance and limitations associated with GNSS determination of AHD heights using AUSGeoid09 and AUSGeoid98 will be defined.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the previous chapter is was stated that there have been problems in the past generating AHD levels using AUSGeoid98, and that AUSGeoid09 has been developed to remedy these problems. It was also stated that current testing of the model does not identify possible local errors and that there is a need to examine the model locally.

These statements are supported in this chapter by a review of literature relevant to the generation of AHD levels using GNSS techniques. This identified the need to determine the accuracy and limitations of AUSGeoid09 within local areas rather than rely on the generic results of existing large scale validations of the geoid model.

The elements of the problem considered by this project can be defined as:

a. Geodesy and geodetic levelling systems
b. Errors associated with AUSGeoid98 and the AHD
c. CORSnet NSW and level determination using GNSS
d. AUSGeoid09 and previous testing of this geoid model in NSW

These elements are discussed in turn by this chapter to gain an understanding of the relationship between the AHD level system and GNSS heights and the current problems associated with the generation of orthometric heights using a GNSS. Once this has been established the production and current validation of AUSGeoid09 will be examined exposing the need for performance and limitations of the model to be assessed by individual users.

2.2 Geodesy and GNSS heights

GNSS systems use several surfaces both real and imaginary to generate coordinates and heights that have practical uses. These surfaces are shown in Figure 2.1. The most tangible is the Earth's actual physical surface or topography. An ellipsoid is a regular surface mathematically defined by the Earth's shape, rotation and general gravitational forces, however it is not defined by local gravity variations and as such is not a level surface. A level surface is defined as a surface at which all points on that surface are of equal gravity and as such it can be used to define the flow of fluids. The objective of any practical levelling system is to define the relationship between a point on the Earth's physical surface and a level surface. As vertical GNSS coordinates are referenced to an ellipsoid they cannot be used to describe the flow of unconstrained fluids. Two points on the ellipsoid could have significantly different gravitational forces acting upon them making it is possible for water to flow from one point to another point higher above the ellipsoidal surface. To be of practical use to a GNSS requires a gravitational model of some form to convert the measured ellipsoidal heights to a height related to gravity. This gravitational model is referred to as a geoid.

The geoid is an irregular shape defined by the Earth's gravitational forces. It is a surface of equal gravity of which at any point on its surface, the surface is perpendicular to the direction of gravity. There are an infinite number of geoids and the geoid at mean sea level is most commonly referred to as mean sea level is often the base for vertical datums.

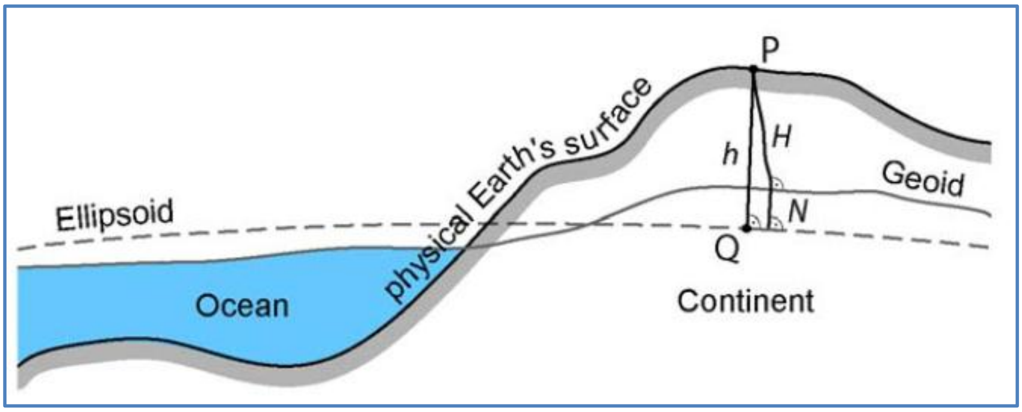

Figure 2.1 Geodetic surfaces (Janssen & Watson 2011)

Figure 2.1 also demonstrates how the ellipsoidal height (h) is converted to an orthometric height (H) using the geoid to ellipsoid separation (N), commonly known as the N value. Thus the expression to convert an ellipsoidal height to an orthometric height becomes:

$$H = h - N \qquad 1$$

It should be noted that the so called straight line orthometric height generated by a GNSS is not strictly an orthometric height (Featherstone & Sproule, 2006). However this convention will be retained in later discussions. It can be seen by the exaggeration of lines H and h in Figure 2.1 that they are not coincident. The angle between the direction of the gravity vector (line H which is actually a curve) and the ellipsoidal normal (line h) is called the deflection of the vertical, and h-N is an approximation of H. This approximation only amounts to several seconds of arc and can generally be ignored in most practical situations (Featherstone, 2007). At this stage it should also be noted that the AHD heights are not strictly orthometric heights either. In order to clarify this distinction the principles upon which the AHD height system is based are presented in the following sections.

2.3 Levels

On a very small scale, such as a building site, the concept of a level is a relatively simple one. A horizontal line described by a simple spirit level can be used as a reference surface that will adequately describe the flow of water as the variations in gravity over this short distance are negligible and fluids will always flow from a higher point towards a lower point. However on a geodetic scale defining a level surface from which it can be determined if one point is at a higher gravitational potential than another becomes somewhat more complex. Over large distances heights determined by spirit levelling are subject to errors caused by the variation of the gravity vector at each setup (Featherstone & Kuhn, 2006) and require corrections to ensure the Earth's gravity field is properly taken into account. The nature of these corrections is defined by the type of levelling system that has been adopted. There are two primary types of height systems that have been identified

(Featherstone & Kuhn, 2006), those that are not related to gravity (geometric) and those that are related to gravity (physical). A brief explanation of the limitations of geometric levelling systems will be given before moving onto the principles of physical height systems.

2.4 Height systems not related to gravity

These are heights measured along straight lines and are grouped as geometrical heights. An ellipsoidal height is one such system and is that used by a GNSS. It is the straight line distance of the normal to the ellipsoid to a point on the Earth's surface as shown in Figure 2.2.

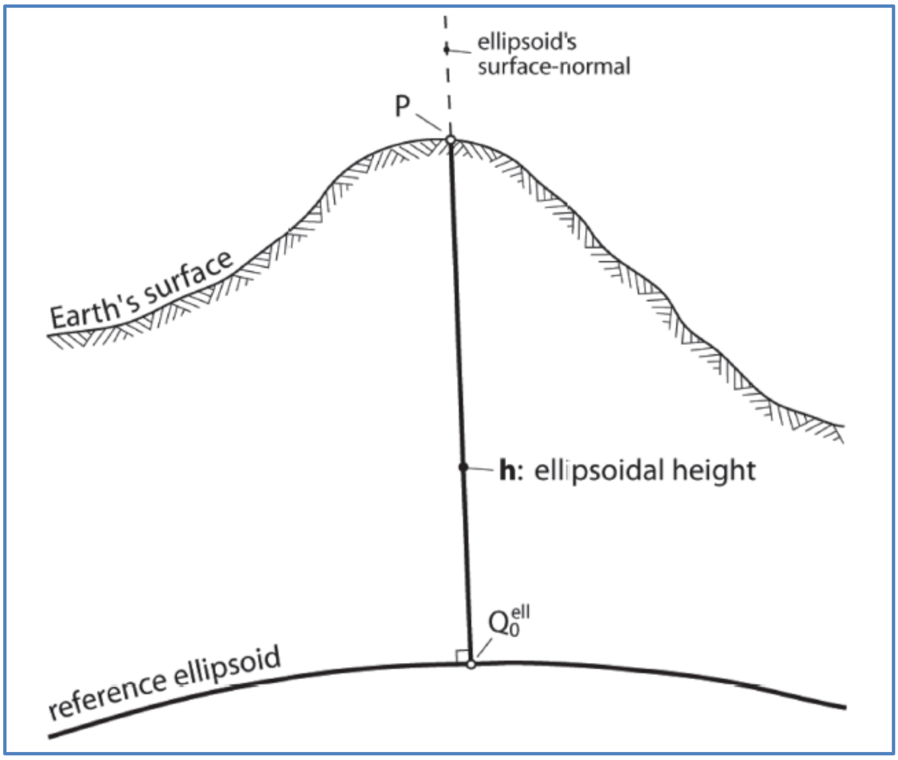

Figure 2.2- The ellipsoidal height system (Featherstone & Kuhn, 2006)

It should be noted that this height is completely independent of gravity and since it is the force of gravity that governs the flow of liquids, this system may give rise to a situation where fluids could flow from a lower point to a higher point. This is possible because a point which is deemed to be higher because of its physical distance above an ellipsoid may be at a point of higher gravitational force than another point deemed lower by its physical distance above the ellipsoid. Fluid will flow from the point of lower gravitational force to the point of higher gravitational force irrespective of their ellipsoidal heights.

As described a GNSS requires an accurate geoid model to convert the ellipsoidal height to an orthometric height that is related to gravity.

2.5 Height systems related to gravity

These can be generalised as natural or physical heights. All physical heights must be based on geopotential numbers and usually use a geoid model as the reference surface. A geopotential number is defined as the difference between the Earth's gravity potential at a point of interest and that on the reference geopotential surface chosen (Featherstone & Kuhn, 2006). Geopotential numbers are not suitable to define height because they have dimensions of length-squared divided by time-squared. In addition, as there is currently no practical way to directly measure gravity potential (Featherstone & Kuhn, 2006) geopotential numbers cannot be used alone to define height. Closely related to the geopotential number system is the Dynamic Height. Here the geopotential number is divided by the average value of gravity for a given region (dimension of length divided by time-squared) to give a unit of length. Physical levelling systems are heavily dependent on gravity measurements and the adoption of a constant gravity value can lead to height distortions (Featherstone & Kuhn, 2006). Other physical height systems have been developed in an attempt to account for the non-parallelism of equipotential surfaces. Figure 2.3 shows how the non-parallelism of equipotential surfaces can cause errors in spirit levelling.

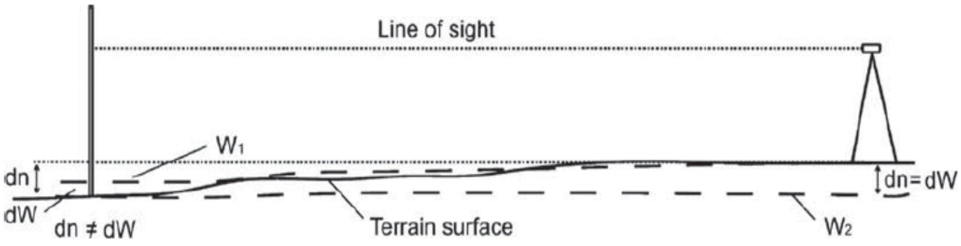

Figure 2.3 Non-parallel equipotential surfaces (Filmer & Featherstone, 2011)

The height difference at the instrument (dn) represents the difference in potential (dW) however the height difference does not equal the change in potential at the staff. These differences are small but accumulate over distance. They are most prevalent when levelling is conducted in a north-south direction or in mountainous terrain (Filmer & Featherstone, 2011). Height corrections are applied to spirit levelling according to the physical levelling system being used.

Three physical levelling systems will be discussed. Although two are not utilised in Australia, a review of their principles has been included as background information to the AHD system as it is a derivation of these principles.

2.5.1 Othometric height system

A variation of the dynamic height system is the Orthometric height system. Here the geopotential number is divided by the average gravity value along the plumbline between the reference geoid and the point of interest. As gravity is not constant the plumbline will be a curve and torsioned as shown in figure 2.4.

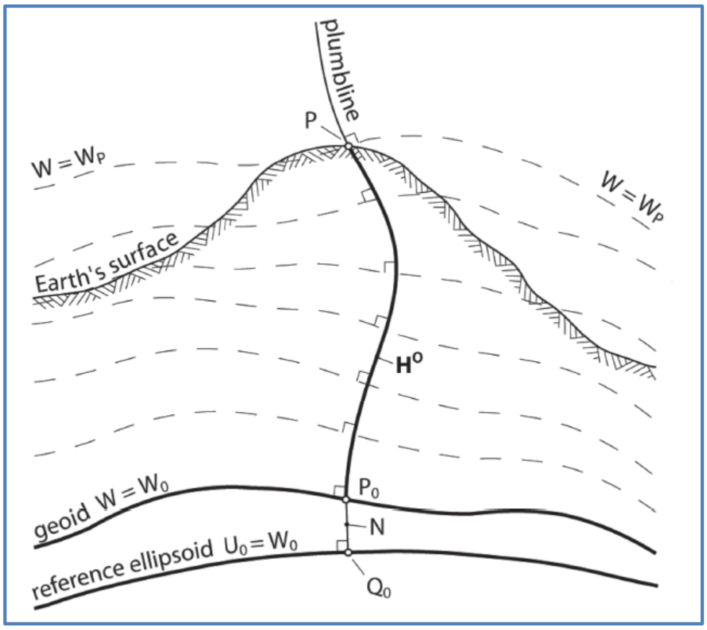

Figure 2.4-The orthometric height system (Featherstone & Kuhn, 2006)

A true orthometric height is not practical as it is not possible to measure gravity within the Earth's topography. A simplified method of approximating the gravity along the plumbline is usually employed to generate the orthometric corrections applied to spirit levelling under this system. Again this approximation of gravity introduces errors in the derived heights (Featherstone & Kuhn, 2006). How these errors are introduced can be demonstrated by looking at the way Helmert orthometric corrections are calculated between two levelling benchmarks BM1 and BM2. The formula for Helmert orthometric corrections is show in Figure 2.5.

$$HOC = \sum_{1}^{2} \frac{g - \gamma_0}{\gamma_0} \Delta n + \frac{\bar{g}_1 - \gamma_0}{\gamma_0} H_1 - \frac{\bar{g}_2 - \gamma_0}{\gamma_0} H_2 .$$

Figure 2.5-Helmert orthometric corrections (Filmer & Featherstone, 2011)

Here g is the simple mean of the gravity surface gravity values at BM1 and BM2. γ_o is a gravity constant and g_1 and g_2 are the integral means of gravity along the plumblines (H^O Figure 2.4). Errors are introduced into g_1 and g_2 as they are calculated using the Simple Poincare Prey reduction which neglects the terrain effects and variations in the Earth's topographic mass density (Filmer & Featherstone, 2011). The crucial point being made here is that this levelling system may not represent local gravity anomalies.

2.5.2 Normal height system

To avoid the need to determine average gravity along the plumbline the Normal height system was devised. An imaginary surface is defined in this system. The telluroid, defined by a projection in the direction of the normal to the reference ellipsoid from a point on the

Earth's surface to a point where the normal gravity is equal to the original points Earth gravity. The normal height becomes the distance measured along the curved normal gravity plumbline between the reference ellipsoid and the point Q on the telluroid (Figure 2.6).

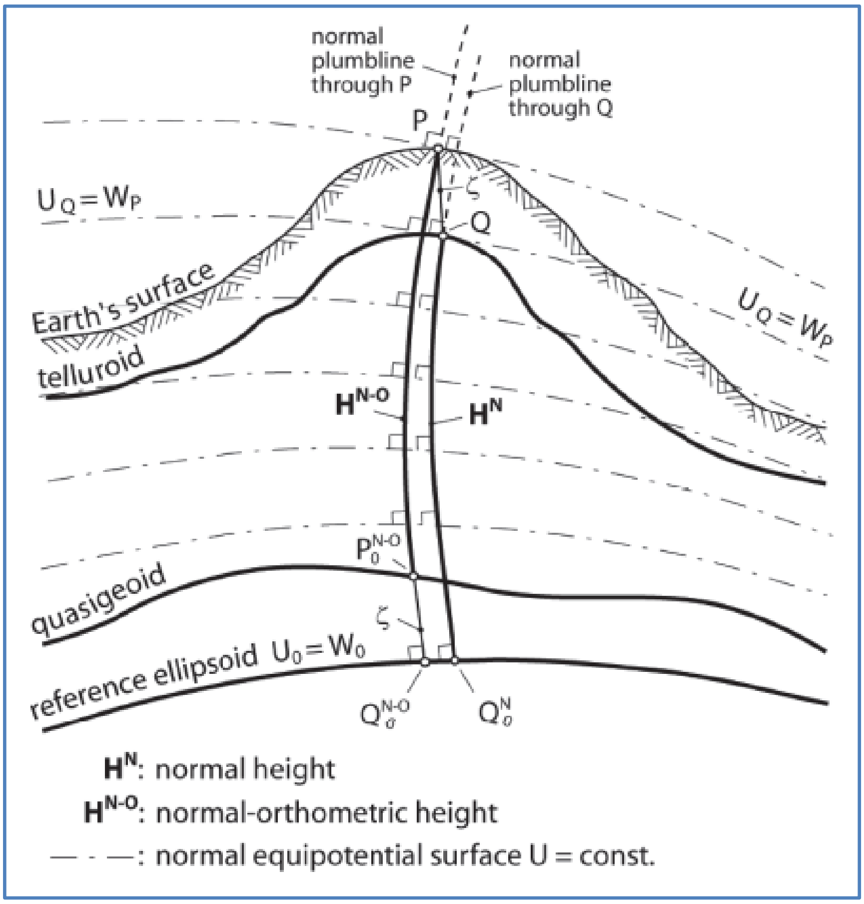

Figure 2.6-The normal and normal-orthometric height (Featherstone & Kuhn, 2006)

Errors are once again introduced into this system by the assumptions made of gravity. The Molondeski normal correction is calculated by the formula shown in Figure 2.7.

$$NC=\sum_{1}^{2}\frac{g-\gamma_0}{\gamma_0}\Delta n+\frac{\bar{\gamma}_1-\gamma_0}{\gamma_0}H_1-\frac{\bar{\gamma}_2-\gamma_0}{\gamma_0}H_2$$

Figure 2.7-Molondeski normal corrections (Filmer & Featherstone, 2011)

Here g remains the is the simple mean of the gravity surface gravity values at BM1 and BM2 however $\bar{\gamma}_1$ and $\bar{\gamma}_2$ are now the integral mean of normal gravity along the normal plumbline (H^N Figure 2.6) at BM1 and BM2. This is computed analytically without regard to local gravity anomalies so again the critical point is that local gravity variations may not be fully represented by this levelling system.

2.5.3 Normal orthometric height system

The Normal Orthometric system has been devised to eliminate the need for gravimetric observations completely. All gravity field related quantities are derived using normal gravity. In this system the quasigeoid is a surface generated by duplicating the normal projection from the point of interest P to the telluroid point Q (Figure 2.6) called the height anomaly, from the reference ellipsoid. The quasigeoid now becomes the reference surface for the normal orthometric height system again shown in Figure 2.6. The normal orthometric height is the only height that can be taken without gravity measurements, requiring only normal orthometric corrections for north-south spirit levelling (Featherstone & Kuhn, 2006*)*. It should be noted the quasigeoid is not an equipotential surface in either the normal or actual gravity field meaning that normal othometric heights are not strictly referenced to a level surface. The AHD is based on a normal orthometric system. It can be shown that AHD normal orthometric corrections are not related to local gravity at all. Figure 2.8 shows the normal corrections used in the AHD levelling system.

$$NOC_R = (A\bar{H} + B\bar{H}^2 + C\bar{H}^3)\phi_{1-2}$$

Figure 2.8-Rapp normal corrections (Filmer & Featherstone, 2011)

> The latitude difference between BM1 and BM2 ($\Phi_{1\text{-}2}$) and the coefficients A, B or C are not related at all to local gravity. These corrections are based solely upon normal gravity. This simplifies the correction process as there is no requirement to observe gravity however this system is least likely to represent local gravity anomalies. Filmer and Featherstone (2011) have shown that the errors in the approximation of $\Phi_{1\text{-}2}$ are insignificant in most circumstances. But what must be noted is that this means it has an insignificant effect on the resulting normal orthometric height. It does not suggest that the resulting height system accurately depicts local gravity and as such it is may not coincide with a purely gravimetric geoid surface.

It can be seen by the definitions in this section that there are numerous difficulties determining accurate geodetic heights. Most frequently encountered is the difficulty in measuring gravity below the Earth's surface. In these instances mathematical approximations are used.

This section has shown that there is a fundamental complication associated with the conversion of an ellipsoidal height to an AHD height. It has been established that the AHD, even if devoid of intrinsic field errors, is not referenced to an equipotential geoid. So N values generated using a purely gravimetric geoid model, such as AUSGeoid98, will differ to the AHD quasigeoid-ellipsoid separations. It is suggested that these differences could be up to 0.15m (Featherstone & Kuhn, 2006). The following sections will show that actual differences between the purely gravimetric AUSGeoid98 and the AHD were much higher due to errors beyond those mentioned in this section.

2.6 The Australian height datum

In 1971 the combined adjustment of 97,320 km of primary levelling and 80,000 km of secondary levelling tied into 32 tide gauges nationwide led to the development of the Australian Height Datum (Roelse, Granger, & Graham, 1975). Prior to 1971, no single vertical datum existed within Australia (Featherstone n.d.). This vertical datum, while not perfect, has served the nation well and is still the gazetted vertical datum of the Australian mainland (Featherstone 2009). Figure 2.9 shows the basic and supplementary spirit level traverses. Sections in yellow represent first order, light green is second order, thin purple is third, dark green is fourth order, red is one-way third order, and blue is two-way levelling.

