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Vertical Datum Transformations across the Littoral Zone

Developing a method to establish a common vertical datum before integrating land height data with near-shore seafloor depth data

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Executive Summary

Australia's coastal zone is of great economic, social and environmental importance. Around 85 per cent of the population lives in the coastal zone (DCCEE, 2009). This area is vulnerable to the projected impacts of climate change, creating a demand for better information to assess the risks associated with sea-level rise and coastal inundation.

Seamless elevation data across the littoral zone is an essential requirement for the assessment of coastal risks, and the development of adaptation and mitigation strategies. Seamless coastal data products require the integration of topographic data with offshore bathymetric data. Elevation data free of discontinuities, where topography and bathymetry merge, is necessary to model coastal processes. A pre-requisite for the integration process is that the respective elevation datasets be related to the same vertical datum.

The fundamental aim of this project was to facilitate the creation of seamless elevation datasets across the littoral zone. This involved developing a method to enable the transformation of ellipsoid height/depth data to other vertical datums of interest (and vice versa). As a result of a 2009 CRCSI pilot project on this topic, in which the research team could not obtain reliable, repeatable and accurate ellipsoidal elevation information from LiDAR data, this project has been carried out and is broken into two stages.

Stage 1 - Ensure that ellipsoid-based LiDAR data can be consistently and accurately produced in Australia.

Stage 2 - Develop an ellipsoid-based vertical datum transformation approach for land and near-shore elevation data, involving the development of a Demonstration Tool.

Topographic and bathymetric LiDAR datasets from a selection of providers and locations were analysed to determine whether Australian Height Datum (AHD) and ellipsoidal elevations met individual project accuracy specifications and were devoid of systematic errors. The results of Stage 1 illustrated that, although LiDAR providers are producing both topographic and bathymetric ellipsoidal and AHD data adequate to meet individual project specifications, residual systematic errors do exist. Typical vertical accuracy requirements are ≤±30cm @ 95% CI for topographic LiDAR and ≤±50cm @ 95% CI for bathymetric LiDAR. The residual systematic errors found are in the order of one to 10cm. As the data provided routinely meets specified accuracy tolerances, it can be argued that current data collection and processing techniques can be considered adequate. The supplied data was deemed suitable for the purposes of this project although it was recognised that residual systematic errors in the ellipsoidal heights would propagate directly through any developed transformation process.

To complete Stage 2 of the project, the inter-relationships between the relevant vertical reference frames were determined, modelled and applied. Due to the localised nature of the geometric and temporal variations in the tidal datums this was not a straightforward task. Traditionally, topographic and bathymetric data have been collected and used independently, for different purposes and relative to different reference systems. The terrestrial vertical datums considered in this project are the Geodetic Reference System 1980 (GRS80) ellipsoid realised through the Geocentric Datum of Australia 1994 (GDA94) and AHD, while the marine datums are Lowest

Astronomical Tide (LAT) which has recently been adopted as Chart Datum (CD) in Australia, Mean Sea Level (MSL), Mean High Water Springs (MHWS), and Highest Astronomical Tide (HAT). The GRS80 ellipsoid realised through GDA94 also applies offshore.

The issue of vertical datum transformation in the littoral zone has been the subject of international research. Projects conducted in the United States (US) and United Kingdom (UK) have been evaluated. Review of international projects, research into the relevant concepts, datasets, and tools, and an investigation of the datasets available in Australia led to the adoption of an ellipsoid-based transformation approach. For this purpose, input data may be relevant to any of six vertical reference surfaces. Ellipsoid based MSL heights derived from coastal tide gauges were used to enhance a satellite altimetry-derived Mean Sea Surface (MSS) which represents MSL. Other tidal datums were modelled through hydrodynamic modelling, and AHD was achieved via AUSGeoid09. Figure 1 demonstrates the relevant vertical datums and relationships.

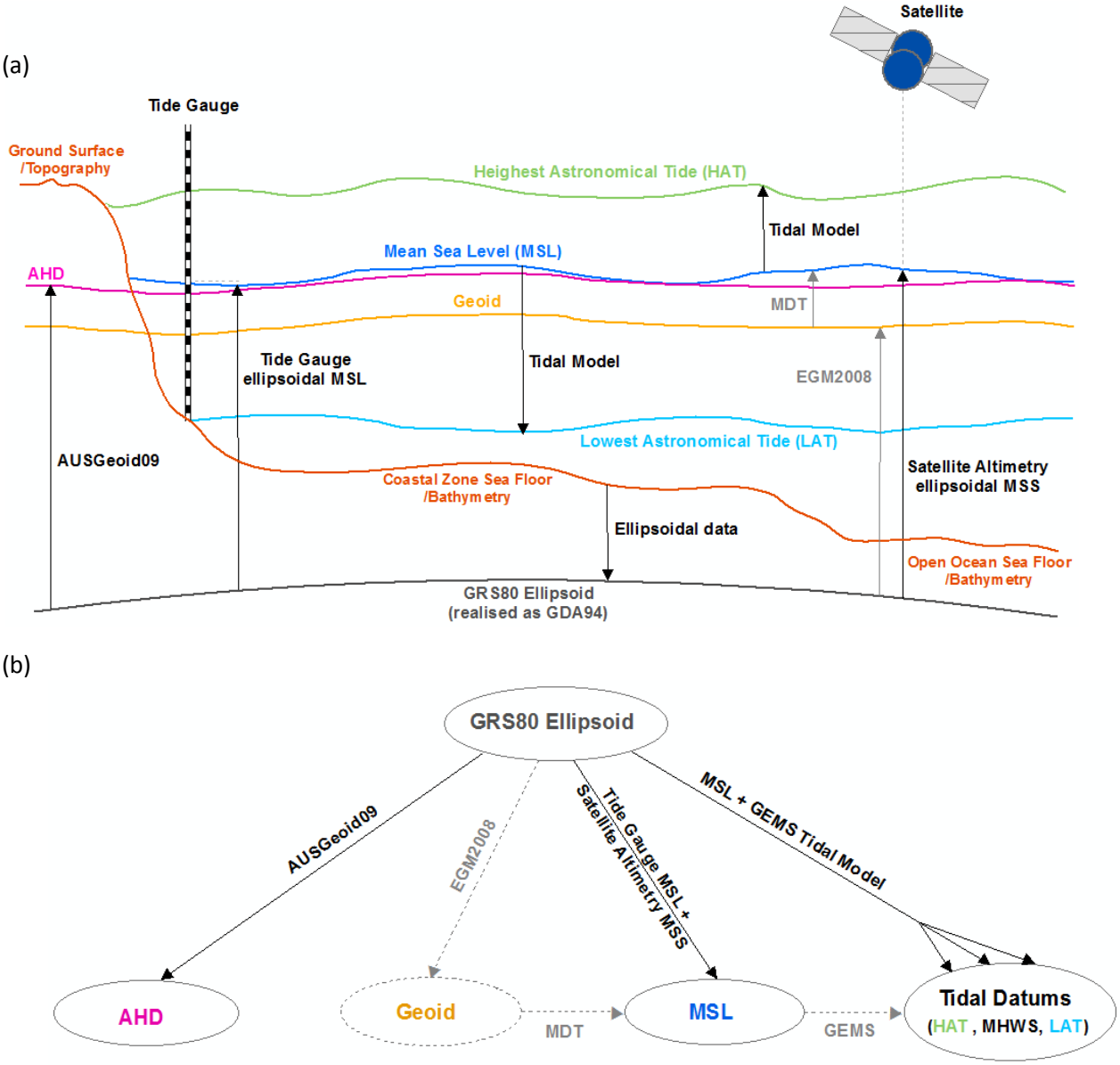

Figure 1. The ellipsoid-based vertical datum transformation approach (a) pictorial representation not including MHWS (surfaces vary in latitude and longitude); (b) transformation process.

Australia is behind its international counterparts in establishing foundation data for transforming between vertical datums. The tide gauge data and metadata available in Australia are not adequate for a project such as this when compared to those in the US and UK. Significant issues with the data include the limited number of gauges around the coast to accurately describe coastal ellipsoidal MSL, the number of existing gauges which are missing MSL and/or ellipsoid data, and the lack of metadata to determine the reliability and accuracy of available tide gauge records. This hinders the determination of a detailed and comprehensive transformation approach as well as its immediate implementation for the entire Australian coast. Until this situation is improved, a suitably accurate vertical datum transformation tool cannot be produced.

Due to current limitations, a Demonstration Tool has been developed as a proof of concept. Gridded separation surfaces have been created for the study area which allow transformation between: ellipsoid-MSL, ellipsoid-LAT, ellipsoid-MHWS, ellipsoid-HAT, and ellipsoid-AHD (and vice versa). The study area for the project extends from the Middle Head Cobblers Bay tide gauge north of Sydney, to the Urangan Storm Tide gauge, north of the Sunshine Coast. The tool may be applied for the area 20km inland of the coastline and seaward to the 2000m bathymetric contour. The inland extent was chosen based on inundation modelling requirements and the seaward extent was an arbitrary value.

The major recommendations for future research and development of a vertical datum transformation tool in Australia are;

- Collation of all existing Australian tide gauge data and metadata and the development of a central tide gauge data repository.
- Increasing the density of tide gauge data around the Australian coast, with a survey of the ellipsoid heights of all new and existing tide gauges.
- Production of a suitable satellite altimetry-derived MSS for Australian waters.
- When improved tide gauge data is available, perform analysis to determine the best methods for aligning the epoch of tide gauge MSLs, coastal tide gauge interpolation, integration with satellite altimetry, and onshore extrapolation.
- Develop improved hydrodynamic model/s and/or alternative interpolation methods for modelling tidal datums.

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List of acronyms

AHD	Australian Height Datum
AHS	Australian Hydrographic Service
AMSA	Australian Maritime Safety Authority
ANTT	Australian National Tide Tables
ATT	Admiralty Tide Tables (UK)
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
BoM	Bureau of Meteorology
CD	Chart Datum
CLS	Collecte Localisation Satellites (France)
CO-OPS	Center for Operational Oceanographic Products and Services (US)
CRCSI	Cooperative Research Centre for Spatial Information
DEM	Digital Elevation Model
DNSC	Danish National Space Centre
DT	Dynamic Topography
DTU	Danish Technical University
EGM2008	Earth Gravitational Model 2008
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
ETRF89	European Terrestrial Reference Frame 1989
GA	Geoscience Australia
GDA94	Geocentric Datum of Australia 1994
GDR	Geophysical Data Record
GEMS	Global Environmental Modelling Solutions
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GRS80	Geodetic Reference System 1980
HAT	Highest Astronomical Tide
ICSM	Intergovernmental Committee on Surveying and Mapping
IHO	International Hydrographic Organization
ITRF	International Terrestrial Reference Frame
LAS	Common LiDAR Data Exchange Format
LAT	Lowest Astronomical Tide
LiDAR	Light Detection and Ranging
LMSL	Local Mean Sea Level (US)
MDT	Mean Dynamic Topography
MGA	Map Grid of Australia
MHW	Mean High Water
MHWS	Mean High Water Springs
MLW	Mean Low Water
MLLW	Mean Lower Low Water (US)
MLWS	Mean Low Water Springs
MSL	Mean Sea Level
MSQ	Maritime Safety Queensland

MSS	Mean Sea Surface
NAD83	North American Datum 1983
NAVD88	North American Vertical Datum 1988
NEDF	National Elevation Data Framework
NGS	National Geodetic Survey (US)
NIB/IB	No Inverse Barometer/Inverse Barometer
NOAA	National Oceanographic and Atmospheric Administration (US)
NTC	National Tidal Centre
NTDE	National Tidal Datum Epoch
OSGM05	Ordnance Survey Gravity Model 2005 (UK)
PCTMSL	Permanent Committee on Tides and Mean Sea Level
POL	Proudman Oceanographic Laboratory (UK)
PSMSL	Permanent Service for Mean Sea Level (global)
QCCCE	Queensland Climate Change Centre of Excellence
SLA	Sea Level Anomaly
SST	Sea Surface Topography
TCARI	Tidal Constituent And Residual Interpolation (US)
TIN	Triangulated Irregular Network
TSS	Topography of the Sea Surface
UCL	University College London
UKHO	United Kingdom Hydrographic Office
UK	United Kingdom
US	United States of America
VDatum	Vertical Datum Transformation (US)
VORF	Vertical Offshore Reference Frame (UK)
WA	Western Australia
WGS84	World Geodetic System 1984

1 Introduction

1.1 Rationale

Australia's coastal zone is of great economic, social and environmental importance. Around 85 per cent of the population live in the coastal zone (DCCEE, 2009). This area is vulnerable to the projected impacts of climate change, creating a demand for better information to assess the risks associated with sea-level rise and coastal inundation.

High accuracy topographic data currently allows simple "bathtub" modelling of sea level rise wherein a location is inundated if its elevation is less than or equal to the projected sea level, regardless of hydrological considerations. The inclusion of high accuracy bathymetric data and the creation of seamless coastal datasets will provide coastal modellers with the ability to consider the hydrological connectivity of the land to the sea and hence model coastal inundation more accurately. The assessment of coastal risks, and the development of effective adaptation and mitigation strategies requires seamless elevation models with a vertical accuracy of better than 0.5m and a horizontal resolution of better than 1 second of arc (30m) (ANZLIC, 2008).

Seamless coastal data products necessitate the integration of topographic height data with bathymetric depth data. Elevation data free of discontinuities, where topography and bathymetry merge, is necessary to accurately model coastal processes. For such high resolution, high accuracy applications, a pre-requisite for the integration process is that the respective elevation datasets be related to the same vertical datum. By establishing a common vertical datum prior to integration, the major source of systematic error is removed. Applications with low accuracy requirements may not require the establishment of a common vertical datum however this project arose out of the National Elevation Data Framework (NEDF) project. For the NEDF, vertical datums were identified as a research issue to be addressed to facilitate the development of a high resolution national DEM with integrated topography and bathymetry (ANZLIC, 2008). The development of such a DEM is also driven by the National Climate Change Adaptation Framework (COAG, 2007).

Traditionally, the hydrographic and topographic communities have operated independently. This has resulted in bathymetric and topographic data being used autonomously and referenced to different vertical datums. Topographic height datasets can be classified into two types of reference systems:

> *Geometric height systems* - Not related to the Earth's gravity field (i.e. ellipsoidal systems useful for example in monitoring crustal movement and airborne mapping); and
>
> *Physical/natural height systems* - Related to the Earth's gravitational field or geoid (e.g. the Australian Height Datum (AHD) which can be used to predict and measure direction and rate of fluid flow amongst other practical applications) (Featherstone, 2006).

In the marine environment, the situation is more complex, with a wider variety of vertical datums being used. Depth measurements are related to tidal datums such as Lowest Astronomical Tide (LAT) or Mean Sea Level (MSL) and primarily support safe navigation but are also the basis for establishing cadastral and maritime boundaries. Chart Datums are employed for the production of hydrographic

charts. Many hydrographic surveyors are now also using the ellipsoid for vertical positioning (Dodd et al, 2010).

In recent years, the use of bathymetric data has moved beyond navigation charts, towards supporting coastal zone management applications (Dodd et al, 2010; Parker, 2002). A number of these applications require a continuous, seamless elevation dataset across the land/sea interface. According to a survey conducted in recent research by Quadros *et al* (2012), 65% of Australian bathymetry users require the integration of bathymetric and topographic data for applications such as storm surge modelling and coastal inundation assessments. Hence there has been a growing investment in near-shore bathymetric and topographic Light Detection and Ranging (LiDAR) surveys around Australia which has led to the development of seamless digital elevation models (DEMs) spanning the land-sea interface. There has been difficulty in the production of these DEMs without a method for establishing a common vertical datum. LiDAR technology is able to provide near-shore depth data, in areas inaccessible to surface vessels.

The applications benefitting from a seamless coastal elevation dataset include, but are not limited to: studying the impacts of sea level rise, storm surge inundation modelling, tsunami inundation modelling, coastal zone management, marine boundary delimitation, habitat restoration, erosion studies, coastal ecosystem modelling, beach renourishment projects, coastal construction and development, shoreline change analysis, improved efficiency of hydrographic surveying by reducing the reliance on tide gauges and tidal models, and building and maintaining the national DEM.

Given the use of different vertical datums for height and depth data, integrating topographic and bathymetric datasets across the coastal zone has been and continues to be problematic. Australian bathymetry users have identified vertical datums as one of the most common problems experienced in this context (Quadros et al, 2012). The problem has also been highlighted in projects such as the development of the Victorian coastal DEM (Quadros and Collier, 2009). There is increasing need and demand for a system to efficiently transform elevations between all the relevant vertical reference surfaces. To achieve this, the relationships between the relevant vertical reference frames need to be determined, modelled and applied. Due to the localised nature of the geometric and temporal variations in tidal datums this is not a straightforward task. Tidal datum surfaces are notoriously difficult to realise in practice because of the temporal and spatial variations they experience and the requirement for long period observation (NOAA, 2007; CO-OPS, 2006).

This project focused on adopting an ellipsoid-based approach for vertical datum transformations of coastal zone elevation data. The ellipsoid is the only surface that is used for modern data collection on both land and sea (Dodd et al, 2010). Traditionally, reference ellipsoids were used to define horizontal datums but with the emergence of high-accuracy Global Navigation Satellite System (GNSS), reference ellipsoids are now also being used to define vertical datums. The GNSS provides accurate, repeatable and cost-effective ellipsoid heights at tide gauges and bench marks which enable ellipsoid-based transformations. While not of particular practical value to many users, an ellipsoidal height datum can be rigorously defined and realised in a repeatable manner. This temporal and geometric stability yields a consistent frame of reference for the purposes of developing transformation models.

The International Federation of Surveyors (FIG, 2006) suggested the Geodetic Reference System 1980 (GRS80) ellipsoid as a suitable base for inter-relating vertical reference surfaces for hydrographic purposes. International projects (discussed in *Section 3* & *Appendix B*) also tend to adopt ellipsoid-based approaches. Given there is an intention to move Australia to a dynamic version of GDA in 2020 with the associated ellipsoidal height datum replacing AHD as the national height reference surface (Dando, 2012) an ellipsoid-based approach is justified. While such an approach is conceptually simple, technically sound and eminently logical, implementation on a national scale is complex and time consuming.

The vertical datum transformation approach and recommendations of this project aim to enable the creation of seamless elevation datasets across the littoral zone, being the zone between the highest and lowest tidal lines. The Demonstration Tool developed for the study area transforms elevation data between a number of common vertical datums. This enables adjacent datasets referenced to disparate vertical datums, to be consistently referenced to the same vertical datum. Once elevation datasets are referenced to the same vertical datum, and any other issues causing data mismatches (refer to *Section 8.2* & Figure 45) are resolved, it will be a relatively straight-forward task to integrate the data into a single elevation model.

1.2 Previous Work

Previous vertical datum research in Australia has been conducted in Queensland and Western Australia. In Queensland, the AUSHYDROID model relating the height of Chart Datum (CD) (LAT in Australia - refer to *Section 3.2*) to the World Geodetic System 1984 (WGS84) ellipsoid was developed in 2004 (Martin and Broadbent, 2004; Todd et al, 2004). AUSHYDROID is the hydrographic equivalent of AUSGeoid (discussed in *Section 4.5*). The model has been developed using the values of LAT and the WGS84 ellipsoid at tidal stations, and extrapolating offshore, using the tidal zoning process, explained as follows. In order to represent the curved CD/LAT surface, it is divided into a number of zones (polygons). These polygons are called tidal zones and are small enough for the curved surface within each zone to be regarded as planar. This approximation simplifies the estimation of the CD/LAT elevation and thus the AUSHYDROID value at any point. The elevation of tidal datums other than CD/LAT could also be interpolated in this way.

In some cases, tidal zoning can result in steps where discrete zones or tidal planes meet (CO-OPS, 2007). AUSHYDROID was created using a triangulated irregular network (TIN) to avoid this problem. However, statistical modelling such as used for AUSHYDROID is not as sophisticated a method for modelling tidal datums as a hydrodynamic model (refer to *Section 12.2*). Hydrodynamic models are very costly to build and there are few currently available. Where they are unavailable/unfeasible for this project, statistical models such as AUSHYDROID will be required. At this stage, AUSHYDROID has only been developed for the Queensland coast and for LAT to WGS84 conversions. A nationwide implementation could provide a convenient means of datum transformation where hydrodynamic models are absent and if the necessary tide gauge data could be acquired.

In February 2009 the Cooperative Research Centre for Spatial Information (CRCSI), with support from Landgate and the Western Australian (WA) Department of Planning and Infrastructure, conducted a pilot project to develop a general approach to vertical datum transformation across the littoral zone (Seager, 2011a and 2011b). The project was based on a WA case study. The intention

was to obtain topographic and bathymetric LiDAR data relative to the ellipsoid and to investigate strategies for creating a seamless ellipsoidal height-based DEM. Following this, methods for transformation to other relevant reference frames such as AHD and tidal datums were to be considered. However, at the time the researchers were unable to obtain reliable and accurate ellipsoidal elevation data from the data providers.