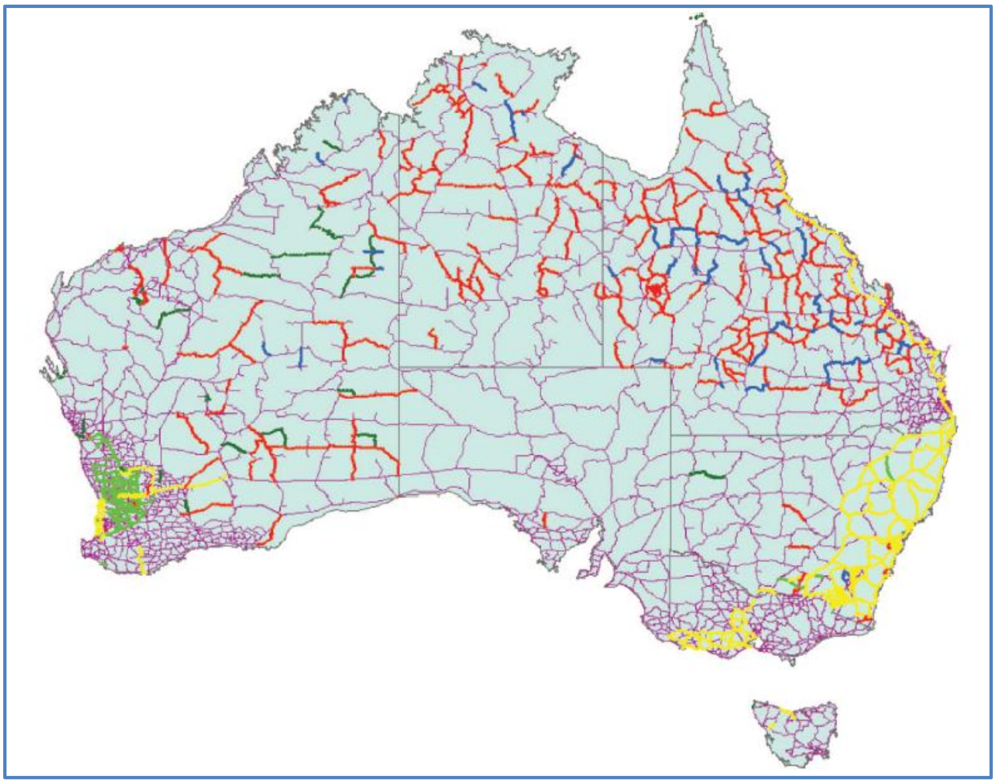

Figure 2.9-Spirit levelling traverses of the ANLN (Featherstone 2009)

Since its inception the validity of the AHD has come under scrutiny. There are several shortcomings of the AHD including a north–south slope of approximately 1.5m due to mean sea level constraints used in the adjustment (Featherstone 2009). All mean sea levels around the nation were given AHD value zero. Suspicion about the mathematical model of tide gauge zero began to surface as early as 1975 when it was noted that holding the gauge values at zero strained the levelling adjustment (Roelse, Granger, & Graham, 1975). This method of adjustment neglected the sea topography caused by the warmer, less dense northern water. In addition tide gauges were often poorly positioned near estuary mouths that locally diluted the salinity of the sea, and the tides were not observed long enough to encompass the entire lunar period. AHD is also affected by the quality of the spirit levelling data as well as the possibility that the methods used to reduce this data were questionable. It has been shown that 8.6% of the levelling failed the ICMS(2004) maximum allowable misclose for its given class and order (Featherstone 2009).

AHD shown previously is a normal orthometric system using normal gravity to calculate corrections instead of observed gravity. Points within the ANLN were only scaled to within about 1.6km accuracy causing some degree of error in the corrections applied (Featherstone 2009) although this has since been shown to be negligible (Filmer & Featherstone, 2011).

The aforementioned problems with the AHD have resulted in a datum surface that does not coincide with any single equipotential surface of the Earth's gravity field (Featherstone 2009). This suggests that AHD heights generated using a purely gravitational model and GNSS will not be accurate. This is of significance because AUSGeoid98 is a purely gravimetric model whereas AUSGeoid09, while based on a gravimetric model has been distorted to fit the troubled AHD.

The differences found between AHD and AUSGeoid98 cannot be attributed entirely to the errors associated with the AHD.

2.7 AUSGeiod98

As suggested in the preceding section, the AUSGeoid98 geoid model has its own problems. AUSGeoid98 was computed on a 2' by 2' grid on the GRS80 ellipsoid from EGM96, the Australian Geological Survey Organisations (AGSO) land and marine gravity database, satellite altimetry derived gravity anomalies and the Australian 27" by 27" digital elevation model (Featherstone 2001).

Each of these components has problems that may have contributed to errors in the determination of the geoid. (Featherstone 2001) lists these as:

a) **Gross errors in the digital elevation model used.**

The Australian Gravity Database from Geoscience Australia is based on the EGM96 global geopotential model produced by the US

National Imagery and Mapping Agency and NASA's Goddard Space Flight Centre. EGM96 used data from the JGP95E digital elevation model which itself was comprised of two separate data sets within the Australian continent. To the west of 140^0 it was based on the Terrain Base digital elevation model, and to the east on the NIMA topographic map holdings. This resulted in a disparity at latitude 140^0 (Featherstone 2001).

b) **Problems with the marine gravity database of the AGSO.**
Not all ship tracks have been crossover adjusted. This has resulted in some ship track errors being undetected. Satellite data has been warped to fit this erroneous data. Other problems existed within the AGSO gravity database. Errors occurred estimating the elevation of some gravity observations. Many of these elevations were determined by barometer only and the datum used is ambiguous and not well documented (Featherstone 2001).

c) **Large density contrasts not associated with topography.**
Topographic mass density data was not available across the entire continent. There are large changes in gravity across the continent not associated with terrain undulations. These could not be accounted for.

So it can be seen that AHD heights derived from GNSS surveys using AUSGeoid98 will almost certainly be subject to some degree of error (Featherstone 2001). These problems have always existed with these surfaces however they are becoming more problematic with the expanding use of single rover real time kinematic GNSS.

2.8 Single rover CORSnet GNSS systems

This section will begin with an overview of the CORSnet NSW system and its basic operation. Following that will be a brief look at the reason behind the increased dependency on the accuracy of the geoid model when generating AHD levels using these systems.

CORSnet NSW is a NSW government funded network of global navigation satellite system continuously operating reference stations that will eventually be expanded to include 70 reference stations that will provide state wide coverage of NSW by the year 2013. Figure 2.10 shows the current state coverage.

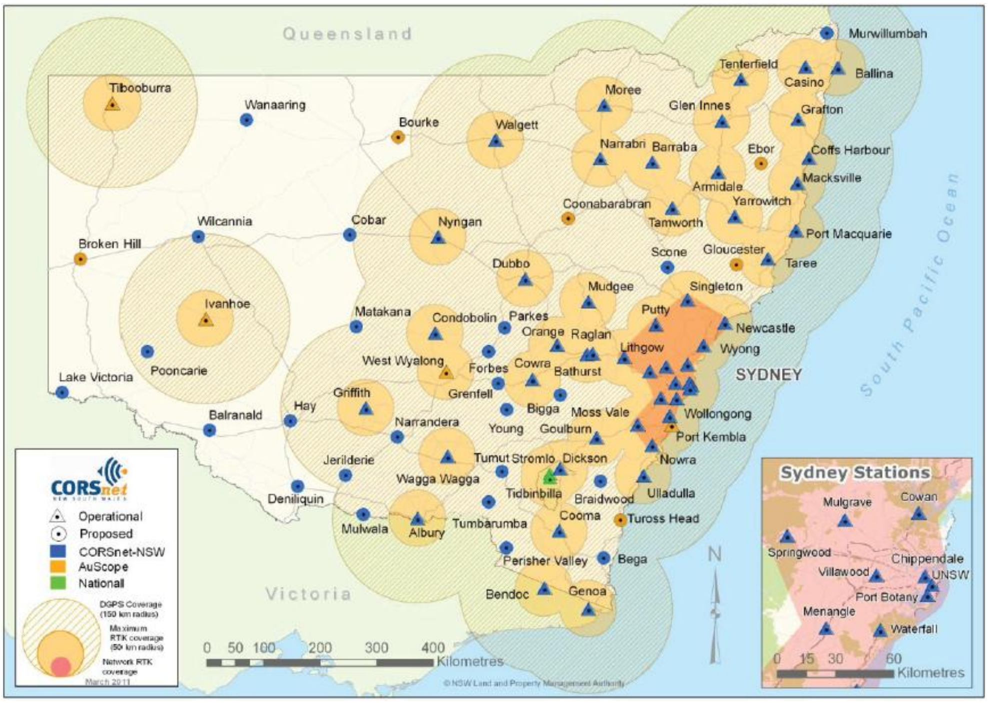

Figure 2.10-CORSnet coverage as of March 2011 (Janssen, Haasdyk & McElroy 2011)

CORSnet NSW provides real time kinematic (RTK) and network real time kinematic (NRTK) corrections in RTCM 3.1 format to users using the internet using networked transport of RTCM via internet protocol (NTRIP). NRTK solutions provide the user with a modelled offset based on a network solution that better represents distance dependant errors than a single reference station solution (Janssen, Haasdyk & McElroy 2011). This allows accurate positioning using a single rover within the areas of coverage. The use of CORSnet systems is bound to increase in coming years as they are less expensive than traditional base and rover systems, are not restricted by radio coverage and licensing fees, and have comparable accuracy to base and rover systems. The user end of the system consists of an antenna, controller and modem to receive correction data.

The heights generated by CORSnet systems are referenced to the GRS80 ellipsoid. It has been shown in previous sections that an ellipsoidal height has no practical meaning. To be of practical use, an ellipsoidal height must be related to the geoid. The method of generating an orthometric height from the ellipsoid height used by traditional differential GPS differs from that used by a CORSnet system.

The problems associated with GNSS heights and the AHD discussed so far were, in the past, largely masked by differential GNSS techniques. More recent techniques using continuously operating reference stations suffer greater errors as a result of the AHD and AUSGeoid98 anomalies.

In traditional base and rover GNSS surveys, a temporary base is set up over an established mark by the operator. The published AHD height of this mark is converted to an ellipsoidal height using the geoid model. The ellipsoidal height of the rover is computed and converted back to AHD using the same geoid model as shown in Figure 2.11 part (a). Thus the resulting AHD height is generated only using the gradient of the geoid model between the two points. Discrepancies between the geoid model and the AHD base (zero AHD) that may result in an offset between the two surfaces are not realised.

When CORS GNSS is used, the ellipsoidal height of the base (in this case the CORS reference station) is precisely calculated. The ellipsoidal height of the rover is calculated by RTK or post processing techniques and the N value of the geoid is used to convert this height to an orthometric height. As the correction for ellipsoid to geoid separation is only used once, discrepancies between the geoid model and the AHD base are realised (Janssen & Watson, 2011) as shown in Figure 2.11 part (b) below.

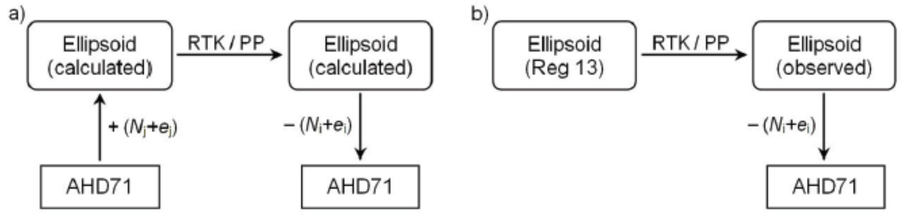

Figure 2: GNSS height transfer methodology using RTK or post processing (PP) in the past (a) and using CORS (b).

Figure 2.11-GNSS height calculation (Janssen & Watson, 2001 p29)

Projections indicate that the surveying industry will be a minority user of the CORSnet system (Janssen & McElroy 2011). Most users will come from industries such as GIS, agriculture, mining or communications, and as such will have a greater dependence on the absolute heights and coordinates generated by these systems. This has prompted initiatives aimed at improving height determination using single rover GPS systems.

2.9 AUSGeoid09

In March 2011, Geoscience Australia released AUSGeoid09. It has been developed to allow heights generated by GNSS equipment to better represent the AHD. This section will look at the development of the new geoid.

Previous Australian geoid models, including AUSGeoid98 are purely gravity based models. AUSgeoid09 differs from previous models in that it comprises two components, gravimetric and geometric.

a) Gravimetric Component

The reference field for AUSGeoid09 is the Earth Gravity Model 2008. Point quasigeoid heights were computed on a 1’x1’ grid relative to GRS80 ellipsoid so as to be compatible with GDA94. The gravimetric component uses the July 2009 land gravity data release from Geoscience Australia, which contains 1.4 million gravity observations and the 9”x9” GEODATA-DEM9S digital elevation model of Australia (Featherstone 2011). As ship track data around Australia is not reliable, altimeter derived gravity anomalies were used in coastal regions. A full description of the development of the gravimetric quasigeoid known as AGQG2009 can be found in (Featherstone 2011). The gravimetric component is depicted in Figure 2.12.

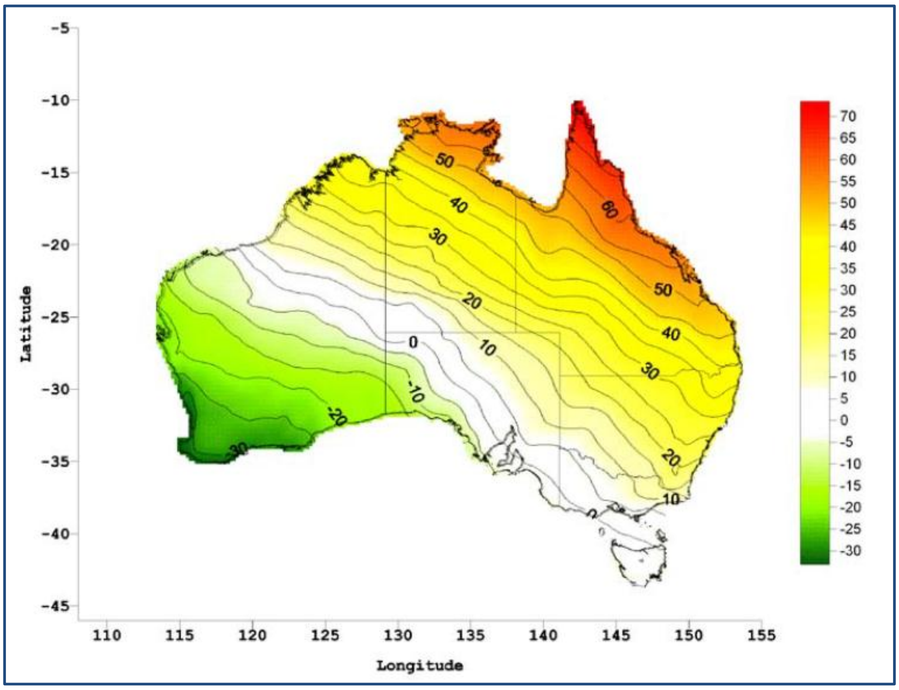

Figure 2.12-The gravimetric component of AUSGeoid09 (Brown, Hu, & Johnston, 2011)

It should be noted that AGQG2009 was developed independently to AUSGeoid09, and is a scientific tool that will not be released to the public. Figure 2.13 shows the difference between the gravimetric quasigeoid model and published AHD heights. The north south slope of the AHD can be seen as well as large localised differences due to levelling errors in the AHD.

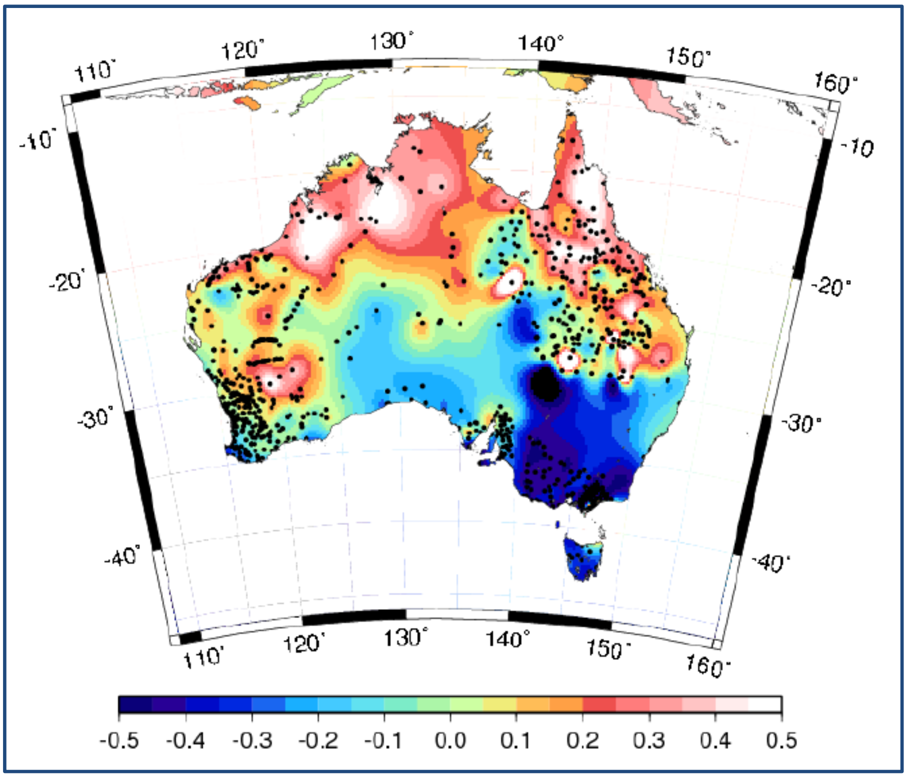

Figure 2.13-Gravimetric quasigeoid to AHD differences (Featherstone W. , 2011)

These differences have been removed by adding a geometric component effectively distorting AGQG2009 to fit published AHD values as described in the next section.

b) Geometric Component

AGQG2009 has been distorted to fit the AHD. This was done even where there are known errors in the ANLN so that GNSS users can employ AUSGeoid09 nationwide to give the best possible fit to the published AHD values (Brown, Hu, & Johnston, 2011).

In total 6794 data points were used to fit the model to the AHD. These comprised of 2561 GNSS-AHD primary points of which the ellipsoidal heights were observed, and a further 4233 secondary point of which the ellipsoidal heights were derived (Featherstone 2011)

To compute the offsets between AGQG2009 and the AHD the AGQG2009 values were bi-linearly interpolated at each of the GNSS-AHD data points. The offsets were LSC-predicted onto the same 1’ x 1’ grid as used by AGQG2009 and algebraically added to produce the combined gravimetric-geometric model (Brown, Hu, & Johnston, 2011). The offsets between the gravimetric and geometric components are shown in Figure 2.14.

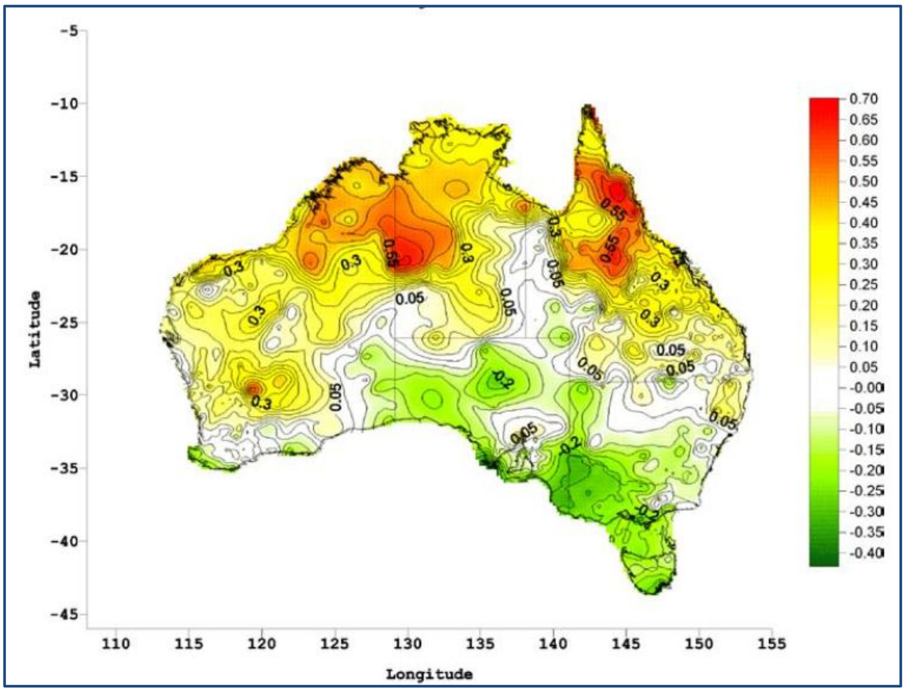

Figure 2.14-The geometric component of AUSGeoid09 (Brown, Hu, & Johnston, 2011).

Rather than omit quality data points for the purpose of checking the model, a method of least square collocation cross validation was used. This involved one point being omitted, and the remaining points used to generate the combined gravimetric and geometric model

The omitted point was then compared to the model for agreement. This was repeated for all the points, and for 9 different correlation lengths of the covariance function. The graph shown in Figure 2.15 plots the RMS value of the differences for each of the nine correlation lengths used.

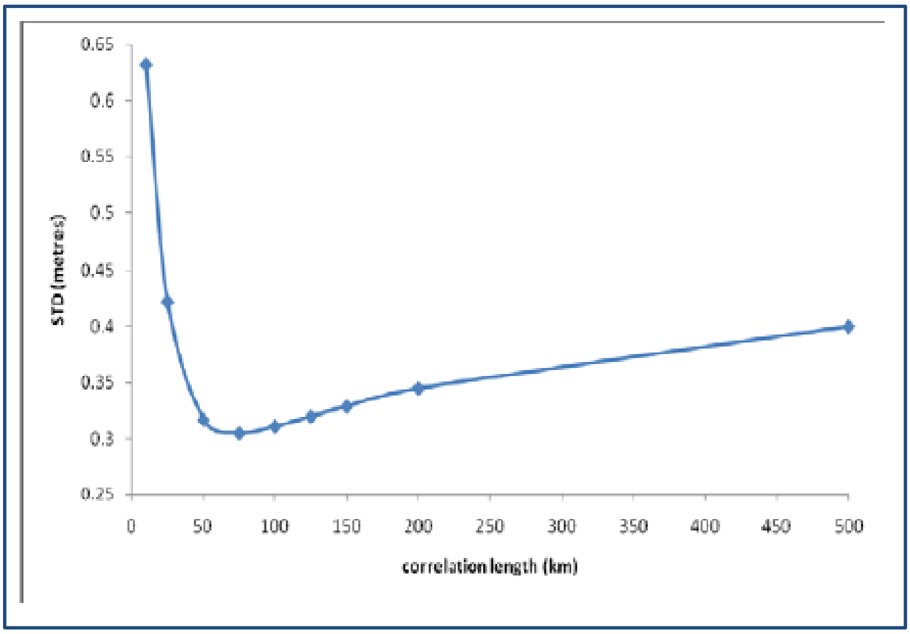

Figure 2.15-Plot of RMS values for each correlation length (Featherstone 2011).

It can be seen that at a correlation length of 75km gives an RMS value of the errors of +/-30mm. A 75km correlation length was adopted for the generation of AUSGeoid09 and this +/-30mm is the RMS referred to in the introduction of this section.

This section has shown how a combination of the gravimetric and geometric components of AUSGeoid09 have resulted in a model that can be used be used by GNSS users to give a significantly better determination of AHD than the purely gravimetric AUSGeoid98. This is because AUSGeoid09 is not a true geoid model. It is a surface that has been designed to represent zero AHD and as such orthometric heights generated by its use should coincide with AHD heights.

It was stated that a least square collocation cross validation was used so that points used to construct the model were not used to verify the model (Featherstone 2011). While this is true in as much as each model created was independent of the point later used to test for fit, the fact remains that the +/-30mm stated here can only apply to the 6794 points used to fit AGQG2009 to the AHD. Further to this, Figure 2.16 shows the differences between AUSGeoid09 derived heights and the ANLN AHD heights for the GNSS-AHD points used in the geometric component generation. It can be seen that even within this dataset differences can be found well beyond the RMS figure quoted.

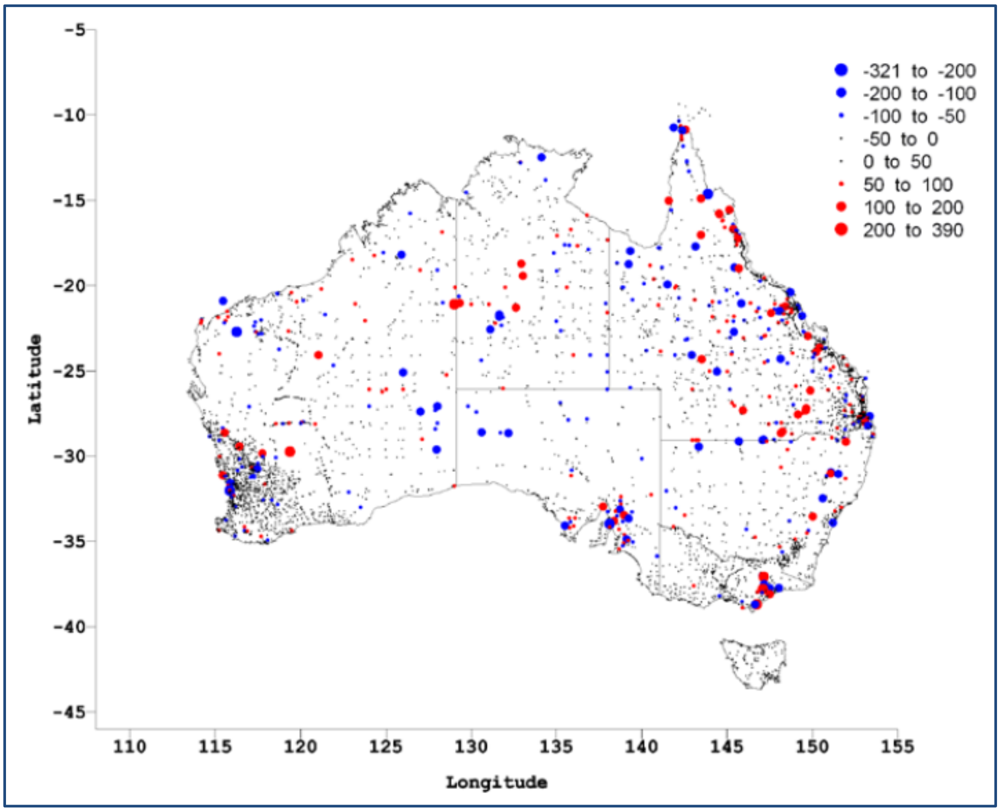

Figure 2.16-Misfit plot of AUSGeoid09 heights (Brown, Hu, & Johnston, 2011)

These points highlight the fact that there are areas where significant differences are known to exist and there may still be areas of unknown differences. This supports the notion that continued validation of the new model, particularly in mountainous and remote areas where data is scarce, should be conducted. Further validation of the model has been conducted in NSW and this will be discussed in the following chapter.

2.10 Current validation of AUSGeoid09 in NSW

Four tests have been performed by the NSW Land and Property Management Authority (LPMA) to assess the performance of AUSGeoid09 in NSW:

a) AUSPOS solutions
b) CORSnet NSW sites
c) Constrained 3D network adjustment fit

d) Minimally constrained 3D network adjustment fit

a) AUSPOS solutions

The ellipsoidal heights of 513 AUSPOS solutions of established benchmarks with accurate AHD heights were determined. The AUSGeoid98 and AUSGeoid09 N values were interpolated and the resultant AHD values compared to published values. As the differences vary from positive to negative, the root mean square (RMS) is used to quantify the differences. The RMS of r residuals (r_1-r_n) is calculated as shown:

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} r_i{}^2}{n}}$$

Figure-2.17-RMS calculation

The RMS went from 0.185m to 0.069m when AUSGeoid09 N values were used. This result may contain some bias as around 100 of the AUSPOS positions used in the comparison were also used in the determination of the geometric component of AUSGeoid09 (Janssen & Watson, 2011).

b) CORSnet NSW sites

A similar test was conducted using 38 CORSnet sites and accurate AHD heights brought in by local tie surveys. Again the RMS values dropped from 0.176m using AUSGeoid98 to 0.043m using AUSGeoid09 (Janssen & Watson, 2011). The better result can be attributed to improved GNSS processing methods used in this test.

c) Constrained 3D network adjustment fit

To test the relative performance of the geoid model as it would be employed in more traditional differential surveys, seven different adjustments of height control points we adjusted and held constrained to their accurate AHD heights. The resulting variance factor and flagged residuals were analysed as an indication of the overall fit. The seven adjustments were chosen to represent different sized adjustment areas giving average baseline lengths of 2km to 130km and height differences of up to 2200m. The smaller adjustments showed significant improvement while the larger adjustments showed minimal improvement, although it is suspected that this is due to distance dependant errors rather than errors in the geoid model (Janssen & Watson, 2011).

d) Minimally constrained 3D network adjustment fit

A final test was conducted using the same data set as the previous test only this time the adjustments were held fixed at one central position and the others were unconstrained. The adjusted heights of the network were compared to the known values of the points and the residuals were analysed. In most cases the accuracy of the AUSGeoid09 results were within the expected accuracy of +/-0.05m stated by Geoscience Australia (Janssen, Watson & McElroy 2010) with the exception of two cases.

Adjustment 6 showed average differences of +/-0.09m and adjustment 7 showed +/-0.14m. The area covered by these adjustments is shown in Figure 2.18.

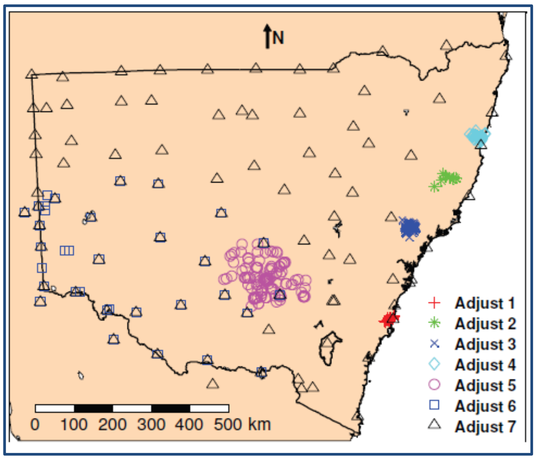

Figure 2.18-The seven adjustment datasets (Janssen, Watson & McElroy 2010)

> Network No 6 and No 7 adjustments covered areas with baselines of up to 390km. These baselines were processed with older software having limited modelling options. In addition, distortions in the AHD are worse over longer distances (Janssen, Watson & McElroy 2010).

This section has examined the four tests that the NSW Land and Property Management Authority has conducted investigating the performance of AUSGeoid09 in NSW. The tests show that in most areas AHD height determination using AUSGeoid09 provides a significant improvement over AUSGeoid98, with the exception of long distance relative tests, although the results of these tests are not conclusive. Generally, the heights derived using AUSGeoid09 will fall within the +/-0.05m stated by Geoscience Australia.

The LPMA has adopted AUSGeoid09 for all operations, and suggests all spatial professionals do the same (Janssen & Watson, 2011). The comparison of AUSGeoid09 and AUSGeoid98 should confirm that AUSGeoid09 is the preferable model to use within the test area.

2.11 Conclusion

This chapter has examined basic geodesy and explored different geodetic levelling systems. An understanding of the relationship between the AHD level system, its method of production, and GNSS heights has revealed that it is unlikely that any purely gravimetric model will accurately generate AHD heights. The likelihood of the purely gravimetric AUSGeoid98 generating accurate AHD heights is further lessened by the problems associated with its production. The new era of single rover GNSS systems coupled with an increasing diversity of users has prompted the need for a geoid model that better represents the AHD. AUSGeoid09 has been produced with an empirically derived geometric component that accounts for the errors in the AHD.

Consideration of this literature has shown that AUSGeoid09 does give a significantly better determination of AHD heights however there are still some areas of known misfit and the possibility of unknown areas of misfit. Differences could be attributed to local variations in gravity that are not represented in the data used to generate AUSGeoid09, or in AHD errors due to the height system chosen, initial levelling or settling of the aging network.

It has also been shown that the majority of the testing done during the production of the model and since its release was done on a nation or state wide basis. Although state and territory authorities have been notified of the known AHD misfits (Brown, Hu, & Johnston, 2011), there is not an abundance of information available to private users relating to the specific areas of misfit. This highlights the need for individual users to verify the performance and limitations of AUSGeoid09 so that informed decisions can be made regarding its use.

CHAPTER 3

METHOD

3.1 Introduction

This chapter will describe the method used to compare AUSGeoid09 and AUSGeoid98 with the objective of gaining a better understanding of the performance and limitations of AUSGeoid09 and AUSGeoid98.

In order to compare the two geoid models and assess the performance of AUSGeoid09 and AUSGeoid98 a method of comparison was designed. This included a standard for comparison, field measurements against this standard and validation of these measurements. Finally a method of analysing the results was devised and carried out.

These objectives were achieved by selecting a test area that was representative of the local region within which the two geoid models could be tested. Inside this test area suitable established AHD benchmarks were selected to be used as a standard for comparison. The precision and accuracy of the field measurements was assessed to ensure the field measurements would yield meaningful and reliable results. Two methods of measurements were chosen to simulate typical field measurements.

The field measurements were used in an absolute test that directly compared the orthometric heights generated by AUSGeoid09 and AUSGeoid98 against the published AHD height of the established marks. A second test was devised to test the gradient of AUSGeoid09 and AUSGeoid98 over a particular section of the Great Dividing Range escarpment.

3.2 The test area

This study encompasses an area of approximately 300 square kilometres, which is centred on the township of Grose Vale, NSW. Grose Vale is a small rural town about 57km northwest of Sydney. It has the Grose River to the south, Hawkesbury River to the east and is bound by the Great Dividing Range to the west as shown by Figure 3.1.

Figure 3.1-The test area (image source Google Earth 2011)

The test area runs from the towns of Richmond and Penrith west across the flood plains of the Hawkesbury River and into the escarpment of the Great Dividing Range as far as the towns of Springwood and Bilpin. The purpose of this study is to compare the two geoid models under typical survey conditions employed by the survey company. The Hawkesbury valley in which the typical surveys are conducted is well represented by the features contained within this site. The Hawkesbury River (starting as the Nepean River to the south of the test area) runs along the escarpment of the Great Dividing Range for the majority of the region, thus a large percentage of the surveys undertaken in the area can be categorised as being either on the Hawkesbury River flood plains or on the escarpment of the Great Dividing Range. Exceptions to this are surveys undertaken further into the Great Dividing Range clear of the rapid rise in elevation found along the escarpment, and surveys undertaken to the far north where the Hawkesbury River runs into the more rugged regions around the Wisemans Ferry crossing. These areas have not been considered in this study.

The area chosen was of particular interest because it contained two strips of development that reached up the escarpment. From Penrith the Great

Western Highway heads west towards Katoomba and from Richmond Bells Line of Road heads west towards Lithgow. As shown in Chapter 2 any geoid to AHD base discrepancies within the region are most likely to occur in mountainous areas. For this reason it was important to include the escarpment in this study. It was noted that the AUSGeoid09 quasigeoid was difficult to model in mountainous regions (Brown, Hu, & Johnston, 2011), so it follows that there is a higher likelihood of error in the escarpment area. Although a regular grid pattern was not able to be achieved along the escarpment the areas of development provided established benchmarks of suitable accuracy and density to test the geoid models in this area.

The test area is well serviced by CORSnet NSW reference stations as shown in Figure 3.2. This typifies the network configuration encountered during most surveys undertaken by the company. It is envisaged that the geometry of the reference stations will provide measurements consistent with the results of the validation tests.

Figure 3.2-Circles indicate 50km operating range of CORSnet reference stations. The Putty and Lithgow reference stations have become operational since this publication (image source Department of Lands 2009)

3.3 Established AHD marks adopted

The NSW Land and Property Management Authority is responsible for the management of NSW state survey marks. Marks are assigned an estimation of accuracy based on adjustments relative to surrounding marks in the network. AUSGeoid09 was generated using marks of predominantly Class LC or higher (Brown, Hu, & Johnston, 2011) so only marks of class LC or better were used in this study. This consisted of a combination of state

Permanent Marks, State Survey Marks and several Trigonometric Stations. Typical marks are shown in Figure 3.3.

Figure 3.3-Class LC or higher permanent marks used in study

AUSGeoid09 is produced on a 1’x1’ grid which equates to about 1.8km on the ground. Where practical marks were chosen at this spacing however this was not always possible. In total 33 established marks were used in this study as listed in appendix B.

3.4 The test equipment

When considering previous studies of geoid models it was noted that they were undertaken using either static differential GPS (Gibbings & McDonald, 2005) or a combination of static, AUSPOS and CORSnet solutions (Janssen & Watson, 2011). With the resources available for this study, static and AUSPOS solutions could not be practically completed. CORSnet solutions are only suitable for a large statewide study whereas this study is focussed on a relatively small region. In addition, the study aims to test the performance of the geoid models under typical survey conditions. The GNSS surveys being considered are undertaken with a Leica 1200 system single rover CORSnet GNSS unit. To satisfy the objectives of the study, and for the convenience of availability, this equipment was chosen. The equipment is a standard survey grade GNSS with no modifications. Any similar system could have been used and for this reason it will not be discussed in detail. Only the precision and accuracy of the equipment has any significance to this study so an assessment of these parameters was conducted (refer 3.5).

Figure 3.4-The Leica 1200 system

The Leica 1200 system GNSS unit consists of three major components.

a) ATX1230+ GNSS antenna-A triple frequency antenna using GPS L1, L2 and L5 and Glonass L1 and L2 bands.

b) RX 1250X controller-Controller configured for RTK operation using CORSnet NSW corrections.

c) 3G Telit modem-A 3G modem-Telit is a London based company that specialises in wireless communication systems. The Modem houses a standard sim card and receives RTK data via a 3G wireless internet connection.

3.5 Validation of the test equipment

Validation of the test equipment involved determining the precision and accuracy of the test equipment. Precision can be described as a measure of the spread of a set of measurements, while accuracy is the closeness of the measurements to the known or most probable value.

These parameters were determined to establish that the equipment could produce meaningful results within the context of the study and to allow possible errors in the AUSGeoid09 and AUSGeoid98 models to be distinguished from expected deviations in the measurements.

As stated earlier, any orthometric height generated using single rover RTK equipment relies upon the N value of a geoid model being used (Janssen & Watson, 2011). For this reason, the accuracy of the instrument could not be assessed against a known AHD height as any orthometric height derived by the instrument would have used the model being tested. In addition to differences caused by any discrepancy between the geoid model and the AHD base, an AHD to orthometric height comparison would have included the error budgets of the initial AHD levelling and any possible disturbance of the mark since its establishment. To overcome these problems the raw ellipsoidal height observed by the instrument was compared to a known independently derived ellipsoidal height.

Each CORSnet NSW reference station has an ellipsoidal height that carries a current Regulation 13 certificate. These certificates are issued by Geoscience Australia and guarantee the standard of the coordinates of the reference station. They are issued for horizontal coordinates and ellipsoidal heights and state the level of uncertainty associated with those coordinates. This allowed the ellipsoidal height of the reference station to be used as an independent and verified value. The springwood reference station was chosen, and the ellipsoidal height transferred by trigonometric heighting to an arbitrary station that could be occupied.

It is widely accepted that network solutions are superior to single reference station RTK solutions (Janssen, Watson & McElroy 2011), although there is some evidence that at close range single reference station RTK solutions may deliver better results (Edwards et al. 2008). As reference station to survey distances usually exceed 10km in surveys undertaken in the area of this study NRTK solutions have been used.

Two data sets containing 30 measurements were collected. One set of 5 second weighted average occupations using a hand help pole and another of 3 minute weighted average occupations using a tripod. These two observation times were taken to simulate a 5 epoch observation taken during a typical topographic survey. This is a standard used by a local company to reduce the effect of outlying observations. No standard had been established by the company regarding the occupation method to be used when establishing a more accurate level, such as a bench marks used for a mean high water definition in a remote location. Opinions vary on the occupation optimal time and technique for such a survey from 60 second window observations separated by 20-40 minutes (Janssen, Watson & McElroy 2011) to 3 minute window observations separated by 40-45 minutes (Leica-Geosystems, 2009). While a 3 minute occupation separated by 45 minutes is easily achieved in practice it was decided to use one 3 minute occupation for this study as it is suggested that the gains made by separated occupations may only be in the order of 5-10mm and as such would not be significant when considered in the context of this study (Edwards et al. 2008).

Figure 3.5 shows the individual observation deviation from the mean of the two datasets.

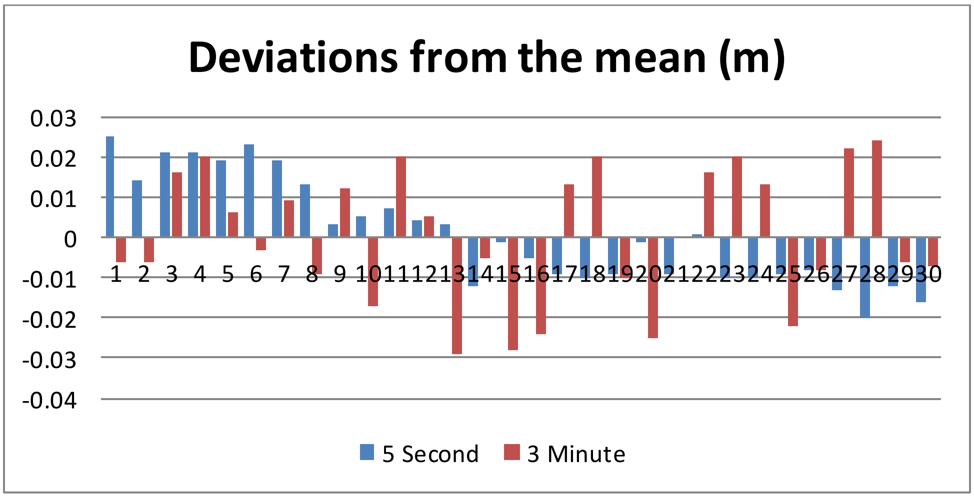

Figure 3.5-Plot of verification observations

This resulted in standard deviations of +/-0.012m for the 5 second observations and +/-0.015m for the 3 minute observations. The mean of the 5 second data set fell 0.07m below the published ellipsoidal height of the CORSnet antenna while the mean of the 3 minute observations fell 0.063m below the published height.