The research concluded that systematic errors in the topographic data indicated a potential problem with the methodology used to produce the ellipsoidal heights. However, these issues were resolved whilst working with the data provider. The bathymetric LiDAR data was collected with the Fugro LADS Mk II system. Although the bathymetric AHD data was found to be acceptable, systematic errors were discovered in the ellipsoid height data. These errors manifested along the flight lines as both "waves" and steps between adjacent flight lines and raised concerns over the data collection and/or processing methodology. The research concluded that the supplied bathymetric data was not suitable for deriving an offshore vertical datum transformation procedure.

This project continued the previous WA CRCSI research by following the aims and objectives set out in *Section 1.3*. Further analysis has been performed on topographic and bathymetric LiDAR data in new study areas. Bathymetric data from the new Fugro LADS Mk 3 system was tested and a discussion on the outcomes of this analysis can be found in *Section 6*.

1.3 Aims & Objectives

The fundamental aim of this project was to facilitate the creation of seamless elevation datasets across the Australian littoral zone by developing a method which enabled the transformation of ellipsoid height/depth related data to other vertical datums of user interest (and vice versa). Given this aim, and in the context of previous work, this led to the two primary objectives outlined below:

Stage 1 - Ensure that ellipsoid-based topographic and bathymetric LiDAR data can be consistently and accurately produced in Australia.

Stage 2 - Develop an ellipsoid-based vertical datum transformation approach for land and near-shore elevation data, involving the development of a Demonstration Tool.

1.4 Study Area

Due to data and time constraints, the littoral zone for the whole of the Australian coast could not be included within the Demonstration Tool for this project, however the approach adopted and recommendations made are applicable to the entire Australian coast. Because of the lack of tide gauge data and adjacent topographic and bathymetric LiDAR data, the Demonstration Tool was restricted to a solution for the case study area along the New South Wales and Queensland coasts. The study area extends from the Middle Head Cobblers Bay tide gauge just north of Sydney, to the Urangan Storm Tide gauge just north of the Sunshine Coast (Figure 2). Strictly speaking, the northern extent of the study area should have been the Marine Operations Base Southport tide gauge. However, the LiDAR data available for the case study existed north of this point, so it was necessary to extend the study area to the Urangan Storm Tide gauge, despite the distance between these two tide gauges being approximately 300km, without any tide gauge data between them.

The Demonstration Tool covers an area from 20km inland of the coastline, defined by an offset from the *GEODATA COAST 1000K 2004* coastline data (described in *Section 4.5*), to the 2000m bathymetric contour as defined by the Australian Bathymetric and Topographic Grid data (described in *Section 4.5*). The inland extent was selected based on inundation modelling requirements and is further discussed in *Section 7.2.4.* Inundation modelling under sea level rise is the major driver for, and application of the tool, therefore it must be applicable onshore. The seaward extent was an arbitrary value. For a future tool, the seaward extent should be limited to depths in which tidal datums apply i.e. to depths where datum separations exceed vertical accuracy tolerances of the data being transformed. For the study area, the 2000m bathymetric contour is offset approximately 30 - 100km from the coastline. Figure 2 shows the location of the case study area within Australia.

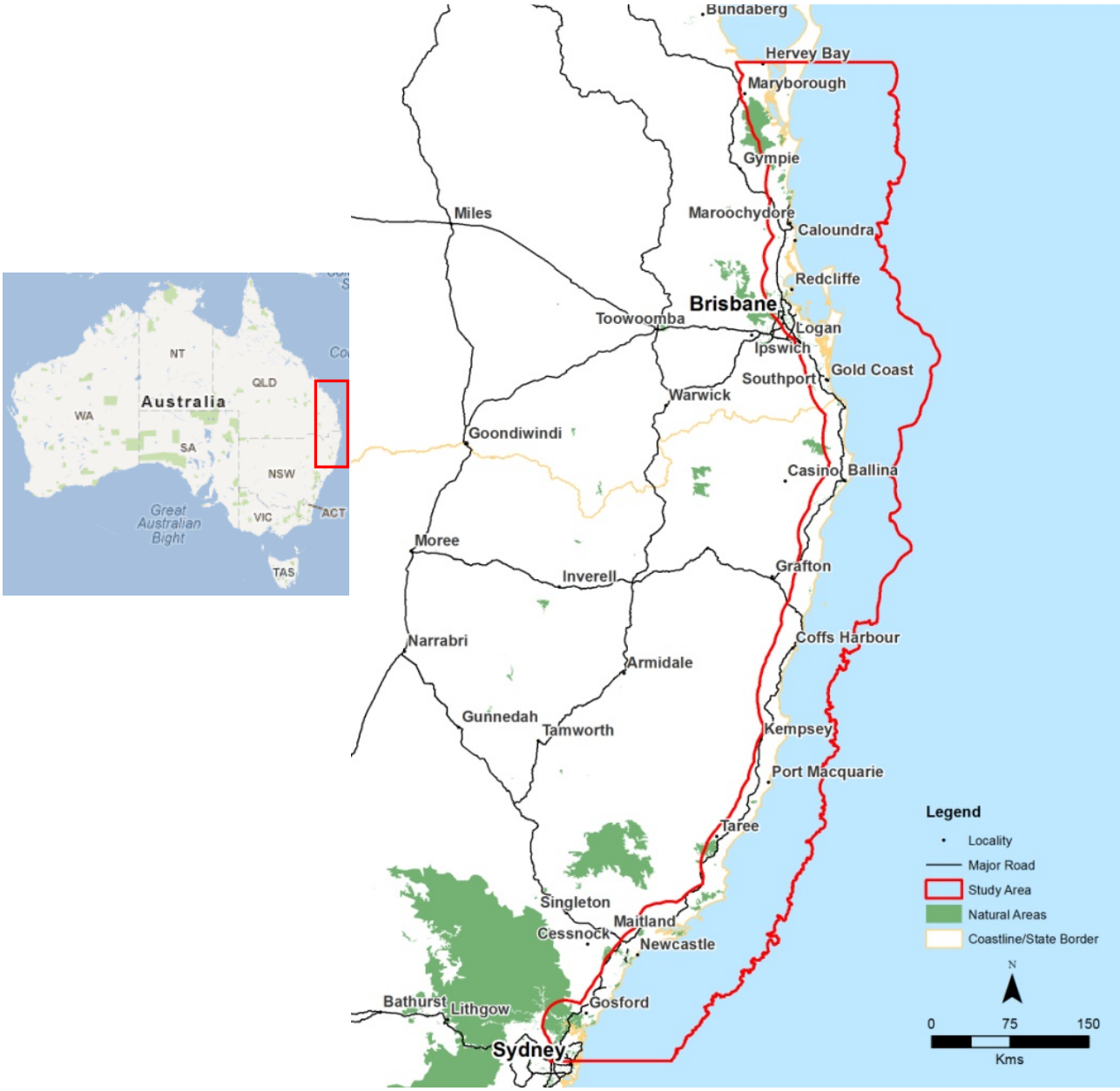


Figure 2. Case study area highlighted in red.

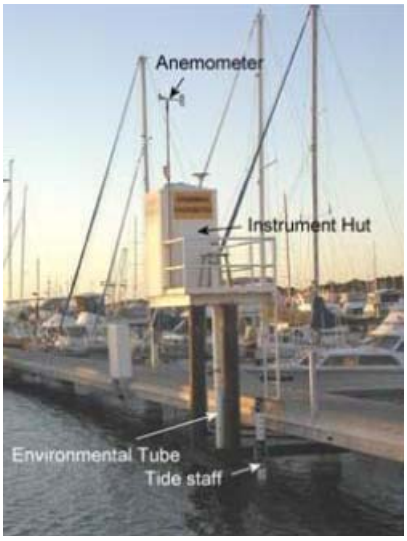
2 Background Concepts

2.1 Australian Tide Gauges

Tide gauges provide an important record of coastal sea level. Tide gauge installations are usually placed on piers and, as depicted in Figure 3 and Figure 4, consist of elements such as (PCTMSL, 2011);

- A data recorder (short term recording device)
- At least one water level sensor (there are a number of different types)
- A method of communicating readings to users
- A method of independently checking the height and time (e.g. a tide staff and clock)
- A station height datum which water level heights are measured relative to
- A tide gauge benchmark of known elevation relative to the station height datum as well as a number of recovery benchmarks
- Ideally devices for measuring wind speed, air and water temperature, and atmospheric pressure so these environmental influences on the water level can be eliminated
- More recently a permanent GNSS receiver to determine ellipsoidal height

The station height datum is an arbitrary value unique to each station, usually defined by the zero of the first tide staff installed. It is established at an elevation below which the water is never expected to fall. The station height datum is referenced to the tide gauge benchmark and is held constant. Water level sensors continuously record the height of the water level with respect to the station height datum allowing derivation of MSL and other tidal datums as required. To calculate MSL, known as the 'still water' level, continuous measurements are averaged for a sufficient time period to allow high frequency motions (e.g. wind waves) and periodic changes (e.g. tides) to be eliminated (PSMSL, 2012). It is important to note that tidal datum heights vary spatially and temporally (refer to *Section 12.2*).



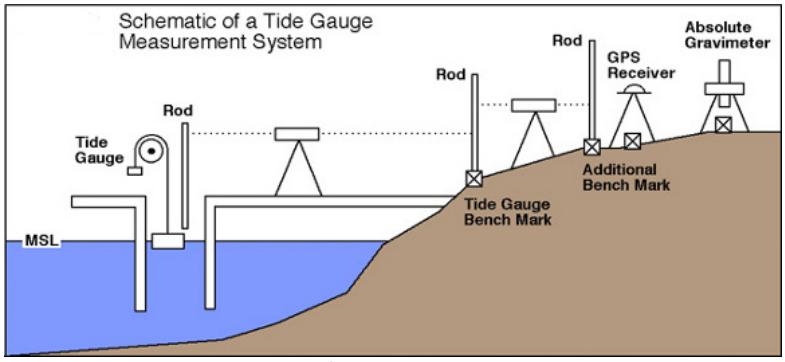


Figure 3. Example of a common tide gauge measurement system (CU, 2011).

Figure 4. SEA-Level Fine Resolution Acoustic Measuring Equipment (SEAFRAME)[1], Hillarys, WA (PCTMSL, 2011).

[1] The NTC maintains 14 standard SEAFRAME stations (plus port operators own two supplementary stations) which measure sea level very accurately. This SEAFRAME network is of a world leading standard.

Water level measurements at tide gauges, along with their associated levelling and GNSS measurements can be subject to a number of errors and influences, as detailed in Table 1. Most of these can be corrected for if enough data, metadata and accurate historical records exist. Unfortunately, in Australia, this supplementary information is rarely available and when metadata records do exist, they are not accessible from a single central repository[2]. As a consequence the level of confidence that can be put in the accuracy and reliability of Australian tide gauge information is often low. Examples of this from Jayaswal (2012) of the Australian Hydrographic Service (AHS) and Dando (2012) of Geoscience Australia (GA) are given in italics in Table 1.