This confirmed that the instrument was of sufficient precision to detect differences in the AHD heights outside the stated value of +/-0.05m however the accuracy of the instrument appeared too low to be suitable for this study.

A more detailed analysis of these results revealed possible weaknesses in the validation test. The higher precision of the 5 second occupations is at odds with the expected results. This could possibly be due to the close proximity of the test to the reference station, giving optimistic results for the short occupation measurements. In addition, the aim of this study is to test the geoid under typical survey conditions. One of the problems with GNSS measurements is the fact that there is no way to guarantee that results of a particular standard at a particular place and time will be repeated elsewhere at another time (Featherstone et al. 2001). So it follows that the validation should be done in a location similar to that of typical survey conditions. The closeness of the test to the reference station was not consistent with this objective.

Furthermore the offset from the antenna reference point to the protective shroud could only be given to an approximate value of +/-0.03m as shown in Figure 3.6.

No records were kept regarding the exact position of the protective housing.

Figure 3.6-Springwood reference station.

This uncertainty combined with the +/-0.054m error budget of the Regulation 13 ellipsoidal height of the reference station meant that the uncertainty of the known ellipsoidal height was most probably beyond the accuracy of the instrument being tested and could account for the apparent low accuracy of the instrument.

A second test was devised to confirm the results of the initial test. A concrete filled pillar (Figure 3.7) has been placed in a position better representing reference station to rover distances and typical survey conditions.

AUSPOS coordinates were established on this pillar and used to verify the instrument

Figure 3.7-Test pillar

Around 6 hours of static data was recorded and reduced using the AUSPOS service (Geoscience Australia) to establish an ellipsoidal height. The same tests as described earlier were undertaken again using this pillar.

3.6 Field measurements

Two types of measurements were taken to simulate the two measurement types described earlier. This involved a 5 second pole mounted measurement and a tripod mounted 3 minute occupation of each mark selected for the study. Measurements were taken using NRTK corrections. Around 5 marks were occupied each field day. This was done firstly using AUSGeoid09 set as the default geoid model allowing the interpolation program in the instrument to generate N values for each model. Once all marks for that day had been occupied each mark was reoccupied using AUSGeoid98. This effectively separated each measurement on the same mark by 20 minutes or more. This was done to provide independent measurements (Janssen, Watson & McElroy 2011) that could be used to cross check the results. This was necessary because the NRTK measurements have to be considered single radiations from the reference station.

The cross check was done by comparing the differences between the two independent ellipsoidal heights taken at each mark. It can be said that each measurement could vary by up to + or – one 95% confidence interval from the most probable value and not be considered an erroneous measurement. The 95% confidence interval established for the precision of the measurements was used. Thus if one measurement was at + the 95% confidence interval and the other at – the 95% confidence interval from the most probable value, their values would differ by twice the 95% confidence interval without either being considered an outlying measurement. On this basis any two measurements that differed by more than twice the 95% confidence interval were flagged as possible outlying measurements. Without knowledge of the most probable value it could not be established which of the two measurements was in error. Once an estimation of the expected values had been determined by any trends in the data the erroneous measurement could be identified. It is noted that two independent measurements that were in error in the same direction from the most probable value could not be detected.

Another method of recording the field data was considered that involved taking one measurement to record and ellipsoidal height then applying the N value as interpolated at each point to derive the AHD value for each model (Gibbings & McDonald, 2005). This is a more effective method if the observed heights are part of an adjusted network. As each measurement in this study is effectively a single radiation the only advantage would be to remove measurement uncertainty from the two values obtained for each model at each mark. It was decided that as the measurement error would be accounted for when analysing the results this was not necessary. Figure 3.8 illustrates the setup for each type of occupation.

Figure 3.8-The two measurement types

A third set of measurements was taken to provide data for a relative test of the geoid gradients across an area of the escarpment. This involved a 3 minute occupation of 9 marks along a selected route across the escarpment. So that a base line could be established NTRIP corrections for these measurements were set use the Mulgrave reference station rather than a network solution.

Due consideration was given to the coordinate quality indicators during all occupations. The Leica 1200 system CQ indicator (coordinate quality) is calculated as the RMS of coordinate errors based on ambiguity fixed double differenced observations, and indicates how much the computed position is likely to deviate from the true value (Leica-Geosystems, 2009). Two values are given for horizontal and vertical coordinates. CQ values were set to a value of 0.05m based on the manufactures specifications, thus outlying measurements were filtered out in the field as would be the case under typical conditions. The CQ indicator is only a measure of precision derived by the internal least square theory of the computed position and not the absolute accuracy of the measurement (Featherstone & Stewart, 2001). It was also noted that these indicators have been found to be optimistic at times (Janssen, Watson & McElroy 2011), & (Edwards et al. 2008), particularly when satellite availability is poor or multipath conditions are encountered. To reduce possibility of outlying measurements not being detected by the CQ filter good sky visibility was maintained for all the measurements. If conditions were not favourable the height was transferred to an arbitrary station nearby to ensure consistency in this regard. These measurements are denoted by the suffix OS in the primary data set (Appendix D).

With the aim of this study in mind it can be seen that the primary focus is on the measurement of height. The horizontal coordinates were recorded for completeness of the records. The CQ values were also recorded to allow some form of quality control on the measurements, although as discussed, the CQ indicator has limited value.

3.7 Conclusion

This chapter has established the method that was used to compare AUSGeoid09 and AUSgeoid98.

A method of comparison was designed that can be summarised as follows:

a) The test area was chosen as it encompassed the major geographical features encountered within the region and importantly the escarpment of The Great Dividing Range

b) Established marks of class LC or better would be used to maintain consistency with the marks used in the production of AUSGeoid09

c) The Leica 1200 system GNSS was chosen for availability and to typify standard surveys undertaken in the area

d) The equipment was validated to ensure it could produce meaningful results within the context of the study

e) 5 second occupations were chosen to simulate topographic survey measurements and 3 minute weighted average occupations were chosen to simulate the establishment of an AHD bench mark. A further 9 marks were occupied using a single reference station correction to relatively test the geoid models in a particular area of the escarpment

f) Vertical CQ filter set to 0.05m based on manufacture specifications however consideration would still need to be given to any possible outlying measurements not detected by the filter. Reasonable sky view was maintained for all measurements

g) The results were used in an absolute comparison of the resulting GNSS heights from both models against established AHD heights and an relative test to analyse the gradients of geoid models in a particular area of the escarpment

The measurements were taken using the methods previously described over a period of several months. The results of these measurements are presented in the following chapter.

CHAPTER 4

RESULTS

4.1 INTRODUCTION

This chapter briefly sets out the field measurements in a way that allows analysis of the results from which conclusions can be drawn and trends in the performance of the geoid models identified.

The results are structured so that comparisons can be made between the results of this study the existing broad scale assessments of AUSGeoid09. Particular attention has been given to the measurements located along the escarpment of the Great Dividing Range.

This chapter will list summaries of the results of the field measurements along with explanations of the processes used to derive them. The field method chosen to compare AUSGeoid09 and AUSGoid98 resulted in four sets of data for the absolute test and one set for the relative test. The two categories of assessment reported by the literature were an absolute test where the AHD height generated by the instrument is compared to the known AHD height of that mark, and a relative test where the gradient of the geoid is used to generate height differences between two points. The absolute test involves a simple quantification of the differences between GNSS generated AHD heights and the published AHD heights using the root mean square of the differences. A relative test has been designed that assesses the gradients of the two geoid models over a particular area of interest by utilising the Mulgrave reference station as a base station in a approach similar to that used in traditional differential surveys.

A detailed analysis of the results will be undertaken in Chapter 5. Only a summary of the primary results will be shown here along with results of the instrument validation and measurement cross validation.

4.2 Validation results

Data at the test pillar (refer section 3.5) was collected for approximately 6 hours and processed using the Geoscience Australia AUSPOS service. An abstract of the report is contained in Appendix F. The derived coordinates are shown in Figure 4.1 and the ellipsoidal height has an estimated precision of 0.005m (1σ).

Station	Latitude (DMS)	Longitude (DMS)	Ellipsoidal Height(m)	Derived AHD (m)
1__	-33 41 18.46283	150 32 06.59607	480.344	456.089

Figure 4.1-AUSPOS results for test pillar.

The two initial 5 second and 3 minute tests were repeated at the concrete pillar to confirm the initial results. The deviations from the mean (a measure of precision) are plotted in Figure 4.2 and the deviations from the AUSPOS derived ellipsoidal height (a measure of accuracy) are shown in Figure 4.3.

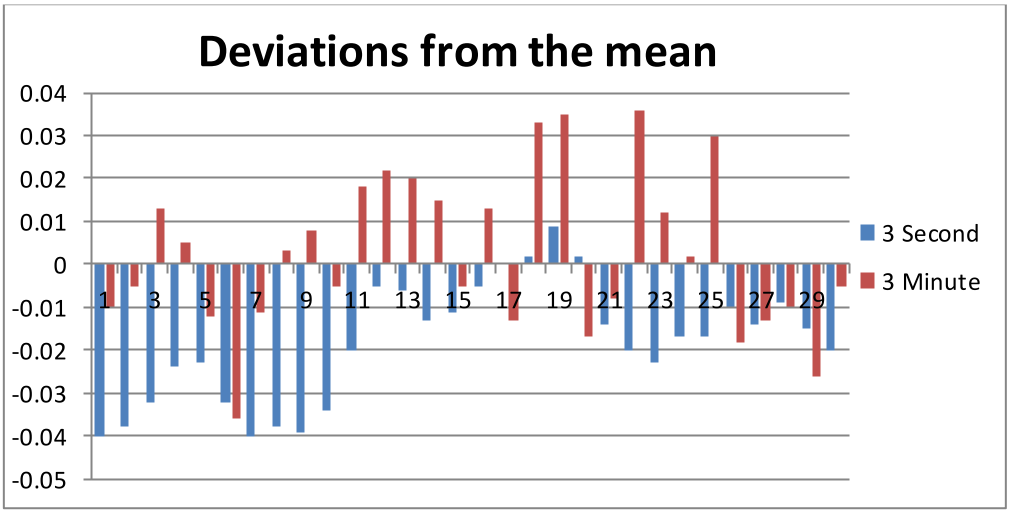

Table 4.2-Deviations of individual observations from the mean of the observations

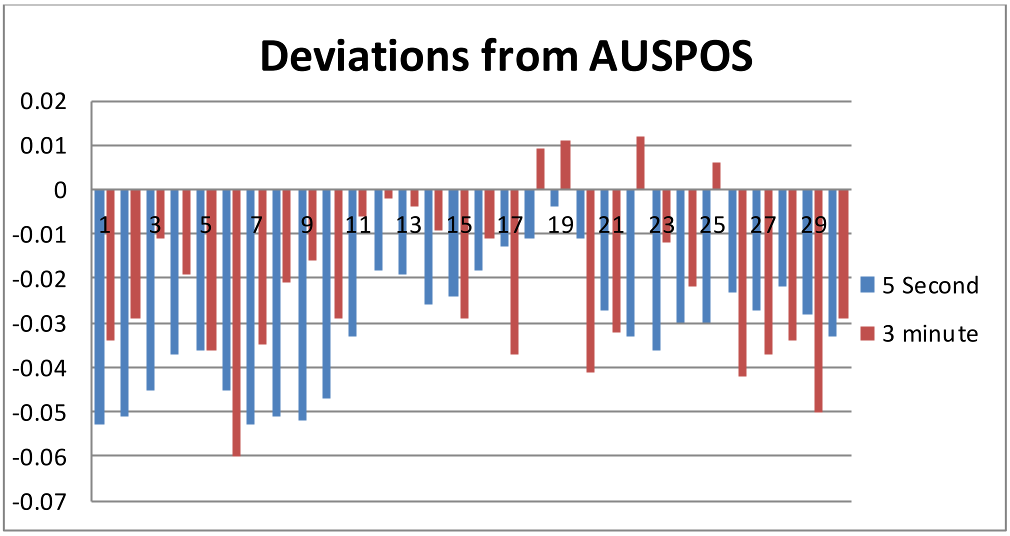

Table 4.3-Deviations of individual observations from the AUSPOS ellipsoidal height

The following results were derived using Student's t Distribution curve and show the expected precision of the measurements.

Measurement	Standard Deviation	95% confidence int.
5 Second	0.014m	+/- 0.029m
3 Minute	0.018m	+/- 0.036m

Table 4.4-Expected precision of the measurements

The following table shows the variation of the mean of the 30 measurements from the AUSPOS ellipsoidal height.

Measurement	Difference from AUSPOS
5 Second	-0.031m
3 Minute	-0.021m

Table 4.5-Expected accuracy of the measurements

4.3 Cross validation

Single rover CORSnet measurements must be treated as radiations to a point and as such an adjusted network could not be formed to check the integrity of the measurements. Each measurement could not be proven by a comparison between the measured and published AHD heights as the accuracy of the GNSS derived AHD height is being questioned by this study. As described earlier a set of redundant ellipsoidal heights have been recorded for each of the marks used in the study so that gross errors in measurements can be identified. The differences between the two measurements at each established AHD benchmark have been plotted in Figure 4.6 and 4.7.

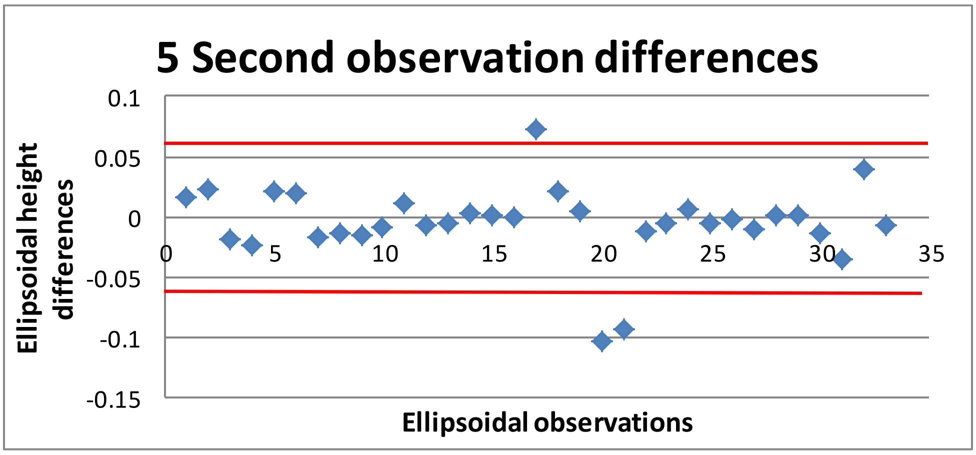

Figure 4.6-Differences between 5 second observation ellipsoidal heights. The horizontal lines represent the 95% confidence interval

Three observations can be seen to be outside the estimated precision. These have been identified as those at PM 81682, PM 9776 and PM 44012.

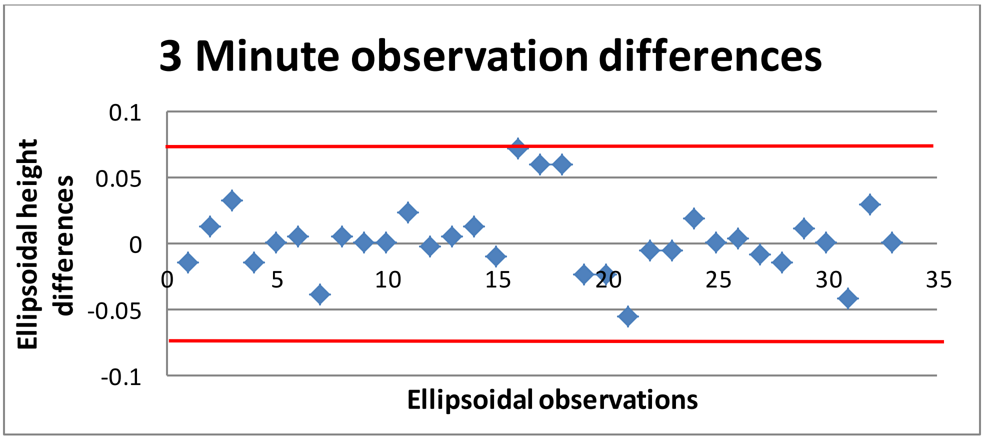

Figure 4.7-Differences between 3 minute observation ellipsoidal heights. The horizontal lines represent the 95% confidence interval

It can be seen that none of the 3 minute observations fell outside the estimated precision.

4.4 Absolute test

The RMS as described in Chapter 1 by Janssen & Watson (2010) is a simple method of quantifying the average of both positive and negative values. It is used in the context of this study to show the average fit of the measured values over the entire test area.

For each of the datasets the RMS was calculated for the height deviations. Thus using the formula shown in figure 4.8 below:

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} {r_i}^2}{n}}$$

Figure 4.8-The root mean square

Where r_i is the difference between the published value of the mark and the measured value, the RMS values for each dataset was calculated as shown in Table 4.9.

Test	RMS
5 second AUSGeoid98	0.142m
5 second AUSGeoid09 I	0.053m
3 minute AUSGeoid98	0.142m
3 minute AUSGeoid09	0.051m

Table 4.9-RMS values of absolute test

It should be noted that these results have been generated from the raw data. Possible outliners have not been filtered out. The identification of outliners and their effects on the results will be discussed in Chapter 5.

4.5 Relative test

An abridged relative test has been generated using the CORSnet NSW reference station as a fixed base station to simulate a traditional differential GNSS survey. The Mulgrave reference station was the sole source of RTK corrections for these measurements allowing each measurement to be treated as a base line from that reference station of which the relative performance of the geoid was tested.

This test was used to assess the gradient of the geoid models across the escarpment of the Great Dividing Range. 9 established marks were chosen in a line heading approximately west from the town of Kurmond towards Kurrajong Heights. This area was chosen because it was identified by the absolute test as an area where the degree of agreement between GNSS derived AHD heights and published AHD heights varied.

As described by Janssen & Watson (2011) traditional differential GNSS surveys use a base set up on a mark of known height. The N value is used to calculate an ellipsoidal height of the GNSS base receiver. Corrections based on this calculated ellipsoidal height are used to correct the observed ellipsoidal height of the rover. The N value at the rover is then used to convert the calculated ellipsoidal height back to an orthometric height (refer Figure 2.11a). The Mulgrave reference station was chosen as the base station for which the following information was obtained from the SCIMS report (Appendix F), the CORSNet NSW Regulation 13 certificate (Appendix E) and Geoscience Australia.

Mulgrave Reference Station

Regulation 13 ellipsoidal height: 45.243m

N value AUSGeoid09 (SCIMS): 23.897m

N value AUSGeoid98 (derived using Winter interpolation software and Geoscience Australia AUSGeoid98 Grid files): 24.09m

AHD (By local tie survey Class A order 1): 21.265m

Based on this information it can be seen that in a traditional differential survey using the Mulgrave station as a base, the calculated ellipsoidal height using AUSGeoid09 would be 45.162m (21.265+23.897). As the Mulgrave reference station's published Regulation 13 ellipsoidal height is 45.243 all ellipsoidal heights observed by the rover were corrected by -0.081m. Similarly using AUSGeoid98 all ellipsoidal heights observed by the rover were corrected by +0.112. These ellipsoidal height corrections were applied to the 9 gradient test measurements and the N value of each geoid model was then used to convert the corrected ellipsoidal height back to an orthometric height. N values for AUSGeoid09 were taken from SCIMS reports and N values for AUSGeoid98 were calculated using Winter interpolation software and Geoscience Australia AUSGeoid98 Grid files.

This supposition is supported by Featherstone et al. (1998) who show that a change in orthometric height using ellipsoidal heights and a geoid model can be calculated by the formula shown in Figure 4.10.

$$\Delta H_{AB} = \Delta h_{AB} - \Delta N_{AB}$$

Figure 4.10-Change in orthometric height over a GNSS baseline A-B (Featherstone, Dentith, & Kirby, 1998)

The ICMS class LC allowable misclose has been shown and is based on the relationship:

$$r = c\sqrt{d}$$

Where c has been defined as 12 and d is the separation of the base and rover in km (ICMS 2007). The results of the relative tests are shown in Table 4.11 and 4.12.