Table 1. Factors that can affect the accuracy and reliability of tide gauge records (PSMSL, 2012; PCTMSL, 2011; Harvey et al, 2002; Aubrey and Emery, 1986).

Type	Issues	Corrections
Measurement errors	- Accuracy of gauge measurements varies with the type and age of equipment and level of maintenance - Rigour with which gauge readings are checked and calibrated - The type and age of levelling and GNSS equipment and rigour of survey methods used - Epoch of water level measurements (ideally at least a 19 year epoch) - Frequency of levelling and GNSS connections (ideally at least yearly)	Requires accurate detailed records about the gauge and its maintenance, as well as levelling and GNSS survey connections so that issues can be accounted for. If water level measurements do not cover the full 19 year epoch (refer to *Section 12.2*), they should be corrected to that epoch. *Australian tide gauges are of varying types and ages, have operated for various periods of time from one to 100 years, with records of calibration or maintenance not kept or not easily accessible. Levelling connections are of various dates, mostly very old, and to different epochs of the AHD. If an ellipsoidal height exists, it may be relative to GRS80, WGS84 or different epochs of the ITRF, of varying quality, or perhaps even derived from AHD via a geoid model. Which datum applies is often unknown. A number of gauges have changed operators numerous times therefore reliability is low.*
Datum errors	- Movement or replacement of gauge equipment can cause levels to differ slightly and often these changes are not recorded - Subsidence of wharf structures - Changes made to gauge datum that may not have been recorded	Requires accurate detailed record of changes to tide gauges and monitoring of the structures they are on, so that changes can be accounted for. *It is known that some Australian gauges have been shifted within their local area, with limited records/metadata about that movement.*
Geological effects	- Tectonic motion at plate boundaries - Earthquakes - Glacial isostatic adjustment - Sedimentation	Collocation of GNSS equipment or regular measurement with GNSS equipment to determine ellipsoid height and monitor land movements.
Hydrological effects	- Gauges are usually located in ports or estuaries so river flow and tidal lag can be present - Flood	These issues aren't generally corrected for and can explain the differences between tide gauge measurements and nearby satellite altimetry measurements. If obvious in the record, the effects of flood may be able to be removed.
Meteorological effects	- Atmospheric pressure - Wind - Temperature	Monthly mean air pressure data are needed to correct for changes in atmospheric pressure. The effects of wind and temperature are largely averaged out over the epoch that tidal levels are calculated for, but if measured can be further corrected for.
Oceanographic effects	- Tides - Shallow water effects - Coastally trapped waves and boundary currents - Storm surge	The effects of tides are averaged out over the epoch that tidal levels are calculated for. The other issues aren't generally corrected for and can explain the differences between tide gauge measurements and nearby satellite altimetry measurements.
Anthropogenic effects	- Oil & groundwater extraction - Changes to dynamics in the area due to new structures, dredging etc	Requires collocation of GNSS equipment to measure ellipsoid height and monitor land movements as well as records of changes to dynamics to account for them in the record.

[2] Technically BoM should hold a copy of metadata regarding levelling, shift, calibrations and accuracy of the tide gauges for standard ports. For other tide gauges, metadata is held by the operating authorities (Jayaswal, 2012).

A significant issue affecting access to Australian tide gauge data is the lack of a central repository. Data is currently held by the operators responsible for each gauge. A wide variety of institutions operate the gauges including the National Tidal Centre (NTC), the AHS, the Australian Maritime Safety Authority (AMSA), as well as many port authorities and state agencies. This makes collating the data and calculating ellipsoidal MSL heights for Australian tide gauges a significant challenge in its own right. The NTC is the primary source of tide tables, tidal streams and tidal constituents for Australia and manage the national data archive for sea levels and tides. However, they only hold data for major ports and do not currently act as a national repository for all Australian tide gauge data. It is unclear what percentage of tide gauge data the NTC hold but using the Queensland coast as an example, approximately 700 gauges exist while the NTC hold data just for the 34 major ports.

In comparison, the US has the Center for Operational Oceanographic Products and Services (CO-OPS) database, a publicly accessible website which makes available all coastal oceanographic products and services. In the UK case, tide gauge data is accessible through the United Kingdom Hydrographic Office (UKHO) which supplies onshore tide gauge data via the Admiralty Tide Tables (ATT) and also holds data from offshore gauges (Turner et al, 2010). The tide gauge infrastructure and management systems in Australia are not sufficient for a project such as this when compared to those in the US and UK.

It should be noted that the AHS and the Intergovernmental Committee on Surveying and Mapping (ICSM) Permanent Committee on Tides and Mean Sea Level (PCTMSL) have a joint project to collate the ellipsoidal heights, levelling connections and tidal heights of continuously operated coastal tide gauges which include major and some secondary ports. Uncertainties will be calculated for existing data, and tide gauges with missing ellipsoidal heights, levelling connections or tidal heights will be identified. However, there are 1000s of additional secondary tide gauges that are not incorporated in this project. The project has been running for at least 5 years and remains ongoing with completion expected by the end of 2012 (Jayaswal, 2012).

The AHS supplied the collated tide gauge data for the purposes of this project. This included 131 continuously operating coastal tide gauges around Australia including on islands, within rivers, and Antarctic gauges. Of these, 111 have MSL values and 71 of these also have ellipsoid heights. Of the 71 gauges with the required data, after those in Antarctica and on distant islands are excluded, 67 remain (the quality of which is unknown) sparsely distributed along the nearly 36,000km of Australian mainland coastline (60,000km including islands) (Figure 5). This is in contrast to the 1,987 gauges available for the about 8,200km of contiguous US coast for VDatum, and the 880 gauges to represent around 18,000km of UK coastline (31,000km including major islands) for VORF. There were 13 tide gauges with the required data available in the study area spread over a distance of greater than 1,000km. These approximate coastline lengths illustrate the dramatic differences in the density of tide gauges per kilometre of coastline.

Of the 67 Australian gauges, there are none in South Australia and in other areas there can be 100s to 1000s of kilometres between gauges. The values of and relationships between tidal datums are only known at the point locations of tide gauges where they are measured. At all locations other than tide gauges, tidal datums must be estimated via modelling (refer to *Sections 12.1 & 12.2*). Therefore a greater density of gauges leads to greater accuracy in modelling tidal datum surfaces. This is especially true in areas of complex coastline such as rivers and bays. When transferring a tidal

datum along the coast, the AHS recommends a maximum distance of 16km between gauges where tidal conditions vary gradually, and 1.6km where conditions vary rapidly. The currently available Australian gauges are too sparse to accurately model tidal datums around Australia. This assumption is tested in (*Section 7.2.1*).

A fundamental requirement of this project is the derivation of ellipsoid MSL heights at tide gauges. As mentioned, the AHS ICSM PCTMSL project provided this project with the data for continuously operating coastal tide gauges around Australia (further discussed in *Section 4.3*). The data comes from 19 different sources. Tidal datum, ellipsoid and AHD heights were provided adjusted relative to LAT at the current National Tidal Datum Epoch (NTDE) of 1992-2011 (refer to *Section 12.2*). However, in a lot of cases there was missing information. For the study area (Figure 1), ellipsoidal MSL heights were required for tide gauges from north of Sydney (the Middle Head Cobblers Bay gauge), to just north of the Sunshine Coast (Urangan Storm Tide gauge). Five of the 18 gauges in this area were missing ellipsoid heights, one of which was also missing a MSL height (Figure 5). It was not possible to acquire or derive this missing data during the project.

Australian tide gauges with both MSL and ellipsoid height values are sparse. The data and metadata are of unknown/varying quality and are difficult to access because there is no central repository. As a result of these constraints, an accurate and reliable transformation tool which provides full coverage of the Australian coast could not be produced unless the density and metadata is improved for the tide gauge network. This project has produced a Demonstration Tool for a Map Grid of Australia (MGA) Zone 56 study area as proof of the concept and recommendations have been made about the need for improved tide gauge records. The procedure required to build the vertical datum transformation tool for other areas of the Australian coastline is described in *Appendix J*.

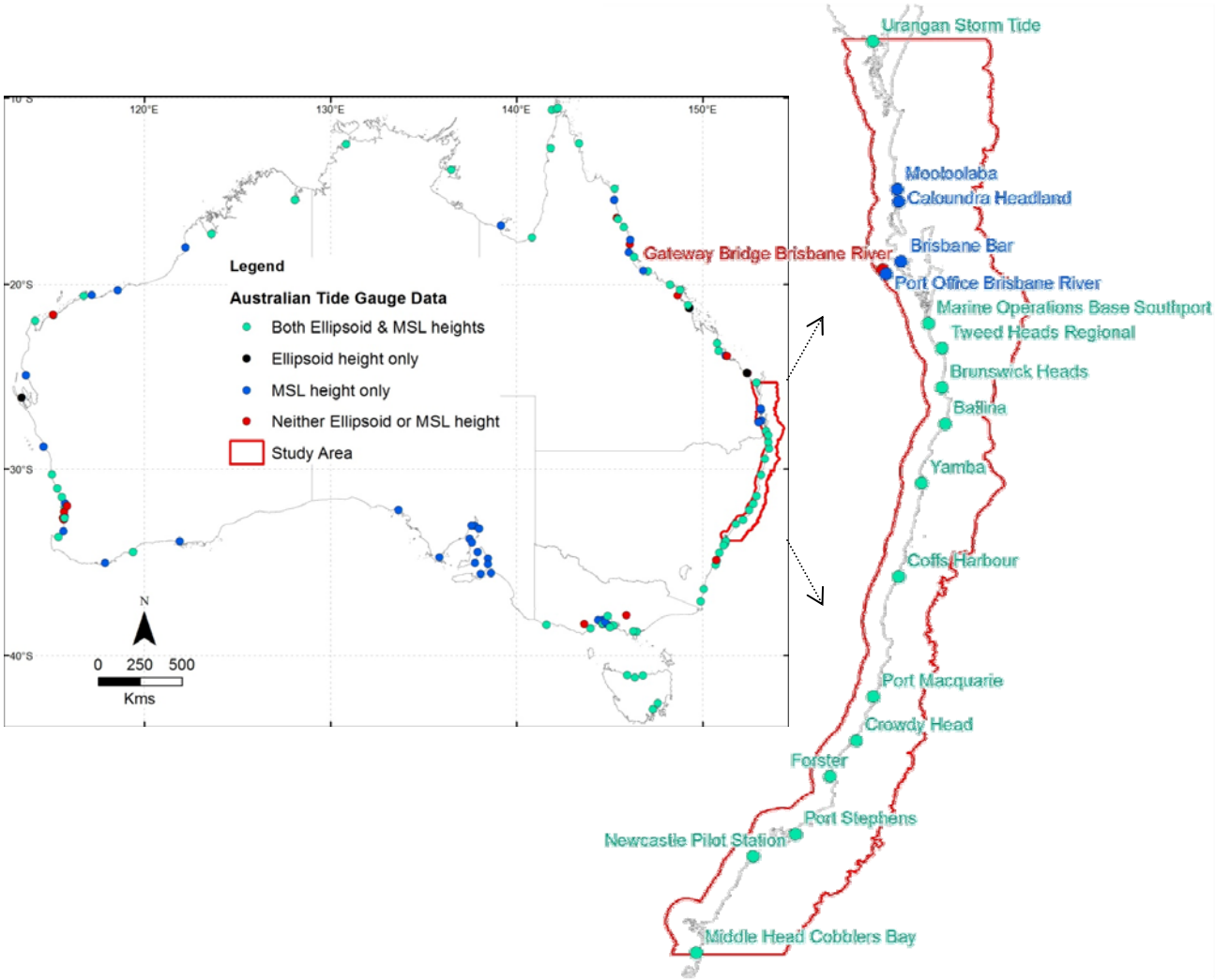


Figure 5. Australian and study area tide gauge data with and without ellipsoid and MSL heights.