Code	Calculated Ellipsoidal height	AUSGeoid 09 N value	Derived AHD	AHD Diff	Class LC allowable misclose
PM 32950	574.534	24.769	549.765	-0.017	0.056m
PM 45003	473.52	24.689	448.831	0.012	0.053m
PM 45502	271.142	24.62	246.522	0.054	0.052m
PM 81032	235.615	24.589	211.026	-0.008	0.052m
PM 45501	211.436	24.569	186.867	0.021	0.050m
PM 81028	161.047	24.524	136.523	0.108	0.049m
SS 26262	172.123	24.474	147.649	0.058	0.048m
SS 18781	157.908	24.447	133.461	0.004	0.046m
PM 81573	122.113	24.417	97.696	0.041	0.044m

Table 4.11-Relative test of AUSGeoid09

The RMS value for the AHD differences shown in the AUSGeoid09 relative test is 0.051m

Code	Calculated Ellipsoidal height	AUSGeoid 98 N value	Derived AHD	AHD Diff	Class LC allowable misclose
PM 32950	574.727	24.899	549.828	-0.08	0.056m
PM 45003	473.713	24.823	448.89	-0.047	0.053m
PM 45502	271.335	24.774	246.561	0.015	0.052m
PM 81032	235.808	24.748	211.06	-0.042	0.052m
PM 45501	211.629	24.733	186.896	-0.008	0.05m
PM 81028	161.24	24.698	136.542	0.089	0.049m
SS 26262	172.316	24.655	147.661	0.046	0.048m
SS 18781	158.101	24.625	133.476	-0.011	0.046m
PM 81573	122.306	24.601	97.705	0.032	0.044m

Table 4.12-Relative test of AUSGeoid98

The RMS value for the AHD differences shown in the AUSGeoid98 relative test is 0.049m

4.6 Conclusion

The results of the field measurements have been presented in a way that allows analysis of the results from which conclusions can be drawn and trends in the performance of the geoid models identified. The following chapter analyses the data and defines the performance of AUSGeoid09 and AUSGeoid98 within the test area.

CHAPTER 5

DISCUSSION

5.1 Introduction

The results of the various tests have been summarised in the previous chapter. In this chapter the results have been analysed with the principle aim of comparing the orthometric heights generated using AUSGeoid09 and AUSGeoid98 with the published AHD heights of established benchmarks. This was done to assess the performance and limitations of AUSGeoid09 and AUSGeoid98.

Before any conclusions could be drawn from these results the reliability of the test measurements were assessed. To determine if this study confirms the performance of AUSGeoid09 as stated by previous authors in Chapter 2, the results of this study were analysed within the context of the existing AUSGeoid09 validations. It was identified in Chapter 2 that individual AUSGeoid09 users should look beyond the results of the broad scale test previously conducted and assess the performance of AUSGeoid09 more critically in the areas of their own work. Therefore a more detailed analysis was conducted of the height differences taking into account the location of the differences within the test area and relating those positions to features of the test area topography.

The objectives stated above were achieved by first cross checking the test data to identify possible gross errors in the measurements. The absolute test results were then compared to RMS values of the height differences as stated by the LPMA NSW and Geoscience Australia and the level of agreement gauged.

The height differences were plotted against the elevation of the established AHD benchmarks to identify the performance of each geoid across the escarpment area. As possible discrepancies were identified in the escarpment area by the absolute test the relative test was analysed to further the understanding of the behaviour of AUSGeoid09 and AUSGeoid98 in this area.

Finally these individual elements have been considered collectively to compare the performance of AUSGeoid09 and AUSGeoid98 and determine the degree of improvement gained by using a combination of AUSGeoid09 and the methods of measurement detailed in this study and to gain an understanding of the performance and limitations of AUSGeoid09 and AUSGeoid98.

5.2 Instrument validation

The initial estimated precision of the measurements remained largely unchanged by results of the AUSPOS validation. A curiosity of the results is the higher precision of the 5 second observations. Initially this was attributed to the closeness of the test site to the reference station however the AUSPOS test shows the same result. Another possible explanation can be seen in Figure 5.1.

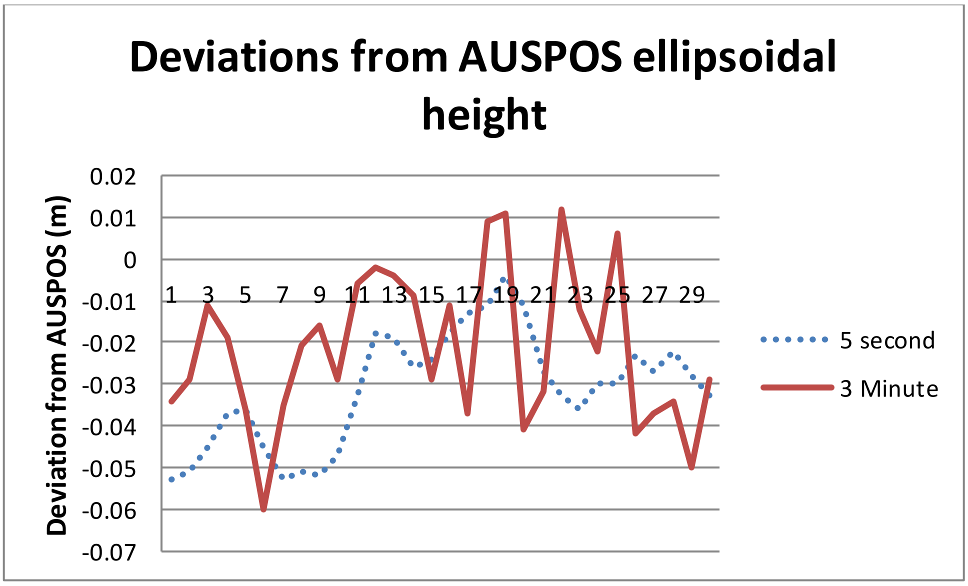

Figure 5.1-Deviation of validation measurements over time. Note that the 5 second plot is over about 2.5 minutes while the 3 minute plot is over about 2 hours

The 5 second observations were recorded continuously with little delay between each measurement. It can be seen that the GNSS measurements tend to gradually drift over time thus the actual spread of such observations may not be fully represented by the 2.5 minute data set. The 2 hour session required to record the 3 minute observations is most probably a better representation of the true spread of the measurements. This could account for the apparently higher precision of the 5 second observations. Janssen, Haasdyk & McElroy (2010) in their assessment of the CORSnet network RTK performance quoted the RMS of the deviation from the mean of the observations as a measure of precision. In a study conducted by these authors 1 second observations taken over 3 days resulted in an RMS of 0.021m. The RMS test applied to the measurements of the 5 second and 3 minute validation data sets of this study gave an RMS of 0.022m and 0.018m respectively, indicating the validation precision results agree with previous studies.

The differences between the mean of the observation ellipsoidal heights and the AUSPOS ellipsoidal height was used as a measure of the accuracy of the instrument. The mean of the 5 second 3 minute observations fell 0.031m and 0.021m below the AUSPOS value respectively. Geoscience Australia suggests accuracies of +/-0.02m are achievable using the AUSPOS service so it can be concluded that the instrument is performing adequately. The higher accuracy of the 3 minute observations was more in line with expectations. The similarity found between the precision and accuracy of the two measurement types resonates throughout the primary data sets.

This validation test demonstrates that the initial validation procedure was misleading and that the GNSS would produce meaningful results within the context of this study.

5.3 Cross validation

Cross validation was performed to test for gross errors in the data sets. The graphs (Figure 4.6 and 4.7) show the absolute differences between each ellipsoidal height measured at the same mark. The horizontal lines represent the maximum difference allowable at the 95% confidence level based on the results of the instrument validation. It was shown that all of the 3 minute measurements fell within allowable tolerances while 3 of the 5 second observation sets have been flagged as possible outliners. These have been identified as those at PM 81682, PM 9776 and PM 44012. As this test is a measure of the absolute differences with no reference to the most probable value it could not be determined at this stage which of the measurements are most likely outside the confidence interval. These measurements were noted and reconsidered once a better understanding of the performance of the geoid models was established.

5.4 Absolute test

The RMS is an overall assessment of the level of fit obtained by each set of measurements. The results for the 5 second and 3 minute tests are practically identical. There is clear evidence that AUSGeoid09 performed significantly better than AUSGeoid98. It should be mentioned here that the accuracy of the established marks have not been considered. As AUSGeoid09 has been developed to fit to the AHD network as it stands (Brown 2010) it was decided that the accuracy of the AHD height would not be dealt with in detail. Limiting the established AHD marks to the same class and order as those used to generate the geometric component of AUSGeoid09 was done to ensure the model was not tested beyond its design parameters. The results of the AUSGeoid09 tests are consistent with those of Brown (2010) and Janssen & Watson (2011). Considering the error budgets of the measurements the RMS values of 0.053m and 0.051m indicated a very good fit for the new geoid. This demonstrates that the empirically derived geometric corrections applied to AUSGeoid09 have successfully improved AHD determination when compared to the purely gravimetric AUSGeoid98.

However this assessment of the geoid models is very general. It does not account for the distribution of individual errors across the test area. The height deviations against the elevation of the marks are shown in the following Figures 5.2 to 5.5. Note that at this stage the possible outlying measurements have not been identified. These graphs clearly demonstrate that while AUSGeoid09 does provide significant improvements in height determination at elevations below about 180m, the agreement between measured and published AHD heights reduces as the elevation rises. This trend is less pronounced in the 3 minute data set. It can be seen that through the same elevation range the agreement for the AUSGeoid98 measurements gradually improves. At elevations of around 400m AUSGeoid98 yielded similar results to AUSGeoid09.

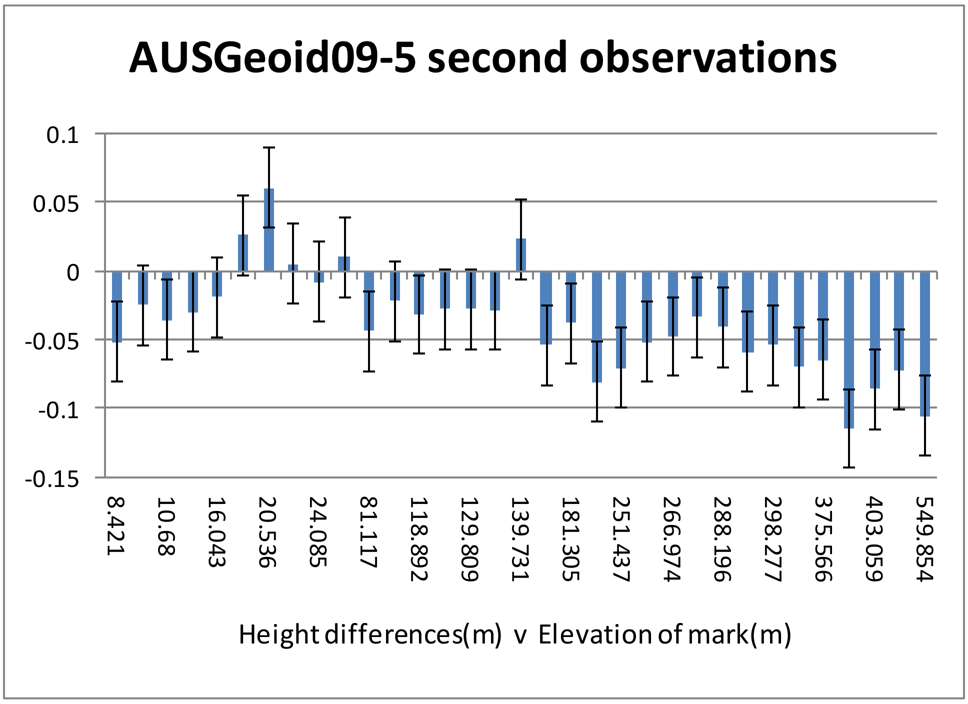

Figure 5.2-Height differences of 5 second AUSGeoid09 measurements plotted against elevation of the mark. Error bars are shown

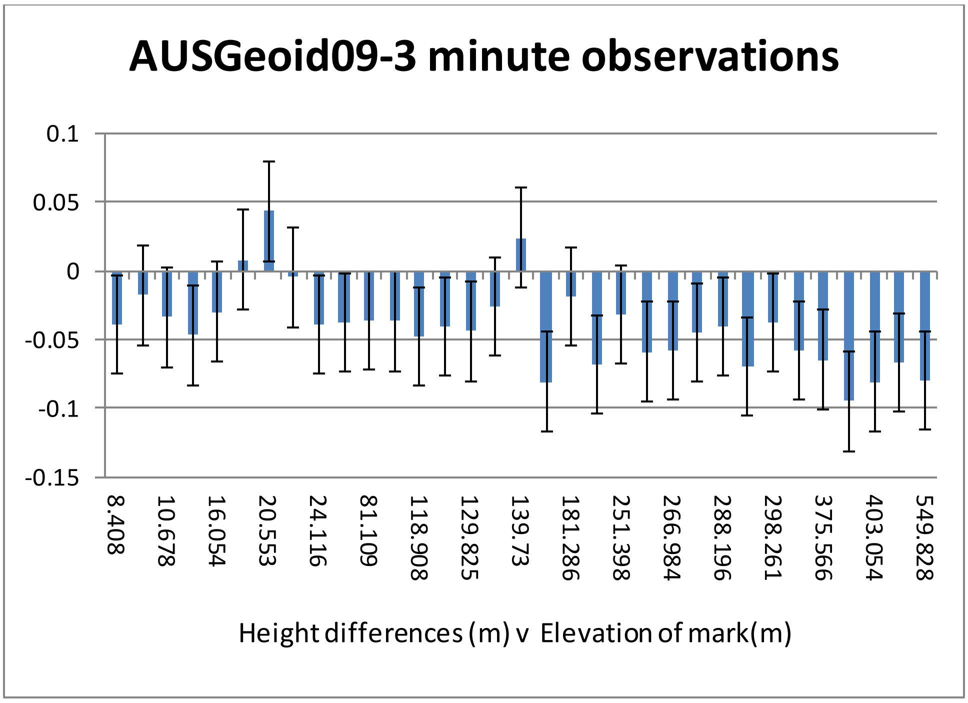

Figure 5.3-Height differences of 3 minute AUSGeoid09 measurements plotted against elevation of the mark. Error bars are shown

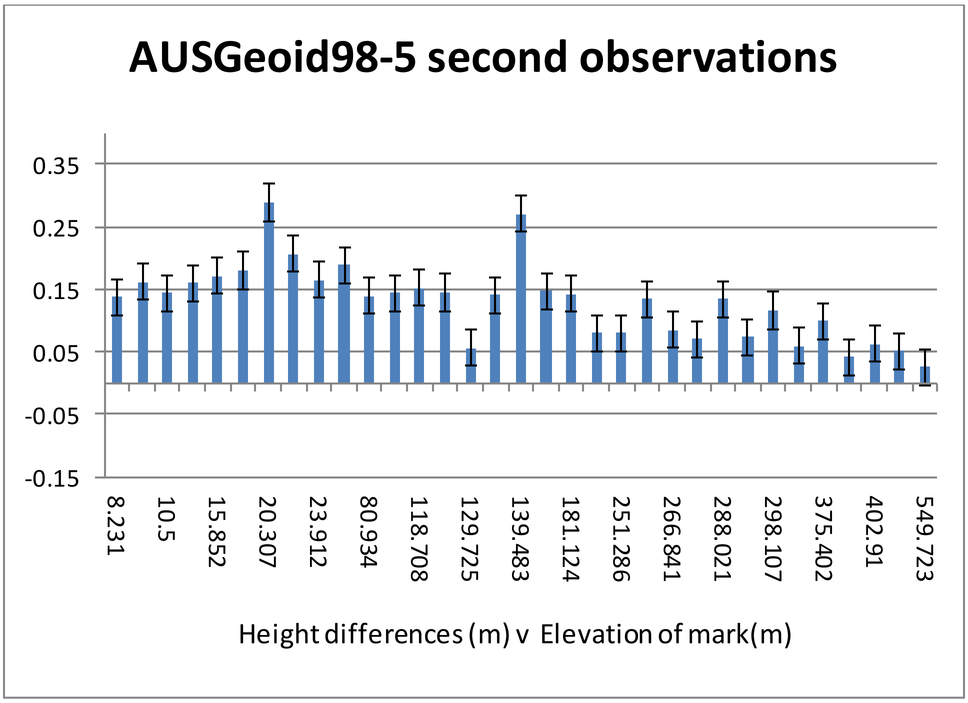

Figure 5.4-Height differences of 5 second AUSGeoid98 measurements plotted against elevation of the mark. Error bars are shown

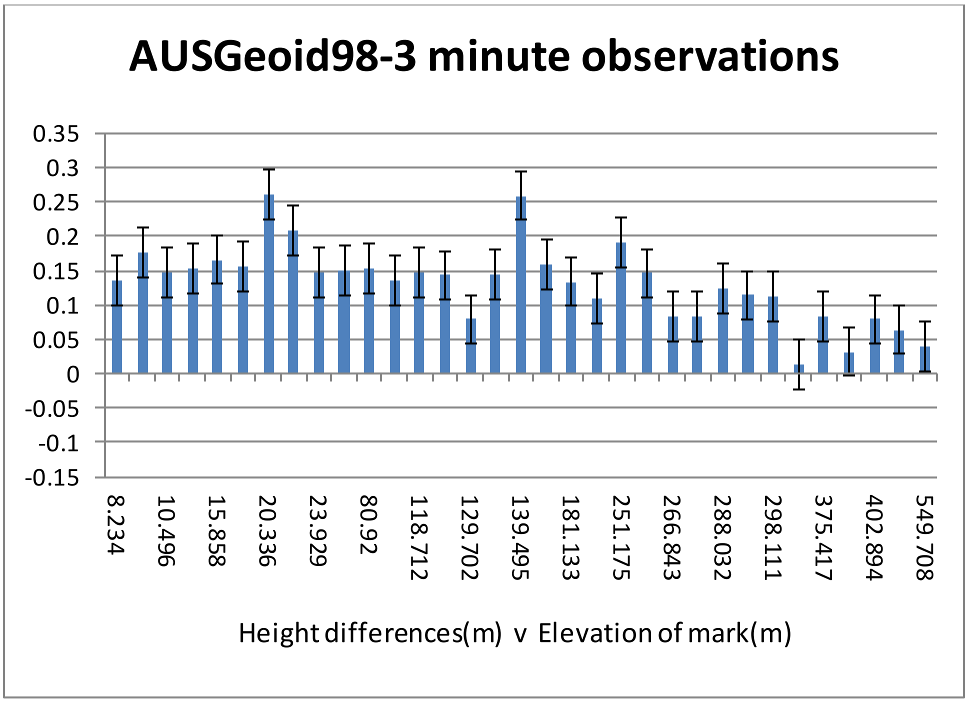

Figure 5.5-Height differences of 3 minute AUSGeoid98 measurements plotted against elevation of the mark. Error bars are shown

The error bars show that these trends are beyond the expected deviations of the measurements. The elevations between 180m and 500m coincided with the steep grades along the escarpment of the Great Dividing Range.

5.5 Identification of outliners

Using the information obtained at this point the outliners flagged by the cross validation (refer section 4.3) were assessed. In order to identify which of the two measurements were most likely outside the 95% confidence interval it was assumed that the height dependant trends evident in the graphs are consistent for marks of similar elevation. This is confirmed by the isopach maps generated from the 3 minute data for each model (Appendix H).

PM 81682 was identified in both the 5 second and 3 minute tests (RL 139.4 in Figures 5.2 to 5.5). The graphs show a disagreement inconsistent with the expected trend in both the AUSGeoid98 tests. This indicates that both of the AUSGeoid98 measurements are most likely in error.

PM 97776 was identified as a possible outliner in the 5 second test (RL 281.0 in Figure 5.2 and 5.4). Both measurements show reasonable deviations from the trends however when the extents of the error bars are considered the AUSGeoid98 measurement appears to have the worst fit.

PM 44012 (RL 129.7 in Figure 5.2 and 5.4) was identified in the 5 second test and it can be clearly seen that the AUSGeoid98 measurement is inconsistent with the trend.

PM 74705 (RL 20.5 in Figures 5.2 to 5.5) was not identified as an outliner by the cross validation. This mark shows a height disagreement in all 4 tests that seems to be inconsistent with surrounding marks. This indicates that there is either a gross error in the field reductions (target height or transfer of height to the arbitrary station) or the mark has settled. A less likely cause could be that at all 4 measurements have errors of similar magnitude and in the same direction from the most probable value. All measurements on this mark were removed from the data sets.

After removal of the outlying measurements the RMS value for AUSGeoid09 remained unchanged. The RMS value for both AUSGeoid98 tests was reduced from 0.142m to 0.131m.

5.6 Relative test

The relative test as used by Gibbings & McDonald (2005) and Janssen & Watson (2011) is best suited to studies involving more tradition differential GNSS methods. Here the height of the base station can be fixed to a known height and the gradient of the geoid model used to calculate a height at another point. Thus the accuracy of the model can be tested in a relative sense over distance and can be compared to the level classes of ICSM’s Standards and Practices for Control Surveys.

A truncated relative test was designed allowing the gradients of AUSGeoid09 and AUSGeoid98 to be assessed across the escarpment area using single rover RTK GNSS measurements. The results of the relative test in this study showed no change in the RMS value for AUSGeoid09, remaining at 0.051m. This is because the RMS test is unaffected by the sign of the differences. Although the derived levels of the relative test have been generally been moved about 0.08 to 0.1m they have gone from above the AHD heights to below the AHD heights. Thus they are generally similar in magnitude however the sign has been reversed.

The results of the AUSGeoid98 test show a significant improvement in the overall fit when AUSGeoid98 is used relatively as the RMS value of 0.049m is comparable to that of AUSGeoid09.