2.2 Other Background Concepts

In order to understand the approach adopted for coastal vertical datum transformation, there are a number of additional background concepts that need to be understood. A summary of these concepts follows and further information is contained in *Appendix A*. The concepts include;

- Tides, Analysis & Prediction
- Tidal Datums & Models
- Satellite Altimetry
- Satellite Altimetry Derived Mean Sea Surface
- Mean Dynamic Topography
- Permanent Tide System
- Spectral Content

The relevant marine reference surfaces are primarily tidal datums which can be determined at tide gauges by averaging a particular phase of tide such as Mean High Water Springs (MHWS) or taking the extreme values for LAT or Highest Astronomical Tide (HAT) (*Section 12.1)*. However, at locations other than tide gauges, modelling is required. Statistical modelling (interpolation/extrapolation) is generally acceptable in the vicinity of primary tide gauges but elsewhere hydrodynamic models are a more reliable way of estimating tide height. Hydrodynamic models are costly to build and there are very few currently available. In Australia, Global Environmental Modelling Solutions (GEMS) is one of only a very limited number of organisations that has developed a national tide model with a resolution of better than 100km (*Section 5.4)*. GEMS is the tide model used in the Demonstration Tool and is discussed in *Section 5.4.* However GEMS could be replaced with a more accurate model should one become available.

Satellite altimetry determines sea surface height relative to an ellipsoid. It provides centimetre accurate measurements in the open oceans, but is less reliable near the coast. Satellite altimetry should be used with caution within 22km of the Australian coastline and rejected entirely within 4km (Deng et al, 2010) (*Section 12.3)*. A Mean Sea Surface (MSS) is a secondary gridded product of satellite altimetry that represents the same physical variable as tide gauge MSL measurements. The accuracy of a MSS is degraded from the original accuracy of altimetry sea surface height measurements, to around three to ten centimetres (worse at the coast) (Andersen, 2012), due to the additional data processing required to produce a MSS. Ellipsoidal MSL tide gauge measurements can therefore be used to enhance a satellite altimetry derived MSS at the coast. The MSS used must match the epoch and ellipsoid of the tide gauge data (*Section 12.4)*.

A MSS comprises the geoid and Mean Dynamic Topography (MDT). MDT is the difference between the geoid and the sea surface due to wind, atmospheric pressure, water temperature, salinity, and currents. The determination of MDT around Australia would add to the understanding of the relationships between vertical datums. It was not used to implement the transformation approach, although is recommended for future development of a high accuracy tool. MDT was modelled as part of the US and UK projects. If MDT is calculated with the direct method (MSS minus geoid), the four issues to be considered are the ellipsoid, permanent tide system, spectral content (*Section 12.7)*, and time period used (*Section 12.5)*. It should be noted that development of a MDT should not difference MSL and AUSGeoid09 heights. As AUSGeoid09 was warped to fit MSL, it largely contains

MDT (Featherstone and Filmer, 2012) and would produce values typically smaller than true MDT. To produce a MDT for Australia via the direct method, a geoid such as the Earth Gravitational Model 2008 (EGM08) or the gravimetric only component of AUSGeoid09 would be required.

The permanent earth tide is the tidal deformation of the Earth's crust. The modelling of this deformation has led to three definitions of the permanent earth tide; tide-free, mean-tide, and zero-tide systems. Corrections for the permanent tide system are intended to improve the precision of geodetic measurement. When combining heights from various sources, they should all be relative to the same permanent tide system to maximise precision. Equations and software are available to convert the permanent tide system of relevant data. The Demonstration Tool adopts the tide-free system (*Section 12.6)*.

3 Review of International Projects

3.1 Overview of Projects

A number of institutions have developed or are in the process of developing vertical datum separation models. These have either been initiated for hydrographic purposes to enable the use of GNSS for referencing depth measurements at sea, or, to enable the creation of seamless coastal datasets. Canada surveyed many tide stations with GNSS and used hydrodynamic modelling and satellite altimetry to produce ellipsoidal separation models in the early to mid 1990s (FIG, 2006; Wells et al, 2004). France undertook the 'BATHYELLI' project in 2005 to develop ellipsoidal separation models again using altimetry, tide gauge observations, and hydrodynamic modelling (Pineau-Guillou and Dorst, 2011). However, it is the more notable examples in the US and UK which are discussed in more detail in this report.

The US, UK and Australian projects are summarised in Table 2. More extensive information on the US VDatum and the UK VORF projects can be found in *Appendix B*. The following section discusses the Australian situation with comparison made to the US and UK activities. The biggest impediment to Australia, in adopting a methodology for vertical datum transformation, is the lack of quality tide gauge data. Despite this, a broad approach has been developed similar to that of VORF, although initiated for reasons akin to VDatum (refer to *Appendix B*).

Table 2. Summary of Projects Reviewed. Refer to *Appendix B Section 12.8* for further information.

	US VDatum	UK VORF	Australia
Project Aim	To support a seamless bathymetric - topographic digital elevation model (DEM).	Primarily navigational objectives i.e. to improve marine safety. Also for improved efficiency of hydrographic surveying etc.	To facilitate the creation of seamless DEMs spanning the land-sea interface to study the impacts of sea level rise.
Project Length	13 years	3 years	1 year to date
No. of Datums	36	24	6
Accuracy	Evaluated in terms of the standard deviations.	10cm in coastal waters and 15cm in the open ocean (one standard deviation).	Unknown
Grid Resolution	E.g. 0.05 degrees in latitude & 0.025 degrees in longitude.	Gridded at 0.008 degree intervals with patches of 0.003 degrees.	Demo Tool - one minute resolution (~1-2km).
Extent	1-2km inland of the MHW to 25 nautical miles (46.3km) seaward.	UK and Irish continental shelves (not on land).	20km inland of the MHW coastline to the 2000m bathymetric contour.
Approach	Minimum spanning tree	Ellipsoid-based	Ellipsoid-based
Modelling the difference between MSL and the geoid	TSS - vertical separation between the orthometric height system NAVD88 geopotential surface and LMSL. Generated using tide gauge NAVD88 values & observed tidal datums, plus hydrodynamic modelling.	SST – vertical separation between MSL and the OSGM05 geoid. Generated by subtracting a tide gauge enhanced satellite altimetry derived MSS from OSGM05.	MDT – N/A for Demo Tool. Fundamental approach - vertical separation between MSL & the EGM2008 geoid. Generated by subtracting a tide gauge enhanced satellite altimetry derived MSS from EGM2008.
No. of Tide Gauges	1,987	880	67 (currently)
Modelling Tidal Datums	Existing hydrodynamic models and specially developed TCARI spatial interpolation technique.	Optimal combination of tide gauge tidal levels, hydrodynamic modelling, and satellite altimetry derived global ocean tide models.	GEMS hydrodynamic model. Other models can replace GEMS and/or specific interpolation technique/s may need to be developed.
Permanent Tide System	Tide-free	Tide-free	Tide-free

3.2 The Australian Situation

Australia has fewer applicable vertical datums than the UK or the US but a greater length of coastline. The two most relevant vertical reference systems on land are the AHD and the GRS80 ellipsoid realised through the Geocentric Datum of Australia 1994 (GDA94)[3]. WGS84, other realisations of ITRF, and the Australian National Spheroid (ANS) could also be considered but these are excluded from this project for the reasons explained below.

The ANS was the ellipsoid behind Australia's previous geodetic datum (AGD66/84). This datum is now obsolete and therefore not considered further. There is a misconception that GDA94, WGS84 and ITRF are identical 'for all practical purposes'. Although this remains a reasonable assumption for low accuracy (~ >1m) applications, it was strictly only true in 1994 when GDA94 was realised. GDA94 is a static datum and since 1994, ITRF and WGS84 have gradually diverged from GDA94 due to the tectonic motion of the Australian plate, and the ongoing refinement of the ITRF and WGS84 (GA, 2012). Although WGS84 and various realisations of ITRF are sometimes used in Australia, for the Demonstration Tool, the ellipsoidal reference system of choice is limited to GRS80 realised as GDA94 as this is the official national datum.

[3] GDA94 is the current geodetic datum in Australia. It based on ITRF92, realised at 1 January 1994.

The horizontal coordinates of input data must also be in the applicable GDA94 MGA Zone. The reasons for this are that GDA94 is the national datum of Australia and the majority of Australian elevation data is referenced to MGA. If users possess elevation data relative to another reference frame such as ITRF 2000, they will be required to pre-transform to GDA94 using the parameters provided on the GA website[4]. There is an intention to move Australia to a dynamic version of GDA in 2020 with the associated ellipsoidal height datum replacing AHD (Dando, 2012). 'Working surfaces' between the new ellipsoidal reference surface and AHD (equivalent to AUSGeoid09) as well as a conventional geoid will be provided. If this intention is carried out, the transformation tool would need to accommodate the change and incorporate the 'working surfaces'.

In the marine environment, there are a greater number of vertical datums to consider. A list of tidal datums as defined by the AHS tidal glossary is provided in Table 14 with those considered in this project being LAT, MSL, MHWS, and HAT. Variations from the AHS definitions may occur in state legislation however the AHS definitions have been adopted. In addition to the four tidal datums, GRS80 ellipsoidal heights as mentioned above, and CD are applicable offshore. CD is the traditional surface to refer depths to on a nautical chart. A CD is generally a tidal datum derived from a phase of the tide, commonly LAT. CD on all current Australian nautical charts is LAT (Martin and Broadbent, 2004) predominantly for the current epoch 1992-2011 however some of the charts first published on LAT are still on the old epoch 1980-1999. The first chart published on LAT in Australia was around 1994 based on a decision made by the AHS to meet technical Resolution A2.5 of the IHO and standardise the CD in use (FIG, 2006). The CD in use before LAT was an approximation of Indian Spring Low Water while port charts used an arbitrary port datum. Currently, the intention is to retain CD as LAT 1992-2011 until there is a LAT epoch that is different to the current epoch by +/- 0.1m. This is not within the next 5-10 years (Jayaswal, 2012). However, there is some debate around this as when MSL is adjusted for sea level rise, high water predictions can be higher than HAT.

The vertical datums selected as relevant are AHD, the GRS80 ellipsoid realised through GDA94, LAT, MSL, MHWS, and HAT. The inclusion of these particular reference surfaces in the vertical datum transformation process is supported by recent research. Quadros *et al* (2012) conducted a bathymetry user needs analysis in which a questionnaire was distributed to Australian users of bathymetry data. Figure 6 shows the datums selected for this project are the same datums recognised as relevant by users. Bathymetry users also recognised CD as relevant which, as mentioned, is LAT in Australia. Very few other datums were recognised as relevant by users.

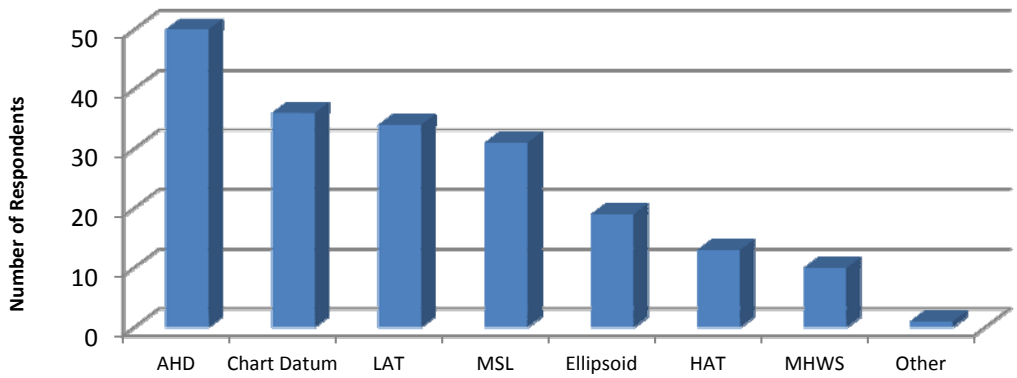


Figure 6. Vertical datums required by Australian bathymetry users (Quadros et al, 2012).

[4] GA, ITRF to GDA94: http://www.ga.gov.au/servlet/BigObjFileManager?bigobjid=GA3795

The ellipsoid-based transformation approach being adopted is depicted in Figure 7. This approach is comparable to that of VORF, using a set of gridded surfaces, each of which defines the separation of one vertical datum from the GRS80 ellipsoid. It combines MSS and tidal model surfaces for ease and speed of computation in applying the vertical transformations. Transformation occurs directly from the ellipsoid to MSL, acknowledging that Earth Gravitational Model 2008 (EGM2008) and the MDT make up the MSS. A MDT surface was not used in the final approach although is recommended. It would add to the understanding of the relationships between vertical datums and may assist in other research such as studies of energy transport mechanisms in inshore waters and of the interplay between river run-off and ocean circulation.

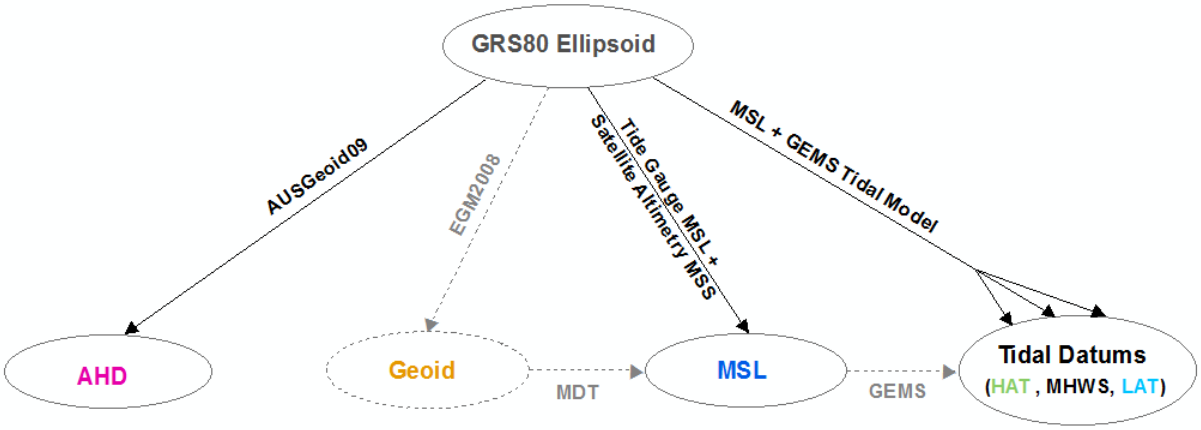


Figure 7. The ellipsoid-based Australian vertical datum transformation approach used in the Demonstration Tool.

The ellipsoid-based approach has advantages over the VDatum minimum spanning tree (refer to *Appendix B Section 12.8*) in that it avoids the compounding of errors caused by traversing ellipsoidal, orthometric, and tidal systems. Using a satellite altimetry derived MSS reduces the number of transformations required. The current VDatum roadmap is fundamentally based on the North American Vertical Datum 1988 (NAVD88), as many of the coastal tide gauges had corresponding NAVD88 measurements and no GNSS ellipsoid measurements (Myers, 2012). The VDatum team has been evaluating whether a new transformation roadmap will be implemented in future years, and have acknowledged ellipsoid-based transformations as an interesting topic for consideration given the increasing use of GNSS. The US process is also based on the fact that their orthometric datum, NAVD88, is essentially a geoid as it only uses one tide station as a control point. Therefore the difference between the US orthometric height datum and MSL is MDT. This approach is not ideal for Australia as many tide gauges are missing AHD values, and AHD is warped to fit MSL at multiple tide stations. In Australia the difference between AHD and MSL is typically smaller than true MDT. Given the intention to move Australia to a dynamic datum in 2020, AHD and AUSGeoid09 will potentially be superseded (although will remain available). Hence it would not be wise to adopt the US method of vertical transformations.

Australia is also unable to adopt one of the methods employed by the UK in which the datums of some tide stations without a direct GNSS observation were connected to the European Terrestrial Reference Frame 1989 (ETRF89) (a realisation of GRS80) by applying the OSGM02 geoid model. In Australia's case this would require the application of AUSGeoid09 to reliable AHD heights at stations with missing ellipsoid heights. Thirty three of the supplied tide gauges are missing AHD heights and those that are available are without metadata and considered generally unreliable as mentioned in *Section 2.1*, so this method would not be acceptable. As the UK had metadata for their tide gauges, they were able to acquire or directly commission GNSS observations where levelling heights (or OSGM02) were unreliable (Iliffe et al, 2007).

Given the current lack of high quality tide gauge data in Australia, the transformation methodology will be kept fairly broad for the Demonstration Tool which will act as a proof of concept rather than an accurate transformation solution. There is little advantage to developing complex methodologies based on current data which may prove invalid when denser, more accurate data is available. Comprehensive methods for aligning the epoch of all tide gauge MSL values, such as the spatial-temporal correlation model used by VORF, are not developed. Currently, if observations span more than one year they are generally assumed equivalent to the 19 year epoch and no corrections are applied. This is because observations of greater than one year include seasonal variation in mean sea level (harmonic constituent Sa) which has a period of about one year and is quite significant in Australian waters. If observations span less than a year, a correction for seasonal variation may be applied because sea level heights in winter can vary significantly from those in summer (Dando, 2012). This approach is accepted at this stage. Similarly, a simple method of interpolation between tide gauge ellipsoidal MSL values along the coast is adopted, rather than developing a complex method such as VDatum's Tidal Constituent And Residual Interpolation (TCARI) or the specific algorithms created by VORF for different types of coastal topography. *Section 7.2* discusses the interpolation methodology in more detail.

4 Data

4.1 LiDAR Data

The LiDAR data as described in Table 3 was obtained in the LiDAR LAS file format for this project. All data supplied in both AHD and ellipsoid reference systems were analysed as part of Stage 1 of the project. The demonstration of the software tool in the study area as part of Stage 2 of the project used the Sunshine Coast datasets.

Table 3. LiDAR data obtained for the project.

Project	Year	Topo/Bathy	Provider	Reference System
Victorian Goulburn Broken Floodplains	2010	Topographic	Fugro Spatial	AHD and Ellipsoid
Victorian Goulburn Broken Floodplains	2011	Topographic	Photomapping Services	AHD and Ellipsoid
Sunshine Coast	2009	Topographic	Schlencker Mapping Pty Ltd	AHD
Sunshine Coast	2012	Bathymetric	Fugro LADS	AHD and Ellipsoid

4.2 The Earth Gravitational Model 2008

EGM2008[5] can be accessed via the National Geospatial-Intelligence Agency EGM Development Team website. If a MDT were to be created for the transformation process, EGM2008 would be used to transform input ellipsoid to geoid heights, as well as subtracted from the integrated MSS to determine MDT values. AUSGeoid09 would not be used as it is warped to fit AHD which means the difference between AUSGeoid09 and MSL is arbitrarily smaller than true MDT. EGM2008 is complete to spherical harmonic degree and order 2159 and uses the tide-free permanent tide system (NG-IA, 2010). It is available in formats including an Environmental Systems Research Institute (ESRI) GRID raster dataset of 2.5minute cell size. The global dataset is split into 45degree subset areas. The subset area indicated by the red arrow in Figure 8 was relevant to this project. Cell values are derived from the original pre-computed geoid undulation point value (in metres) located at the south west corner of each cell. The geoid undulations are referenced to the WGS84 ellipsoid which would need to be converted to GRS80 if a MDT were to be created.