Brown et al. (2010) has shown that for baselines under 100km less than 3% of measurements fell outside ICMS (2004) class LC levelling specifications when using AUDGeoid09 compared to 41% for AUSGeoid98. Gibbings & McDonald (2005) showed similar results for AUSGeoid98 with 39% of baselines outside class LC specifications although the results improved for baselines exceeding 5km. This study shows 34% of AUSGeoid09 measurements fell outside class LC levelling compared to 23% of AUSGeoid98 measurements. It is recognised that this is a small data set generated by point GNSS positions with precisions of around +/-0.036m so these percentages could vary significantly if the measurements were repeated. Due to the small data set and limited accuracy of the measurements the results of this test are considered inconclusive regarding compliance with levelling classes. What has been demonstrated is that over the base lines assessed, AUSGeoid09 is not likely to produce significantly improved AHD determination than AUSGeoid98. This suggests that over the baselines assessed, the geometric corrections applied to AUSGeoid09 have offset the surface rather than drastically changed its shape. This can be demonstrated by consideration of the gradients of the two geoid models as shown in Figure 5.6 below. The separation between the two surfaces changes by 0.054m over the 8.4 km section shown. This is not significant in practice as the survey measurements have an error budget of +/- 0.036m.

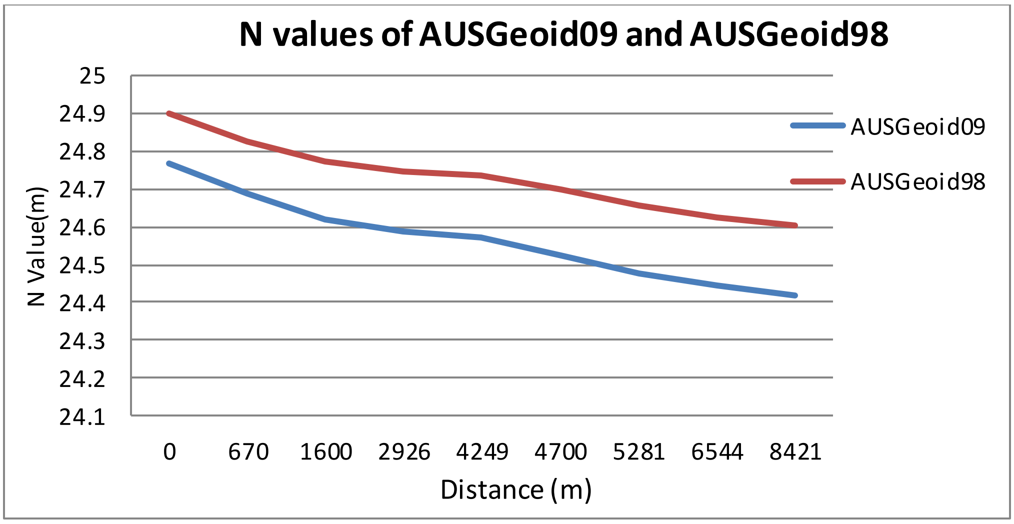

Figure 5.6-Plot of N values from the base of the escarpment (0m) to the top of Kurrajong Heights (8421m).

The results from section 5.4 indicate that through this section the AHD base is tending away from AUSGeoid09 and towards AUSGeoid98 by a distance of around 0.1m. This reveals that there is not enough empirical AHD height data in this region to align AUSGeoid09 onto the AHD base. The offset between the two geoid surfaces created by fitting AUSGeoid09 to the north south slope of the AHD is evident in this plot.

5.7 Implications

The motivation for this study arises from the desire to gain a better understanding of the performance and limitations of AUSGeoid09 and AUSGeoid98.

The results show that while AUSGeoid98 did not perform any worse than AUSGeoid09 when used relatively it did not convincingly perform better than AUSGeoid09 in any aspect of the study. Therefore there is no justification for its use within the test area using the equipment and method employed by this study.

AUSGeoid09 does provided a better means of determining AHD heights when the geoid model is used to directly convert ellipsoidal heights to orthometric heights. The accuracy of the orhometric heights when compared to published AHD heights is high and consistent and AHD heights generated on the flood plains of the Hawkesbury River using AUSGeoid09 could be expected to fit the AHD within the +/-0.085m suggested by previous authors (Brown, Hu, & Johnston, 2011). However this is not the case across the escarpment of the Great Dividing Range. This will not be a problem from a surveying perspective as surveys are generally connected to established AHD benchmarks. What has become evident is that due consideration should be given to the selection of these connecting marks along the escarpment area, particularly the very steep slopes of Kurrajong heights. It may be that a slightly more distant mark at a similar height to the survey will better represent AHD at the survey site than a closer mark that is considerably different in height to the survey.

5.8 Further research

Within the context of this study the extent of the test area should be extended across the Great Dividing Range to assess the performance of AUSGeoid09 at higher altitudes and more rugged terrain. The test area was chosen to be representative of the local region and due to the uniformity of the Great Dividing Range along the escarpment it is expected that the results of this study can be extrapolated across the extent of that topographic feature. This should be confirmed by further field measurements.

This research has not established the cause of the discrepancy found along the escarpment area, however the literature has demonstrated that the normal orthometric correction method adopted for the AHD is not related to local gravity. The agreement between the results of the relative test for both models indicate that within the test area the empirical corrections applied to AUSGeoid09 have shifted the geoid rather than severely distorted the purely gravimetric AGQG2009 (at least along the cross section tested). If this was proven AUSGeoid09 could be considered a block shifted gravimetric model within the test area and this would explain why it deviates from a levelling system not related to local gravity (refer section 2.7). Alternatively the discrepancy could be caused by the AGQG2009 not accurately depicting an equipotential surface along the escarpment as gravimetric modelling is difficult in mountainous regions (Brown, Hu & Johnston 2011). Further investigation in to the cause of this discrepancy is needed.

The compliance of GNSS heights derived using AUSGeoid09 with levelling classes has been briefly examined in this study. This investigation was limited by the accuracy of NRTK GNSS measurements and is considered inconclusive. Further research in this area is needed.

5.9 Conclusion

The results of this study show that when used with the equipment and observation methods detailed in this study AUSGeoid09 will provided absolute orthometric heights that agree with published AHD heights better than AUSGeoid98. The RMS of the height differences improved by a factor of 2.5 based on the entire test area when AUSGeoid09 was used.

It has also been demonstrated that the level of agreement between AUSGeoid09 orthomtric heights and published AHD heights was not consistent throughout the test area. On the flood plains of the Hawkesbury River the GNSS orthometric heights generated using AUSGeoid09 generally differed from the published AHD heights by little more than the expected measurement variations whereas AUSGeoid98 generally differed by about +0.15m. On the escarpment of the Great Dividing Range the improvement associated with the use of AUSGeoid09 is much less. Using AUSGeoid98 at heights of around 400m resulted in height differences of comparable magnitude to AUSGeoid09 however there is no evidence to support the continued use of AUSGeoid98 as it did not convincingly perform better than AUSGeoid09 in any test conducted by this study.

It has been demonstrated that in steep areas the performance of AUSGeoid09 can vary significantly. Therefore it is important to understand how these differences relate to the topography so that sensible decisions can be made when connecting surveys to established AHD coordinates. This study has shown that in these circumstances connecting to vertical benchmarks that are at a similar height to the survey site will yield a better representation of AHD heights at the survey site than a benchmark at a significantly different height to that of the survey.

CHAPTER 6

CONCLUSION

6.1 Conclusion

A study has been conducted to establish the accuracy of AHD heights generated using AUSGeoid09 and AUSGeoid98 within a test area of the Hawkesbury Valley NSW. Using published AHD heights as the standard for comparison, the accuracy of each model has been assessed to gauge the level of improvement if any, gained by the use of AUSGeoid09.

A relative test indicated that there were no significant gains in accuracy associated with the relative use of AUSGeoid09 gradients to generate AHD heights however this test was based on a small dataset and may not be indicative of the entire region. When the entire test was considered the RMS value of the absolute height differences improved from 0.131m to 0.051m when AUSGeoid09 was used instead of AUSGeoid98.

The results show a significantly better absolute determination of AHD using AUSGeoid09 within the test site, using the equipment and methods adopted by this study. However the level of improvement is not consistent throughout the test area. It was found that AUSGeoid09 did not improve the accuracy of the AHD heights generated along the escarpment of the Great Dividing Range.

This research draws attention to the need for GNSS users to have an understanding of the performance and limitations of the geoid models they use in order to make sensible decisions regarding their use.

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APPENDIX A: PROJECT SPECIFICATION

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG8411/8412 Research Project

Project Specification

For: Michael Marion

Topic: Verify the performance of Ausgeoid09 with respect to local AHD values within the Hawkesbury region.

Supervisor: Dr Peter Gibbings

Project Aim: To test the AHD values generated by Ausgeoid09 against the AHD values of local established marks and report on any significant differences.

Objectives: Using Corsnet GNSS measurements the study will examine the correlation between AHD values generated using the recently released Ausgeoid09 and the AHD values of local benchmarks in the Hawkesbury region.

Field of Study: Surveying and geodetic science.

Central questions: 1.What is the accuracy and precision of the equipment that will be used in the study?

2. How does the geoid model perform with respect to local established bench marks?

3. How dependable are the established marks?

4. Do the AHD values differ enough to be significant given the expected accuracy and precision of the equipment used?

Value of the study: It is expected that the study will either verify the correlation between the geoid and local AHD or show discrepancies between the two. This information will be used to evaluate the way in which AHD values generated by GNSS will be used on survey plans within the study area as surveys in flood prone areas are often conducted some distance from established marks.

It is also of interest to determine how well the geoid model fits local marks. Despite the fact that local AHD may suffer from errors in theory and methodology, levelling traverse errors, and settling of the marks, it is still at this point to be adopted. While AHD was a significant achievement forty years ago and has served the nation well, the study may highlight the need for a new Australian height datum.

Methods: The study will consider the expected precision and accuracy of Coresnet GNSS observations over the distances and terrain that the new geoid will be tested. Thus allowing the study to determine if differences found in AHD values generated using the geoid model are significant with respect to expected variations of the measuring equipment.

The equipment will be verified against ellipsoidal values of Corsnet reference stations. A testing station will be established near each reference station to be used in the verification, and the ellipsoidal height of the station will be determined by trig levelling from the antenna of the reference station. The ellipsoidal height measured by the GNSS unit can then be directly compared to the published ellipsoidal height of the Corsnet reference station.

At each station, the instrument will then be set to receive corrections from different Corsnet reference stations to verify the effects of distance and topography on the accuracy and precision of the equipment.

Once all field data has been collected, standard deviations and confidence intervals shall be calculated for both the variation from the known value, and the mean value, to establish the accuracy and precision of the equipment.

Observations will then be taken on local bench marks throughout the region and the differences between GNSS generated AHD values and SCIMS published values will be logged.

Programme:

1. Establish verification procedures for corsnet GPS equipment, verify the equipment to be used.
2. Research development of Ausgeoid09 and the establishment of AHD in the local area.
3. Design field procedure to test correlation between Ausgeoid09 and local AHD values in the Hawkesbury region.
4. Collect observations on local established bench marks.
5. Analyse field data, report on differences and performance of Ausgeoid09 in the local area.

As time permits:

Combine research and field data to develop guidelines to be used when dealing with the accuracies to be stated on plans that show GNSS generated levels.

Develop a local geoid for Leica 1200 GPS to fit established AHD benchmarks if significant differences are found.

AGREED:

…………………………….	…………………	………………………………….	…………………
Michael Marion	Date	Dr Peter Gibbings (supervisor)	Date

Amendment: A

APPENDIX B: SCIMS MARKS

Part A Primary study

SCIMS No	AHD	EASTING (MGA)	NORTHING (MGA)	CLASS	ORDER
PM 1677	251.366	281274.24	6286148.997	LA	L1
PM 3790	24.077	291159.328	6278602.151	LB	L2
TS 10365	221.101	282298.782	6272260.971	B	2
SSM 13842	375.501	275330.304	6269270.555	LB	L2
SSM 32950	549.748	279692.192	6288268.563	LB	L2
PM 35132	383.812	273884.695	6269034.473	LB	L2
PM 38504	263.803	281699.266	6272331.19	LB	L2
PM 38512	266.732	279854.219	6271881.881	LB	L2
PM 38555	288.155	277341.387	6269419.739	LB	L2
SSM 38590	297.506	277423.474	6271074.181	LB	L2
PM 38608	291.993	278086.098	6270470.74	LB	L2
PM 38636	449.857	271702.812	6269008.312	LB	L2
PM 38578	326.927	276784.96	6270482.337	LB	L2
PM 44012	129.781	287649.567	6289021.28	LB	L2
PM 44019	99.036	290954.595	6289552.672	LB	L2
PM 44024	181.721	285524	6288672	LB	L2
PM 44028	137.637	289422	6291201	LB	L2
PM 45473	118.86	289422	6291201	LB	L2
PM 46058	22.12	285658.132	6278172.875	LC	L3
PM 46063	34.032	283899.354	6276148.758	LC	L3
PM 46075	81.073	286298.135	6280989.501	LB	L2
PM 46080	125.621	283156.258	6281051.426	LB	L2
PM 67535	8.496	299046.095	6281750.557	B	2
SSM 74052	16.024	296883.678	6279185.54	LC	L3
PM 74695	11.523	288930.683	6280867.553	LB	L2
PM 74704	8.369	291953.626	6281334.982	LB	L2
PM 74705	20.548	287830.518	6278179.117	LB	L2
PM 77441	10.644	296436.349	6281556.217	LB	L2
PM 77447	16.448	294290.818	6278807.783	LB	L2
PM 80478	402.475	279635	6282390	LC	L3
PM 81026	172.769	284423.845	6286175.138	B	2
PM 81682	139.754	284221.88	6288506.637	B	2
SSM 97776	280.602	278310.653	6271305.616	B	2

Part B relative test

SCIMS No	AHD	EASTING (MGA)	NORTHING (MGA)	CLASS	ORDER
SSM 18781	133.465	285751.484	6285285.887	B	2
SSM 32950	549.748	279692.192	6288268.563	LB	L2
PM 44008	85.946	287192	6284741	LB	L2
PM 45501	186.888	282186.854	6285533.38	LB	L2
PM 45502	246.576	281374.404	6286077.628	LB	L2
PM 81028	136.631	283511.286	6285517.86	B	2
PM 81032	211.018	281745.696	6285629.72	B	2
PM 81573	97.737	286209.072	6284794.378	B	2
SSM 26262	147.707	284819.86	6285298.662	B	2

APPENDIX C: VALIDATION OBSERVATIONS

Part A

5 second validation occupations

Pt ID	Ortho Ht	Ellip Height	HZ CQ	V CQ
1	456.142	480.397	0.009	0.016
2	456.14	480.395	0.009	0.016
3	456.134	480.389	0.009	0.015
4	456.126	480.381	0.008	0.013
5	456.125	480.38	0.008	0.014
6	456.134	480.389	0.008	0.014
7	456.142	480.397	0.009	0.016
8	456.14	480.395	0.012	0.02
9	456.141	480.396	0.014	0.024
10	456.136	480.391	0.013	0.023
11	456.122	480.377	0.014	0.024
12	456.107	480.362	0.016	0.028
13	456.108	480.363	0.021	0.035
14	456.115	480.37	0.021	0.037
15	456.113	480.368	0.021	0.037
16	456.107	480.362	0.021	0.036
17	456.102	480.357	0.02	0.034
18	456.1	480.355	0.019	0.032
19	456.093	480.348	0.018	0.031
20	456.1	480.355	0.017	0.028
21	456.116	480.371	0.015	0.026
22	456.122	480.377	0.015	0.026
23	456.125	480.38	0.015	0.026
24	456.119	480.374	0.015	0.026
25	456.119	480.374	0.016	0.027
26	456.112	480.367	0.015	0.026
27	456.116	480.371	0.014	0.024
28	456.111	480.366	0.014	0.024
29	456.117	480.372	0.014	0.024
30	456.122	480.377	0.013	0.023

Part B

3 minute validation occupations

Pt ID	Ortho Ht	Ellip Height	HZ CQ	V CQ
1	456.123	480.378	0.011	0.017
2	456.118	480.373	0.01	0.016
3	456.1	480.355	0.009	0.013
4	456.108	480.363	0.011	0.016
5	456.125	480.38	0.011	0.016
6	456.149	480.404	0.011	0.018
7	456.124	480.379	0.01	0.016
8	456.11	480.365	0.011	0.019
9	456.105	480.36	0.01	0.017
10	456.118	480.373	0.011	0.019
11	456.094	480.35	0.009	0.017
12	456.091	480.346	0.01	0.019
13	456.093	480.348	0.01	0.02
14	456.098	480.353	0.011	0.021
15	456.118	480.373	0.01	0.022
16	456.1	480.355	0.011	0.022
17	456.142	480.381	0.01	0.022
18	456.055	480.335	0.012	0.025
19	456.078	480.333	0.012	0.026
20	456.13	480.385	0.011	0.025
21	456.152	480.376	0.014	0.033
22	456.077	480.332	0.011	0.025
23	456.101	480.356	0.009	0.021
24	456.111	480.366	0.008	0.018
25	456.083	480.338	0.01	0.025
26	456.131	480.386	0.008	0.017
27	456.126	480.381	0.009	0.022
28	456.123	480.378	0.008	0.02
29	456.139	480.394	0.009	0.022

APPENDIX D: PRIMARY DATA SET

Part A

5 Second AUSGeoid09 occupations

Code	Easting	Northing	Ortho Ht	Ellip Height	HZ CQ	V CQ
1677	281274.289	6286148.993	251.437	276.066	0.026	0.047
3790	291159.326	6278602.135	24.085	48.178	0.017	0.036
10365	282298.808	6272260.959	221.182	243.254	0.016	0.027
13842	275330.322	6269270.567	375.566	399.71	0.015	0.024
32950	279692.222	6288268.569	549.854	574.623	0.012	0.023
35132	273884.709	6269034.511	383.927	408.097	0.016	0.022
38504	281699.249	6272331.186	263.855	287.918	0.011	0.019
38555	277341.376	6269419.737	288.196	312.297	0.017	0.042
38608	278086.095	6270470.729	292.052	316.175	0.019	0.045
38636	271702.792	6269008.289	449.929	474.155	0.018	0.019
44012	287649.604	6289021.247	129.809	154.337	0.015	0.024
44019	290954.591	6289552.675	99.058	123.525	0.009	0.016
44028	289431.081	6291216.954	137.666	162.223	0.011	0.017
45473	291936.906	6291397.649	118.892	143.398	0.012	0.024
46058	285658.141	6278172.879	22.115	46.305	0.011	0.018
46075	286298.146	6280989.504	81.117	105.391	0.017	0.034
46080	283156.272	6281051.448	125.649	150.012	0.009	0.019
67535	299046.078	6281750.603	8.521	32.567	0.008	0.017
74052	296883.717	6279185.59	16.043	40.045	0.014	0.025
74695	288930.691	6280867.55	11.553	35.764	0.012	0.016
74704	291953.632	6281335.021	8.421	32.588	0.011	0.014
77441	296436.368	6281556.22	10.68	34.77	0.009	0.013
77447	294290.834	6278807.819	16.422	40.462	0.012	0.038
81026	284423.885	6286175.098	172.823	197.34	0.009	0.024
81682	284221.908	6288506.625	139.731	164.338	0.012	0.042
OFFSET STATIONS						
38512OS	279856.588	6271872.712	266.974	291.104	0.008	0.025
38578OS	276805.395	6270486.068	327.014	351.168	0.008	0.013
38590OS	277392.063	6271085.378	298.277	322.44	0.013	0.02
44024OS	285568.236	6288684.672	181.305	205.88	0.017	0.025
46063OS	283889.274	6276124.189	34.051	58.211	0.01	0.016
74705OS	287837.629	6278200.159	20.536	44.68	0.008	0.022
80478OS	279650.42	6282354.968	403.059	427.586	0.01	0.02
97776OS	278314.19	6271316.156	281.032	305.125	0.011	0.043

Part A

3 minute AUSGeoid09 occupations

Code	Easting	Northing	Ortho Ht	Ellip Height	HZ CQ	V CQ
1677	281274.283	6286149	251.398	276.027	0.016	0.044
3790	291159.319	6278602.15	24.116	48.209	0.013	0.03
10365	282298.81	6272260.96	221.169	243.241	0.01	0.017
13842	275330.322	6269270.567	375.566	399.71	0.015	0.024
32950	279692.229	6288268.566	549.828	574.597	0.013	0.025
35132	273884.706	6269034.5	383.907	408.076	0.015	0.021
38504	281699.261	6272331.192	263.862	287.926	0.008	0.014
38555	277341.363	6269419.746	288.196	312.297	0.013	0.036
38608	278086.098	6270470.734	292.063	316.186	0.008	0.03
38636	271702.794	6269008.298	449.924	474.15	0.01	0.015
44012	287649.601	6289021.251	129.825	154.353	0.014	0.023
44019	290954.594	6289552.685	99.073	123.539	0.011	0.02
44028	289431.078	6291216.949	137.663	162.22	0.008	0.013
45473	291936.914	6291397.652	118.908	143.414	0.007	0.015
46058	285658.142	6278172.886	22.125	46.314	0.01	0.017
46075	286298.143	6280989.506	81.109	105.382	0.009	0.02
46080	283156.276	6281051.446	125.662	150.024	0.007	0.016
67535	299046.078	6281750.599	8.514	32.559	0.009	0.018
74052	296883.701	6279185.576	16.054	40.056	0.01	0.017
74695	288930.687	6280867.552	11.57	35.782	0.011	0.015
74704	291953.627	6281335.017	8.408	32.575	0.01	0.013
77441	296436.369	6281556.221	10.678	34.767	0.008	0.011
77447	294290.824	6278807.82	16.44	40.479	0.012	0.039
81026	284423.889	6286175.101	172.85	197.367	0.01	0.023
81682	284221.907	6288506.605	139.73	164.338	0.01	0.034
OFFSET STATIONS						
38512OS	279856.586	6271872.716	266.984	291.115	0.009	0.026
38578OS	276805.391	6270486.063	327.002	351.156	0.008	0.013
38590OS	277392.06	6271085.377	298.261	322.423	0.018	0.031
44024OS	285568.243	6288684.666	181.286	205.861	0.013	0.019
46063OS	283889.277	6276124.181	34.099	58.258	0.012	0.021
74705OS	287837.621	6278200.16	20.553	44.698	0.007	0.018
80478OS	279650.424	6282354.969	403.054	427.581	0.012	0.023
97776OS	278314.2	6271316.148	281.043	305.192	0.012	0.042