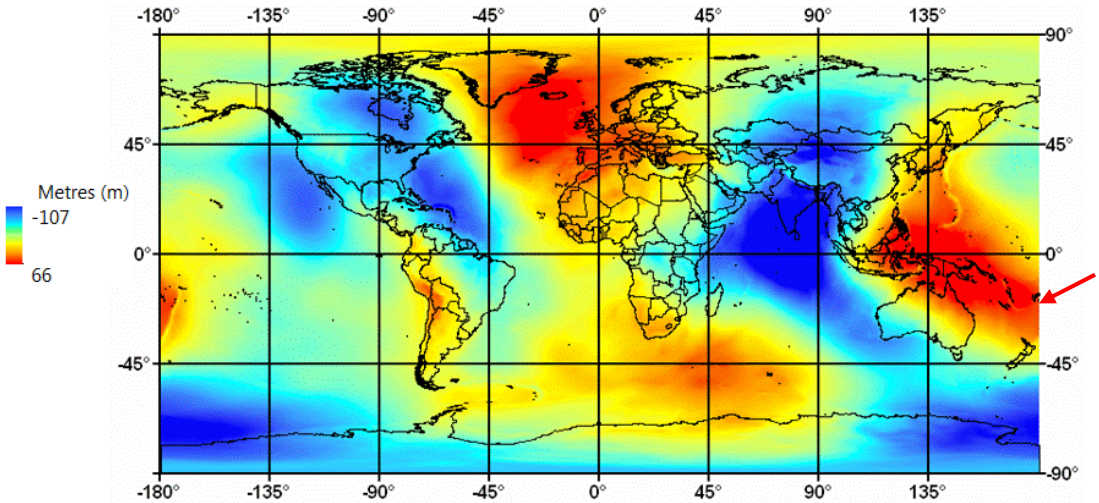


Figure 8. EGM2008 global 2.5 minute geoid undulations in 45 x 45 degree subsets (NG-IA, 2010).

4.3 Australian Tide Gauge Data

Australian tide gauge data (discussed in *Section 2.1)* available as at November 2011 was supplied as an Excel spreadsheet by Jayaswal (2012). It is important to note that this data is provisional and incomplete as the AHS-ICSM PCTMSL project is still ongoing. The final values supplied by State/Commonwealth Agencies in the future may be different.

The current data is for continuously operating coastal tide gauges around Australia, including standard and some secondary ports. The information supplied for each tidal station includes the station name, state, tidal port number, latitude, longitude, ellipsoid height below LAT, tidal datum heights above LAT for the current NTDE of 1992-2011, AHD height above LAT, the source of the data, the years for Sa/Ssa (seasonal variation in mean sea level), MSL with and without the long term trend, the four major harmonic constituents, and the tidal ratio. However, there are a number of issues in addition to those discussed in *Section 2.1*. The degree of missing data can be seen in *Appendix C*, represented by the yellow cells. As it is known that not all continuous operating tide

[5] NG-IA, EGM2008: http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/egm08_gis.html

gauges have 19 years of observations, the tidal datum heights are all calculated using the Australian National Tide Tables (ANTT) formula to provide a uniform method of determination rather than having a combination of "observed" tidal levels and "calculated" tidal levels. Hence they are not as accurate as they would be if determined from 19 years of observations. The MSL (Z_0) value is impacted by the 'years for Sa/Ssa' (the seasonal variation coefficient) which is often less than 19 years and some secondary ports have had Sa/Ssa inferred from a standard port. No accuracies currently exist as there is no additional metadata.

The data required reformatting to allow creation of a spatial dataset in ArcGIS. The latitude and longitudes were supplied in mixed formats including degrees minutes seconds, and degrees and decimal minutes, with and without the symbology. This was manually separated into degrees, minutes and seconds where applicable and decimal degrees calculated. A point shapefile was created, projected to MGA Zone 56 coordinates, and the study area gauges extracted. Figure 5 shows which gauges around Australia and in the study area have ellipsoid and MSL heights, one or the other of these, or neither.

4.4 Danish Technical University Mean Sea Surface

The DTU10 MSS was created by Andersen (2012). As described in *Section 12.4*, it is the average over 17 years of the sea surface height relative to the Topex/Poseidon ellipsoid (refer to *Appendix A Section 12.4*) and a mean-tide permanent tide system. The 'remove-restore' two step procedure and all the issues mentioned in *Section 12.4* were addressed in the creation of the MSS. The DTU10 MSS is freely available for download from the Danish Technical University (DTU) website at resolutions of one or two minute cell size along with the DTU10ERR interpolation error file reflecting the accuracy of the MSS. The interpolation error is the combined error from the two steps in the development of the DTU10 MSS. This error file is used during the integration of the MSS with tide gauge MSL to reject low accuracy DTU10 MSS values.

Before the MSS could be used, it required conversion to the GRS80 ellipsoid and a tide-free permanent tide system using the GUT software (*Section 5.3*). The GUT software would not accept the version of the MSS downloaded from the DTU website, so the two minute version available with GUT was used. The MSS used is with the atmospheric pressure or inverse barometer (IB) correction applied (refer to *Appendix A Section 12.4*). The difference between IB and NIB MSS can be up to about ±15cm (Rosmorduc et al, 2011). If integrating a MSS with instantaneous tide gauge sea level observations or observations averaged over short time periods (e.g. days to months), the MSS should have NIB correction (or the tide gauge data IB correction), as tide gauges measure the sea surface under the atmospheric conditions that pertain and hence such data has NIB correction (Andersen and Knudsen, 2009). However, as this project used long-term average tide gauge data (e.g. a year or longer) the IB correction becomes negligible as it largely cancels over yearly cycles, so an IB corrected MSS was suitable for integration with tide gauge data. Where only short term tide gauge records were available, harmonic analysis was performed to derive MSL for the National Tidal Datum Epoch (NTDE). By using the component frequencies of the short term observations to produce a long term estimate of MSL, pressure fluctuations are eliminated.

4.5 Geoscience Australia Data

Three datasets available from the Geoscience Australia[6] website were used in this project; Australian coastline data, AUSGeoid09, and the Australian Bathymetry and Topography Grid. The coastline data was used in the vertical datum transformation process as the best available representation of the study area coastline, including islands, from which to offset distances for tide gauge MSL interpolation, and the area of satellite altimetry validity. AUSGeoid09 was used to facilitate the conversion from ellipsoid to AHD heights and vice versa. However, it is known that AUSGeoid09 is not as effective on or near the coast due to a lack of underlying gravity data, so an evaluation of AUSGeoid09 in the coastal zone was conducted (refer to *Section 7.1*). The Australian Bathymetry and Topography Grid was used to define the offshore extent of operation of the tool.

The Australian coastline data, *GEODATA COAST 1000K 2004,* is a vector representation depicting Australia's coastline, and State and Territory borders. The GA (2004) user guide states that coastline data represent the position of Mean High Water (MHW), the seaward edge of coastal mangroves, inlet closing lines and those parts of the coastline that are otherwise ill-defined. The coast at MHW was originally determined from aerial photography flown at, or very near, the time of MHW. Mangrove coastline is defined as being on the seaward edge of coastal mangroves which may approximate MLW. The mouths of narrow inlets and rivers have been closed off by straight lines. The closure point essentially represents the break between mainly riverine waters (rivers, bays, harbours, inlets) and mainly marine waters. Indefinite coastline is that part of the coastline where MHW could not be determined from the source material, including cliff overhangs and exposed sand bars. The level of detail in the source mapping means data is particularly suited to regional, State-wide and national applications and is used as the standardised reference database of coastline and State borders. The data is available in geographical coordinates (latitude and longitude) in decimal degrees using GDA94 and in three formats including ArcView Shapefiles.

AUSGeoid09 has a one minute cell size (approximately 1.8km) grid representing the difference in height between the GRS80 ellipsoid (realised through GDA94) and AHD. It is a national grid covering between 108°E, 160°E, 8°S, and 48°S, and is accurate to 0.03m across most of Australia (GA, 2012). AUSGeoid09 has two components, gravimetric and geometric. The gravimetric component uses EGM2008 global gravity model, ~1.4 million land gravity anomalies from the Australian national gravity database, the nine second GEODATADEM9S DEM of Australia, and altimeter-derived marine gravity anomalies from the DNSC2008GRA grid (Brown et al, 2011; Featherstone et al, 2010). The gravimetric component is termed AGQG2009 and represents the difference in height between the GRS80 ellipsoid and the geoid. The geometric component in AUSGeoid09 accounts for the spatially varying offset between AGQG2009 and the AHD. This offset is due to distortions in the realisation of AHD caused by holding 30 tide gauges fixed at zero MSL for 1966-1968 around the Australian coast and then performing a national level adjustment based on those fixed points. The geometric component uses a primary dataset of 2638 co-located GNSS-AHD heights as well as a secondary dataset of 4233 levelling junction points to provide higher-resolution (Featherstone et al, 2010; Brown et al, 2011). AUSGeoid09 can be downloaded as a text file from the GA website.

[6] Australian Government, Geoscience Australia: http://www.ga.gov.au/

The Australian Bathymetry and Topography Grid produced in June 2009 is a consistent, high-quality nine arc second bathymetric grid for Australian waters. As stated in the GA (2009) product report, its extent includes the Australian water column jurisdiction lying between 92°E and 172°E, and 8°S and 60°S. Input datasets used to create the grid are Multibeam, charts, Laser Airborne Depth Sounder (LADS), satellite altimetry measurements, Australian topography, New Zealand topography, and Shuttle Radar Topography Mission DEM. The 2000m depth contour was selected from the 500m interval contours associated with the grid and used as the offshore extent of the study area. The grid is provided in ESRI grid and ER Mapper formats and can be downloaded from the Geoscience Australia website for a cost of AU$99.00.

5 Tools

5.1 LAStools

LAStools[7] is a set of highly-efficient individual command line tools that process data stored in LAS format, which is the common LiDAR data exchange format. Written in C^{++} by Isenburg (2011), the tools are an efficient way to perform an assortment of conversion, reformatting and data inspection tasks. They can be downloaded from the LAStools website however in some cases, licensing may be required. Licensing for the tools used in this project is as follows; LASmerge is open-source and Lesser General Public Licensed, LASboundary and LASclip can only be used freely for strictly non-commercial and strictly non-military purposes in case of personal, educational, or not-for-profit humanitarian use, and LASdiff is a variation on the original version specifically created for this project by Isenburg (2011). For the current project and Demonstration Tool, no license has been obtained, but a license should be obtained in order to include the existing LAStools executables or source code in functional software that is created.

Stage 1 of the project used LASdiff to subtract LiDAR files referenced to AHD, from otherwise identical LiDAR files referenced to the ellipsoid, to create a LiDAR derived geoid model for analysis. Further analysis was performed on this LiDAR derived geoid model after converting it to a surface using LASboundary to compute boundary polygons for the LiDAR files which were used to create surfaces with LP360 (*see Section 5.2*). Stage 2 of the project built LASclip which clips away points falling into polygonal shapes, and LASmerge which can merge several LAS files into one, into the demonstration Python tool as part of the vertical datum transformation process.