Part B

5 second AUSGeoid98 occupations

Code	Easting	Northing	Ortho Ht	Ellip Height	HZ CQ	V CQ
1677	281274.28	6286149.008	251.286	276.066	0.021	0.048
3790	291159.329	6278602.145	23.912	48.192	0.012	0.025
10365	282298.814	6272260.967	221.021	243.27	0.016	0.027
13842	275330.333	6269270.558	375.402	399.69	0.015	0.024
32950	279692.22	6288268.571	549.723	574.622	0.013	0.025
35132	273884.709	6269034.502	383.771	408.081	0.017	0.023
38504	281699.253	6272331.187	263.668	287.932	0.015	0.026
38555	277341.379	6269419.739	288.021	312.274	0.015	0.04
38608	278086.096	6270470.732	291.919	316.194	0.01	0.036
38636	271702.803	6269008.304	449.806	474.163	0.016	0.028
44012	287649.624	6289021.214	129.725	154.431	0.017	0.038
44019	290954.599	6289552.674	98.892	123.538	0.008	0.014
44028	289431.084	6291216.95	137.496	162.228	0.009	0.014
45473	291936.911	6291397.63	118.708	143.392	0.008	0.016
46058	285658.138	6278172.88	21.914	46.294	0.009	0.016
46075	286298.138	6280989.504	80.934	105.398	0.01	0.022
46080	283156.276	6281051.449	125.476	150.017	0.008	0.016
67535	299046.079	6281750.604	8.334	32.573	0.008	0.017
74052	296883.713	6279185.582	15.852	40.047	0.011	0.017
74695	288930.688	6280867.546	11.363	35.763	0.013	0.018
74704	291953.631	6281335.029	8.231	32.587	0.011	0.013
77441	296436.369	6281556.223	10.5	34.78	0.01	0.014
77447	294290.818	6278807.827	16.268	40.497	0.016	0.05
81026	284423.882	6286175.106	172.622	197.319	0.013	0.034
81682	284221.922	6288506.616	139.483	164.266	0.012	0.042
OFFSET STATIONS						
38512OS	279856.59	6271872.717	266.841	291.128	0.011	0.036
38578OS	276805.379	6270486.063	326.884	351.186	0.013	0.039
38590OS	277392.057	6271085.38	298.107	322.419	0.017	0.029
44024OS	285568.243	6288684.667	181.124	205.875	0.017	0.024
46063OS	283889.279	6276124.19	33.872	58.22	0.009	0.015
74705OS	287837.62	6278200.163	20.307	44.641	0.009	0.024
80478OS	279650.433	6282354.985	402.91	427.584	0.01	0.023
97776OS	278314.182	6271316.169	280.927	305.228	0.015	0.043

Part B

3 Minute AUSGeoid98 occupations

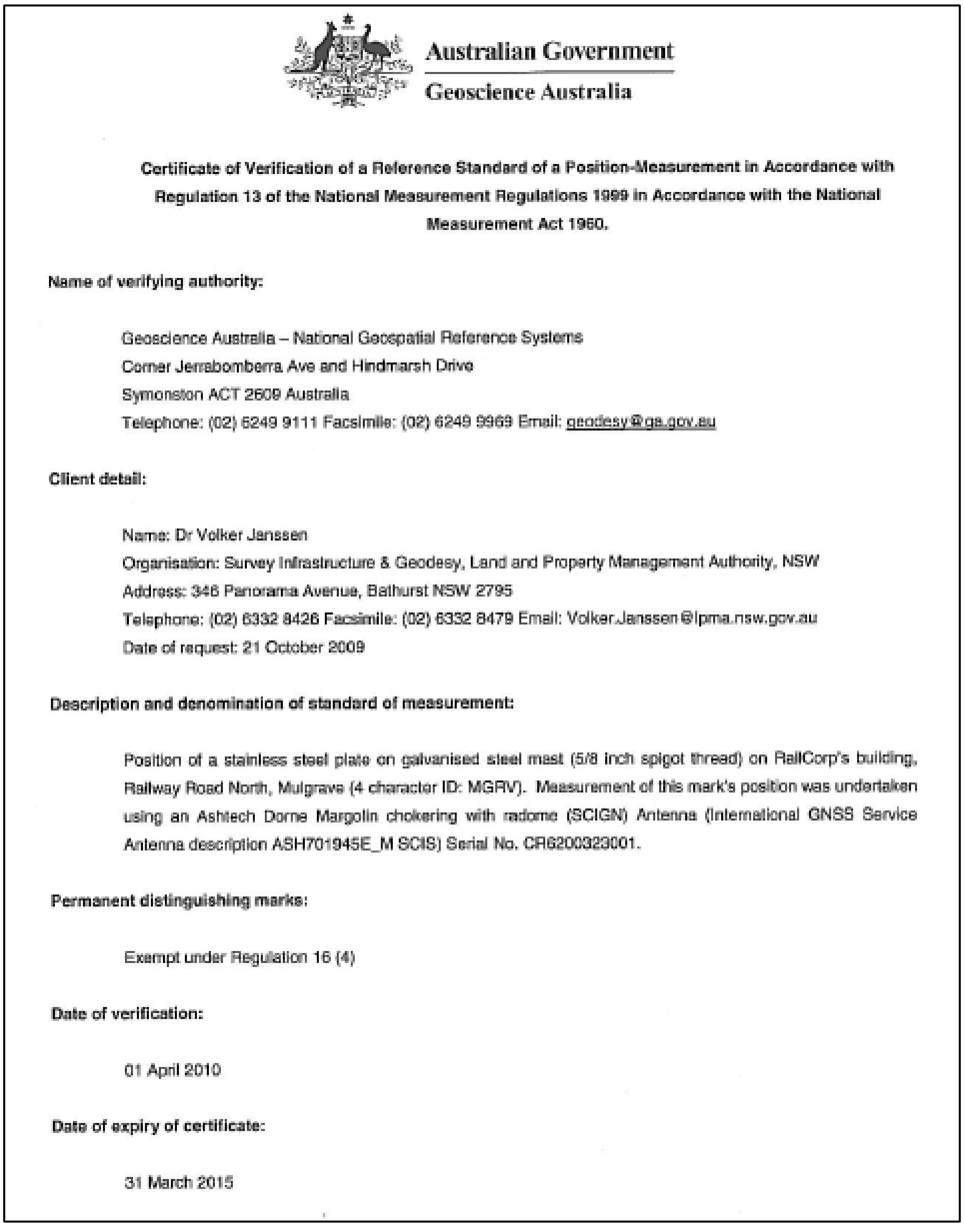
Code	Easting	Northing	Ortho Ht	Ellip Height	HZ CQ	V CQ
1677	281274.011	6286148.763	251.175	275.955	0.021	0.049
3790	291159.323	6278602.152	23.929	48.209	0.012	0.025
10365	282298.81	6272260.96	220.992	243.241	0.01	0.017
13842	275330.327	6269270.56	375.417	399.705	0.016	0.026
32950	279692.225	6288268.583	549.708	574.607	0.013	0.025
35132	273884.711	6269034.5	383.78	408.09	0.016	0.022
38504	281699.253	6272331.186	263.657	287.921	0.012	0.02
38555	277341.375	6269419.733	288.032	312.285	0.014	0.037
38608	278086.101	6270470.734	291.879	316.154	0.021	0.041
38636	271702.794	6269008.298	449.793	474.15	0.01	0.015
44012	287649.62	6289021.217	129.702	154.408	0.016	0.035
44019	290954.6	6289552.675	98.9	123.545	0.008	0.015
44028	289431.087	6291216.95	137.493	162.225	0.01	0.016
45473	291936.912	6291397.637	118.712	143.396	0.008	0.016
46058	285658.138	6278172.88	21.911	46.291	0.01	0.017
46075	286298.138	6280989.499	80.92	105.384	0.01	0.022
46080	283156.277	6281051.448	125.478	150.019	0.008	0.016
67535	299046.078	6281750.599	8.32	32.559	0.009	0.018
74052	296883.709	6279185.575	15.858	40.053	0.012	0.019
74695	288930.686	6280867.552	11.371	35.771	0.015	0.019
74704	291953.623	6281335.025	8.234	32.589	0.011	0.014
77441	296436.37	6281556.221	10.496	34.776	0.01	0.014
77447	294290.814	6278807.824	16.292	40.521	0.01	0.032
81026	284423.88	6286175.108	172.611	197.308	0.011	0.03
81682	284221.923	6288506.62	139.495	164.278	0.012	0.041
OFFSET STATIONS						
38512OS	279856.588	6271872.717	266.843	291.13	0.01	0.032
38578OS	276805.373	6270486.065	326.893	351.195	0.014	0.042
38590OS	277392.06	6271085.377	298.111	322.423	0.018	0.031
44024OS	285568.245	6288684.66	181.133	205.885	0.015	0.022
46063OS	283889.277	6276124.181	33.91	58.258	0.012	0.021
74705OS	287837.622	6278200.165	20.336	44.669	0.008	0.021
80478OS	279650.43	6282354.983	402.894	427.568	0.011	0.024
97776OS	278314.201	6271316.163	280.915	305.216	0.01	0.036

Part C

3 Minute relative test occupations

Code	Easting	Northing	Ortho Ht	Ell Height	HZ CQ	V CQ
SSM 32950	279692.245	6288268.545	-	574.615	0.01	0.021
PM 45008	280215.865	6286580.948	-	473.601	0.009	0.019
PM 45502	281374.492	6286077.629	-	271.223	0.01	0.021
PM 81032	281745.727	6285629.701	-	235.696	0.016	0.034
PM 45501	282186.884	6285533.38	-	211.517	0.012	0.028
PM 81028	283511.32	6285517.823	-	161.128	0.01	0.018
SSM 26262	284819.889	6285298.629	-	172.204	0.016	0.033
SSM 18781	285751.508	6285285.892	-	157.989	0.01	0.017
PM 81573	286209.102	6284794.387	-	122.194	0.019	0.035

APPENDIX E: REGULATION 13 CERTIFICATE



Australian Government
Geoscience Australia

Certificate of Verification of a Reference Standard of a Position-Measurement in Accordance with Regulation 13 of the National Measurement Regulations 1999 in Accordance with the National Measurement Act 1960.

Name of verifying authority:

Geoscience Australia – National Geospatial Reference Systems
Corner Jerrabomberra Ave and Hindmarsh Drive
Symonston ACT 2609 Australia
Telephone: (02) 6249 9111 Facsimile: (02) 6249 9969 Email: geodesy@ga.gov.au

Client detail:

Name: Dr Volker Janssen
Organisation: Survey Infrastructure & Geodesy, Land and Property Management Authority, NSW
Address: 346 Panorama Avenue, Bathurst NSW 2795
Telephone: (02) 6332 8426 Facsimile: (02) 6332 8479 Email: Volker.Janssen@lpma.nsw.gov.au
Date of request: 21 October 2009

Description and denomination of standard of measurement:

Position of a stainless steel plate on galvanised steel mast (5/8 inch spigot thread) on RailCorp's building, Railway Road North, Mulgrave (4 character ID: MGRV). Measurement of this mark's position was undertaken using an Ashtech Dorne Margolin chokering with radome (SCIGN) Antenna (International GNSS Service Antenna description ASH701945E_M SCIS) Serial No. CR6200323001.

Permanent distinguishing marks:

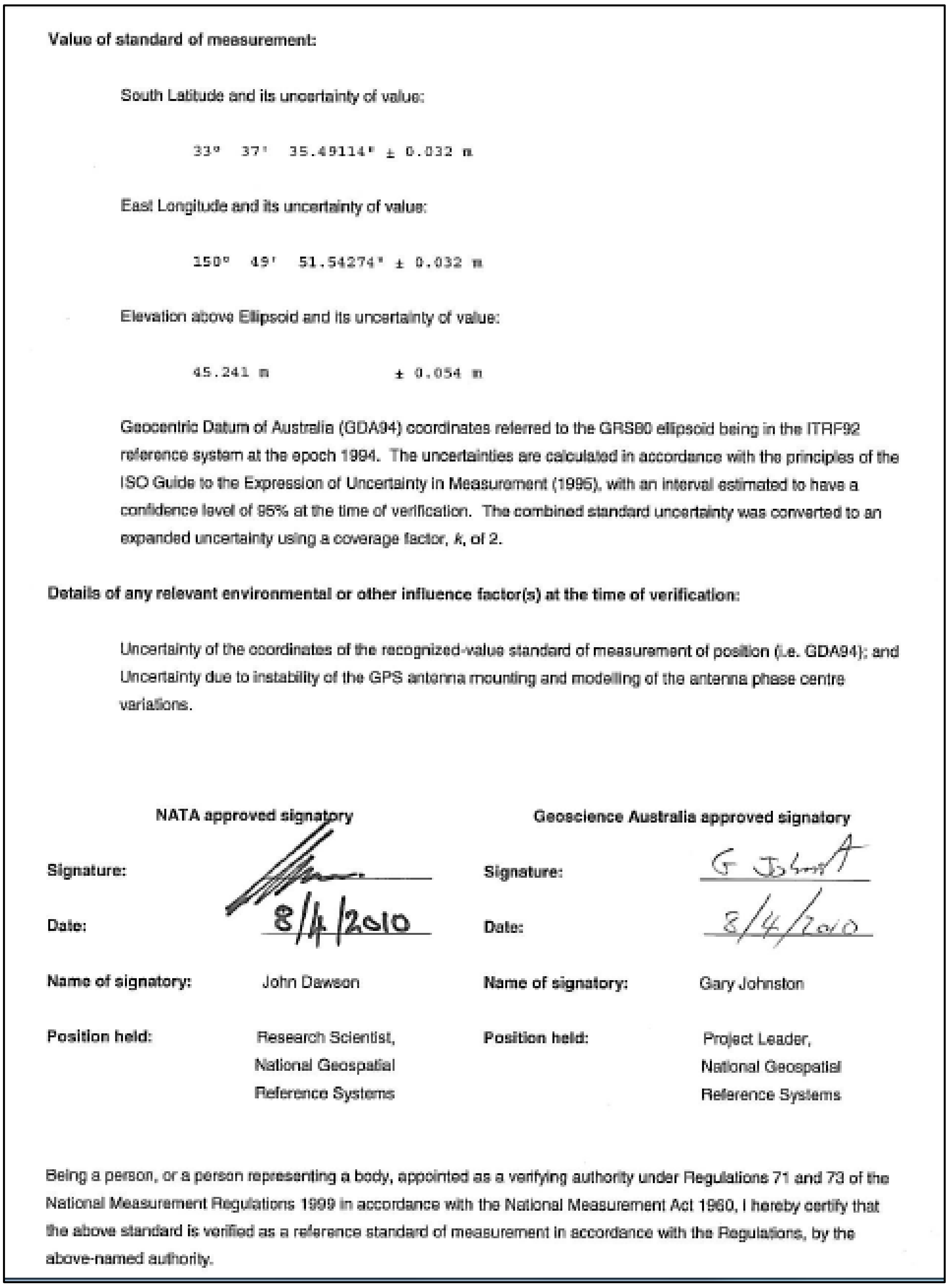
Exempt under Regulation 16 (4)

Date of verification:

01 April 2010

Date of expiry of certificate:

31 March 2015



Value of standard of measurement:

South Latitude and its uncertainty of value:

33° 37' 35.49114" ± 0.032 m

East Longitude and its uncertainty of value:

150° 49' 51.54274" ± 0.032 m

Elevation above Ellipsoid and its uncertainty of value:

45.241 m ± 0.054 m

Geocentric Datum of Australia (GDA94) coordinates referred to the GRS80 ellipsoid being in the ITRF92 reference system at the epoch 1994. The uncertainties are calculated in accordance with the principles of the ISO Guide to the Expression of Uncertainty in Measurement (1995), with an interval estimated to have a confidence level of 95% at the time of verification. The combined standard uncertainty was converted to an expanded uncertainty using a coverage factor, *k*, of 2.

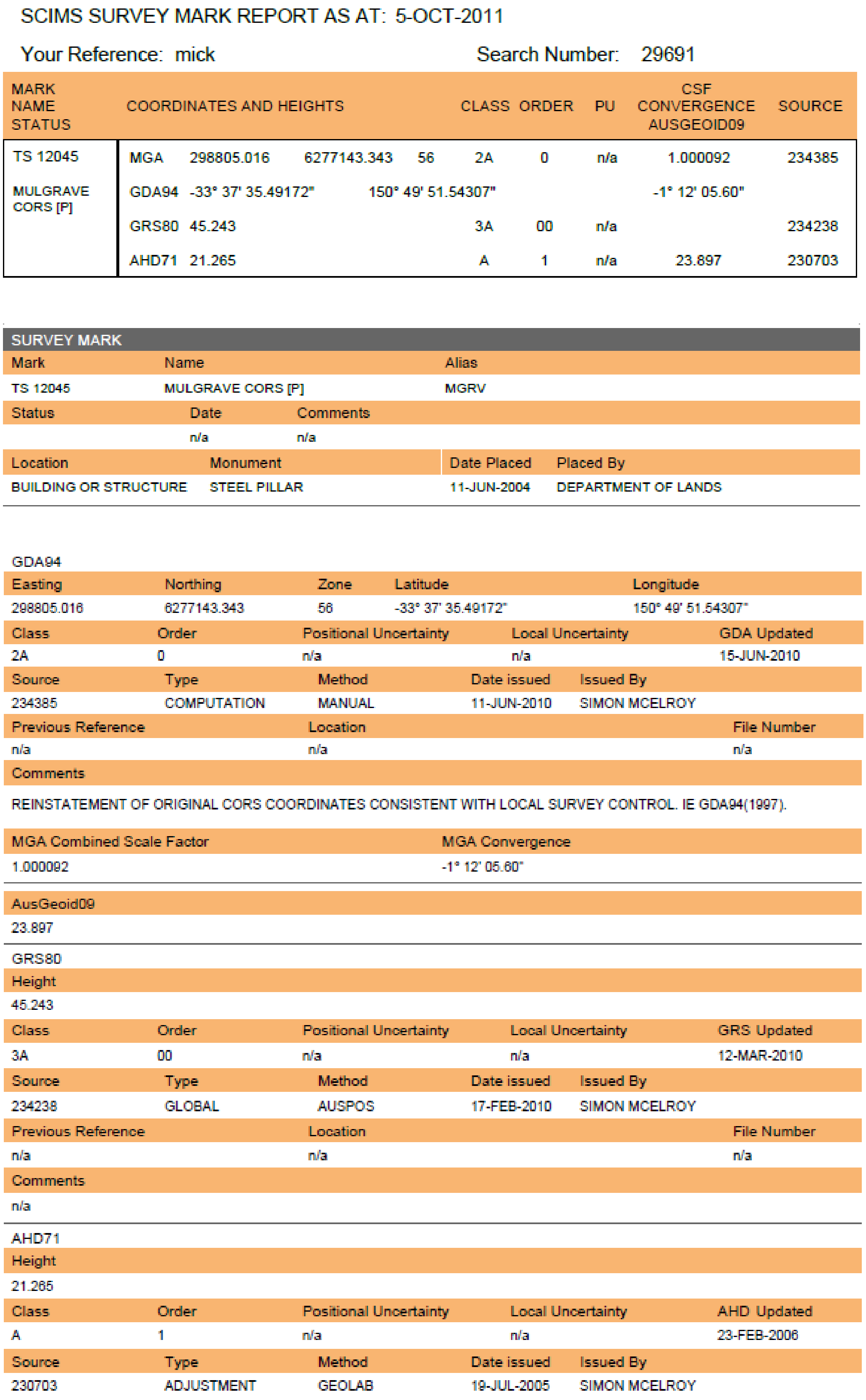
Details of any relevant environmental or other influence factor(s) at the time of verification:

Uncertainty of the coordinates of the recognized-value standard of measurement of position (i.e. GDA94); and Uncertainty due to instability of the GPS antenna mounting and modelling of the antenna phase centre variations.

NATA approved signatory		**Geoscience Australia approved signatory**	
Signature:		**Signature:**	
Date:	8/4/2010	**Date:**	8/4/2010
Name of signatory:	John Dawson	**Name of signatory:**	Gary Johnston
Position held:	Research Scientist, National Geospatial Reference Systems	**Position held:**	Project Leader, National Geospatial Reference Systems

Being a person, or a person representing a body, appointed as a verifying authority under Regulations 71 and 73 of the National Measurement Regulations 1999 in accordance with the National Measurement Act 1960, I hereby certify that the above standard is verified as a reference standard of measurement in accordance with the Regulations, by the above-named authority.

APPENDIX F: SCIMS REPORT



SCIMS SURVEY MARK REPORT AS AT: 5-OCT-2011

Your Reference: mick Search Number: 29691

MARK NAME STATUS	COORDINATES AND HEIGHTS	CLASS	ORDER	PU	CSF CONVERGENCE AUSGEOID09	SOURCE
TS 12045	MGA 298805.016 6277143.343 56	2A	0	n/a	1.000092	234385
MULGRAVE CORS [P]	GDA94 -33° 37' 35.49172" 150° 49' 51.54307"				-1° 12' 05.60"	
	GRS80 45.243	3A	00	n/a		234238
	AHD71 21.265	A	1	n/a	23.897	230703

SURVEY MARK

Mark	Name	Alias
TS 12045	MULGRAVE CORS [P]	MGRV

Status	Date	Comments
	n/a	n/a

Location	Monument	Date Placed	Placed By
BUILDING OR STRUCTURE	STEEL PILLAR	11-JUN-2004	DEPARTMENT OF LANDS

GDA94

Easting	Northing	Zone	Latitude	Longitude
298805.016	6277143.343	56	-33° 37' 35.49172"	150° 49' 51.54307"

Class	Order	Positional Uncertainty	Local Uncertainty	GDA Updated
2A	0	n/a	n/a	15-JUN-2010

Source	Type	Method	Date issued	Issued By
234385	COMPUTATION	MANUAL	11-JUN-2010	SIMON MCELROY

Previous Reference	Location	File Number
n/a	n/a	n/a

Comments
REINSTATEMENT OF ORIGINAL CORS COORDINATES CONSISTENT WITH LOCAL SURVEY CONTROL. IE GDA94(1997).

MGA Combined Scale Factor	MGA Convergence
1.000092	-1° 12' 05.60"

AusGeoid09
23.897

GRS80

Height
45.243

Class	Order	Positional Uncertainty	Local Uncertainty	GRS Updated
3A	00	n/a	n/a	12-MAR-2010

Source	Type	Method	Date issued	Issued By
234238	GLOBAL	AUSPOS	17-FEB-2010	SIMON MCELROY

Previous Reference	Location	File Number
n/a	n/a	n/a

Comments
n/a

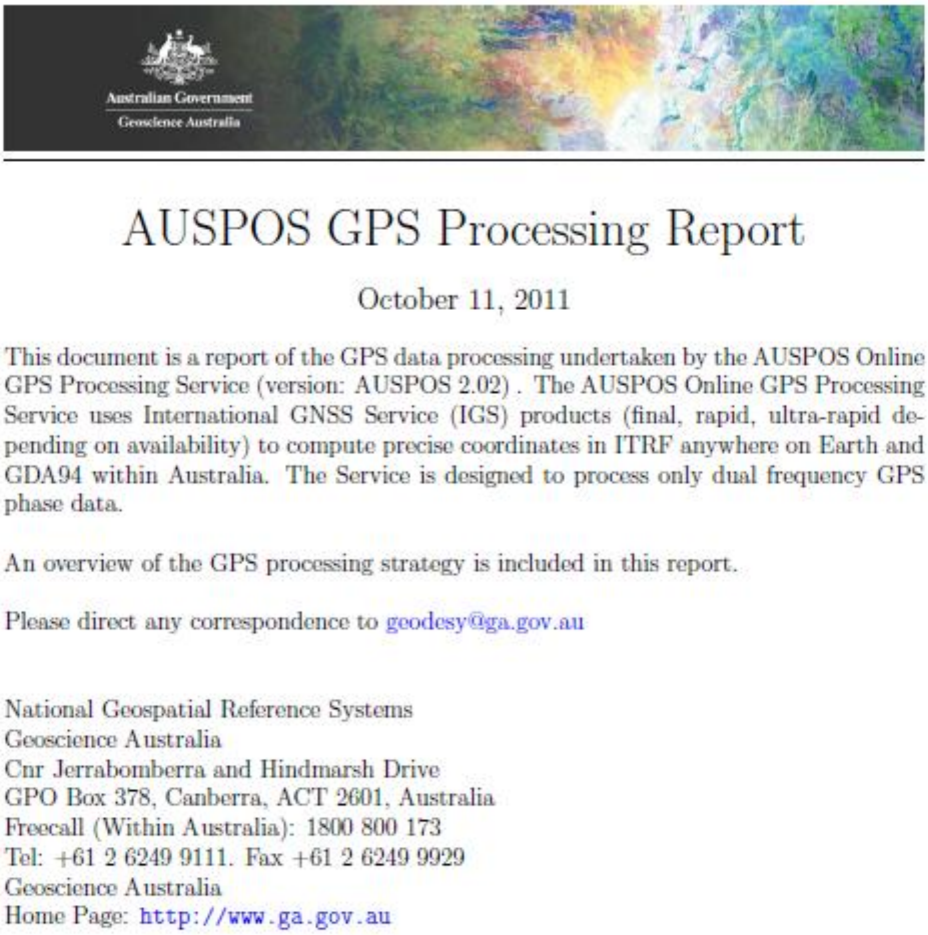
AHD71

Height
21.265

Class	Order	Positional Uncertainty	Local Uncertainty	AHD Updated
A	1	n/a	n/a	23-FEB-2006

Source	Type	Method	Date issued	Issued By
230703	ADJUSTMENT	GEOLAB	19-JUL-2005	SIMON MCELROY

APPENDIX G: AUSPOS REPORT



Australian Government
Geoscience Australia

AUSPOS GPS Processing Report

October 11, 2011

This document is a report of the GPS data processing undertaken by the AUSPOS Online GPS Processing Service (version: AUSPOS 2.02) . The AUSPOS Online GPS Processing Service uses International GNSS Service (IGS) products (final, rapid, ultra-rapid depending on availability) to compute precise coordinates in ITRF anywhere on Earth and GDA94 within Australia. The Service is designed to process only dual frequency GPS phase data.

An overview of the GPS processing strategy is included in this report.

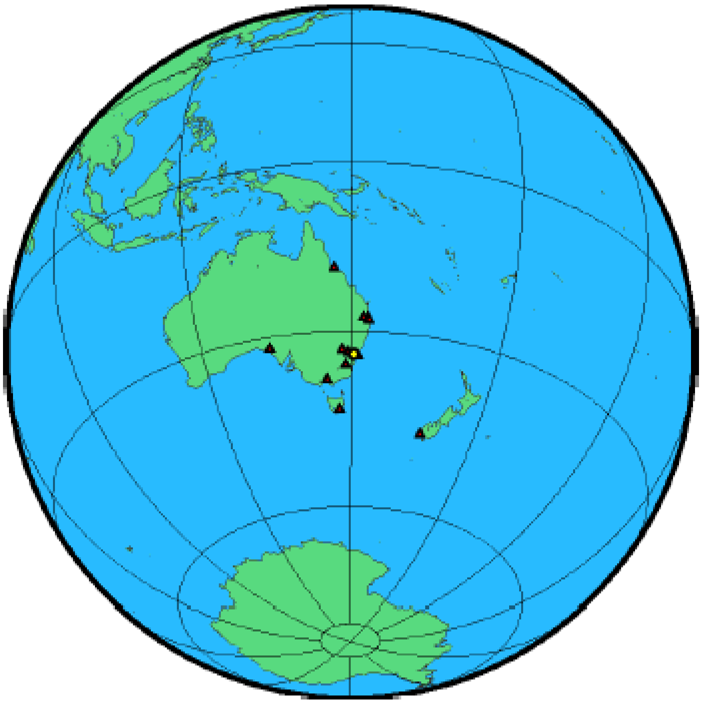
Please direct any correspondence to geodesy@ga.gov.au

National Geospatial Reference Systems
Geoscience Australia
Cnr Jerrabomberra and Hindmarsh Drive
GPO Box 378, Canberra, ACT 2601, Australia
Freecall (Within Australia): 1800 800 173
Tel: +61 2 6249 9111. Fax +61 2 6249 9929
Geoscience Australia
Home Page: `http://www.ga.gov.au`

All antenna heights refer to the vertical distance from the Ground Mark to the Antenna Reference Point (ARP).

Station (s)	Submitted File	Antenna Type	Antenna Height (m)	Start Time	End Time
1__	1__2780.11o	LEIAX1203+GNSS NONE	0.000	2011/10/05 07:16:00	2011/10/05 14:07:00

2 Processing Summary



Date	User Stations	Reference Stations	Orbit Type
2011/10/05 07:16:00	1__	BATH BEE2 CEDU GATT HOB2 MOBS PARK PYGR ROBI STR1 SYDN TID1 TOW2 UNSW	IGS rapid

Remark: An IGS Rapid Orbit product has been used in this computation, IGS Rapid orbits are usually of very high quality. However, to ensure you achieve the highest quality coordinates please resubmit approximately 2 weeks after the observation session end to ensure the use of the IGS Final Orbit product.

3 Computed Coordinates, GDA94

For Australian users Geocentric Datum of Australia (GDA94, ITRF92@1994.0) coordinates are provided. GDA94 coordinates are determined from ITRF coordinates by Geoscience Australia (GA) derived coordinate transformation process. GA recommends that users within Australia use GDA94 coordinates. For general and technical information on GDA94 see `http://www.ga.gov.au/earth-monitoring/geodesy/geodetic-datums/GDA` `html` and `http://www.icsm.gov.au/icsm/gda/gdatm/`

3.1 Cartesian, GDA94

Station	X (m)	Y (m)	Z (m)
1__	-4625720.502	2613360.201	-3518012.655
BATH	-4594792.114	2699284.310	-3494246.070
BEE2	-5043446.201	2547349.349	-2949131.581
CEDU	-3753472.142	3912741.025	-3347961.028
GATT	-5012218.440	2628002.724	-2931853.180
HOB2	-3950071.271	2522415.184	-4311638.520
MOBS	-4130635.783	2894953.071	-3890531.452
PARK	-4554254.329	2816652.524	-3454060.942
ROBI	-5034843.830	2523322.857	-2984064.614
STR1	-4467102.304	2683039.504	-3666949.971
SYDN	-4648240.014	2560636.530	-3526319.014
TID1	-4460996.057	2682557.107	-3674443.850
TOW2	-5054582.675	3275504.547	-2091539.869
UNSW	-4644468.651	2549957.940	-3538921.079

3.2 Geodetic, GRS80 Ellipsoid, GDA94

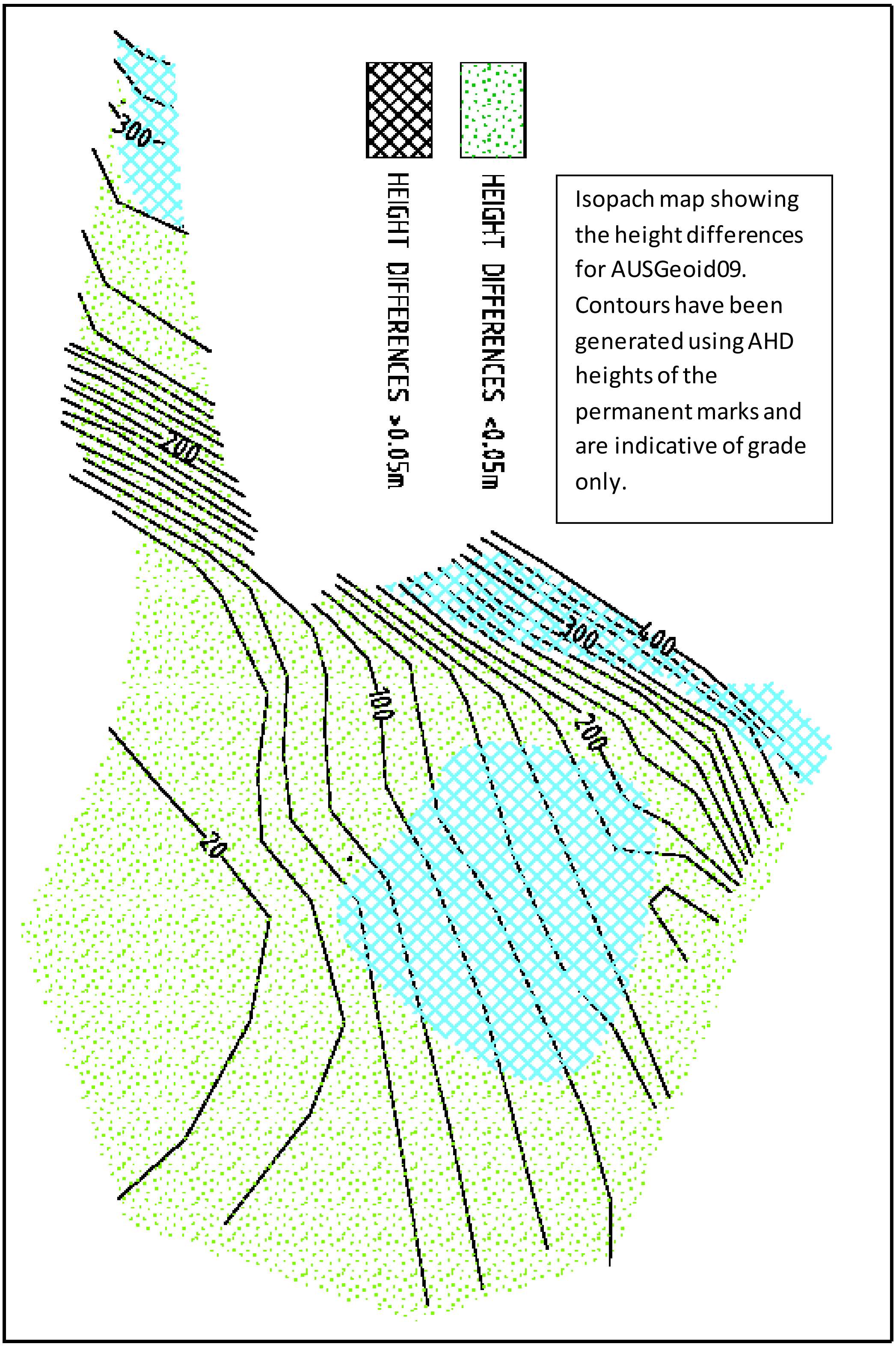
AHD is computed from an Australia wide gravimetric geoid model that has been aposteriori fitted to AHD. The derived AHD is only provided for sites within the extents of the AUSGEOID09 product, see `http://www.ga.gov.au/earth-monitoring/geodesy/geodetic-datums/geoid.html`.

Station	Latitude (DMS)	Longitude (DMS)	Ellipsoidal Height(m)	Derived AHD (m)
1__	-33 41 18.46283	150 32 06.59607	480.344	456.089
BATH	-33 25 46.90205	149 34 01.95936	756.6140	731.470
BEE2	-27 43 13.21509	153 12 09.07948	54.8133	13.666
CEDU	-31 52 00.01656	133 48 35.37610	144.8009	153.595
GATT	-27 32 38.17764	152 19 52.00041	140.5817	98.687
HOB2	-42 48 16.98574	147 26 19.43665	41.1175	44.736
MOBS	-37 49 45.89903	144 58 31.20748	40.6544	35.879
PARK	-32 59 55.58161	148 15 52.58997	397.4475	374.359
ROBI	-28 04 37.08888	153 22 52.50912	65.2893	25.085
STR1	-35 18 55.93955	149 00 36.18068	800.0131	780.871
SYDN	-33 46 51.18411	151 09 01.35787	85.6731	62.633
TID1	-35 23 57.15620	148 58 47.98524	665.4019	646.330
TOW2	-19 16 09.42757	147 03 20.46607	88.2123	29.458
UNSW	-33 55 03.63437	151 13 54.63389	86.9691	64.451

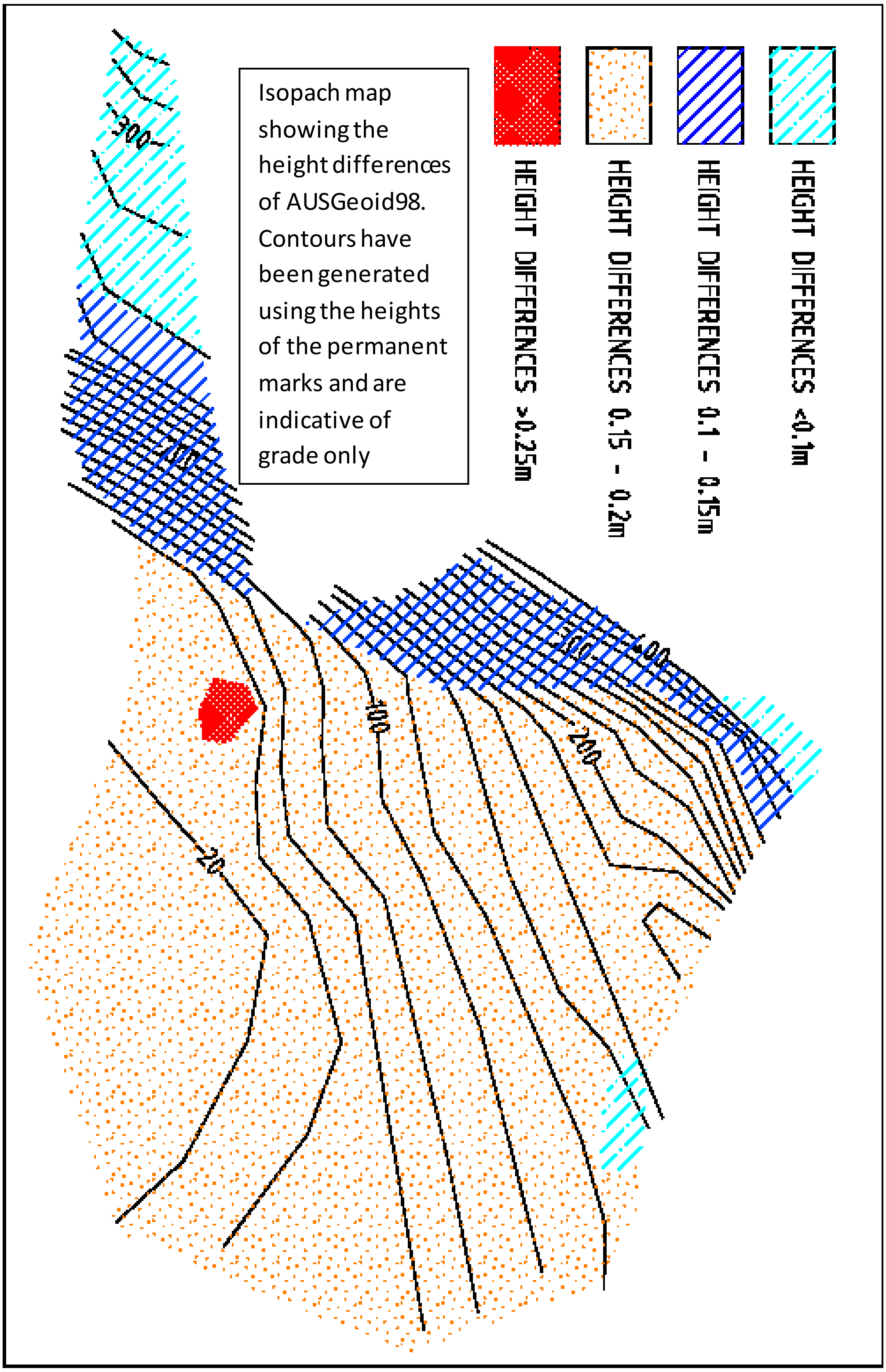
3.3 MGA Grid, GRS80 Ellipsoid, GDA94

Station	East (m)	North (m)	Zone	Ellipsoidal Height (m)	Derived AHD (m)
1__	271522.968	6269658.913	56	480.344	456.089
BATH	738680.565	6298128.348	55	756.614	731.470
BEE2	519963.677	6933760.234	56	54.813	13.666
CEDU	387415.786	6473725.242	53	144.801	153.595
GATT	433957.498	6953137.986	56	140.582	98.688
HOB2	535873.422	5260777.209	55	41.118	44.737
MOBS	321819.612	5811180.032	55	40.654	35.879
PARK	618140.010	6348138.988	55	397.448	374.360
ROBI	537459.197	6894212.658	56	65.289	25.085
STR1	682726.042	6090110.670	55	800.013	780.871
SYDN	328742.577	6260601.380	56	85.673	62.633
TID1	679807.878	6080884.471	55	665.402	646.330
TOW2	505851.351	7869375.336	55	88.212	29.458
UNSW	336547.293	6245564.263	56	86.969	64.451

APPENDIX H: ISOPACH MAPS



Isopach map showing the height differences for AUSGeoid09. Contours have been generated using AHD heights of the permanent marks and are indicative of grade only.



Isopach map showing the height differences of AUSGeoid98. Contours have been generated using the heights of the permanent marks and are indicative of grade only