[7] Martin Isenburg, LAStools: http://www.cs.unc.edu/~isenburg/lastools/

5.2 ArcGIS and Python

The vertical datum transformation Demonstration Tool was written using the Python 2.5 programming language and runs as an ArcToolbox geoprocessing script in ArcGIS 10.0. The vertical separation surfaces used by the tool were created using the ArcInfo software license level and the ESRI extensions 3D Analyst and Spatial Analyst, as well as the external QCoherent LP360 extension for ArcGIS. ArcGIS is ESRI's suite of geographical information system (GIS) software products for Windows. LP360 is a tool specifically designed for processing LiDAR LAS format point cloud files. Python is an open-source, object-oriented, cross-platform language that is automatically installed with ArcGIS. These tools were selected for the development of the demonstration software primarily as they are familiar to the researcher and are capable of achieving the objectives. However, they are not necessarily ideal. Having the tool function as a script within ArcGIS restricts access to users with an ArcInfo license or the 3D Analyst and Spatial Analyst extensions, and more powerful programming languages exist that might produce a more efficient solution.

5.3 European Space Agency GOCE User Toolbox (GUT)

The European Space Agency (ESA) Gravity and Ocean Circulation Experiment (GOCE) User Toolbox[8], also known as GUT, facilitates the processing of GOCE data products and other satellite altimetry products such as MSS and MDT. The tool supports applications in oceanography and geodesy via a command line interface fundamentally based on spherical harmonic mathematics. It can be used on Windows PCs, UNIX/Linux Workstations and Mac and works primarily with the netCDF file format. It can be downloaded (after registration) from the ESA GUT webpage and comes with tutorial and user guide documents along with a set of data and models. For this project it has been used to convert the reference ellipsoid and permanent tide system of some of the required datasets (*Section 7.2*).

5.4 The Global Environmental Modelling Solutions Tide Model

The GEMS tide model was available due to previous use in a research project in 2007. There are a limited number of other tidal models produced by organisations at lower resolution or at a more local level, but GEMS provides a balance between extent and resolution. It is generated from a number of harmonic constituents statistically calibrated at the model boundaries to replicate known tidal behaviour in Australian waters, based on tide gauge data (Hubbert, 2007). A coarse global tide model (Grenoble) is used at the boundaries of GEMS and integrated with four regional tide models that vary in their coverage, harmonic constituents and resolution to form GEMS. The AMSA tide model covers the southern and eastern parts of Australia on a 5" grid, 60" localised tidal analysis is used for north-western Australia, while the other models have been generated at a higher resolution for the Victorian and Queensland regions. For the regions covered by more than one model, the model with the highest resolution is used to compute the tidal heights. The main factors that impact on flow in the tide model, and therefore the tide heights, are the resolution of the model, the bathymetry and the coastal boundary. The harmonic constituents contained within the five models incorporated in the GEMS tide model are shown in Table 4.

[8] ESA, GUT: https://earth.esa.int/web/guest/software-tools/gut/about-gut/overview

Table 4. The Composition of the GEMS Hydrodynamic Model (Hubbert, 2007).

Harmonic Constituent	Period (hours)	Speed (degrees/solar hour)	AMSA Net Water Movement Project (5" resolution)	Grenoble Global Tides (30" resolution)	GEMS Victorian Coastal Ocean Model (1" resolution)	Tidal Analysis in North West Shelf (60" resolution)	GEMS Queensland Coastal Ocean Model (1" resolution)	Description of the Tidal Harmonic Source: (Manly Hydraulics Laboratory, 2007)
M_2	12.42	28.984	✓	✓	✓	✓	✓	Principal lunar semidiurnal constituent.
S_2	12.00	30.000	✓	✓	✓	✓	✓	Principal solar semidiurnal constituent.
K_2	11.97	30.075	✓	✓		✓	✓	Lunisolar semidiurnal constituent.
N_2	12.66	28.436	✓	✓	✓	✓	✓	Larger lunar elliptic semidiurnal constituent.
$2N_2$	12.91	27.885		✓				Lunar elliptic semidiurnal second-order constituent.
K_1	23.93	15.044	✓	✓	✓	✓	✓	Lunisolar diurnal constituent.
O_1	25.82	13.943	✓	✓	✓	✓	✓	Lunar diurnal constituent.
P_1	24.07	14.956	✓			✓	✓	Solar diurnal constituent.
Q_1	26.87	13.398	✓	✓	✓		✓	Larger lunar elliptic diurnal constituent.
S_a	8765.82 (364.96 days)	0.041				✓	✓	Solar annual constituent.

Prior to using the GEMS tide model in the vertical datum transformation process, its accuracy was assessed against the Australian tide gauge data supplied by the AHS. Results can be seen in the *Section 7.3*. The value of the comparison between the GEMS tide model and standard tide gauges may be limited due to the fact that standard tide gauge data was used in the development of the tide model. It is assumed that if the tide model performs well at the tide gauges around the case study area, it should perform well between gauges in the case study area. GEMS noted that the tide model supplied for this project may not perform reliably in bays with a narrow entrance, where the bathymetry and tidal flow could not be adequately represented, as the best resolution of GEMS is 1km.

6 Stage 1 - Ellipsoid Heights from LiDAR

The LiDAR datasets mentioned in *Section 4.1* were analysed to determine whether the relationship between their corresponding AHD and ellipsoidal heights met an acceptable accuracy and did not contain any systematic errors. The methodology adopted for this analysis is depicted in Figure 9. As the collection and processing procedures for topographic and bathymetric LiDAR are different, the findings were different for the land and sea data. Topographic LiDAR is collected relative to the ellipsoid and AUSGeoid09 geoid separations are subsequently applied to achieve AHD heights. In contrast, the bathymetric LiDAR data process derived ellipsoid and AHD heights independently of one another, with AHD results based on tide gauge data and ellipsoid results based on GNSS.

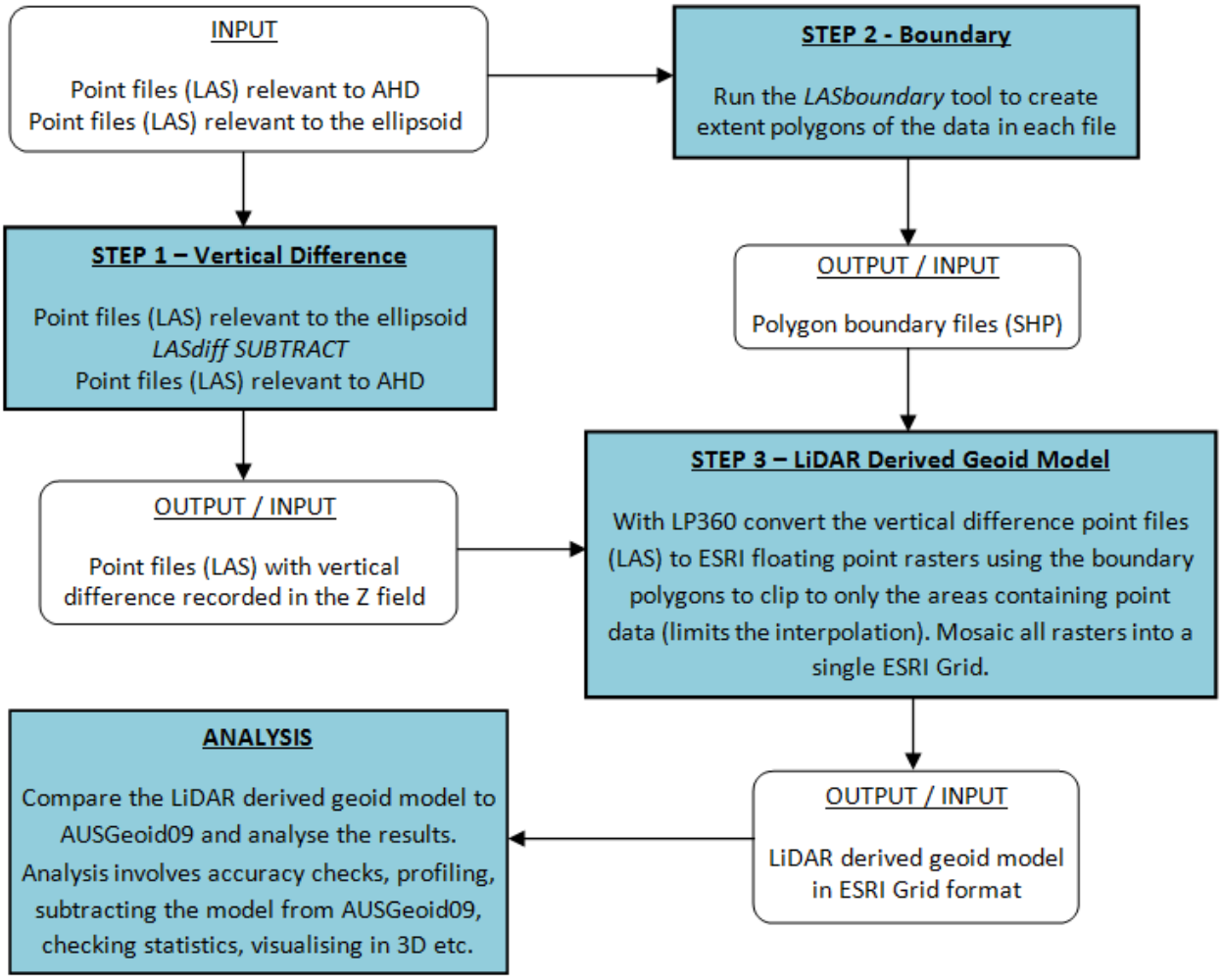


Figure 9. Stage 1 methodology.

All topographic datasets were found to be within the required project accuracies (typically ≤±30cm 95% CI) when compared to ground control. The following results focus on the Victorian Goulburn Broken Floodplains topographic LiDAR as representative of all topographic data. Accuracy was tested against about 30 ground control points distributed within the LiDAR coverage boundary. Despite meeting the overall required project accuracy, a small systematic bias in the order of a few centimetres (up to 12cm) was present. This bias was discovered through creation of a LiDAR derived geoid model and its subsequent subtraction from AUSGeoid09, as represented by Equation 1.

LiDAR Derived Geoid Model = $LAS_{Ellipsoid}$ - LAS_{AHD} Equation 1.

Difference Surface = *AUSGeoid09* - *LiDAR Derived Geoid Model* ...1.1

The difference surface resulting from Equation 1 was expected to be without slope, with an average value of zero, and a standard deviation within project accuracy tolerance. Although the average value and standard deviation met these expectations, the difference surface revealed a non-linear height variation of up to four centimetres (surface texture) as well as one centimetre steps. The surface texture is depicted in the sample profile shown in Figure 10, with the sharp spikes the one centimetre steps and the general non-linear trend the texture. The surface texture must originate in the production of the ellipsoidal height data set as is not a result of applying AUSGeoid09. The steps, which were also found in the previous CRCSI work (Seager, 2011a) mentioned in *Section 1.2*, were found to exist between the original point data and not as a result of processing for the analysis.

The suggestion that stepping may be due to AUSGeoid values being interpolated at the one centimetre level (Seager, 2011a) was supported by this analysis. Figure 11 shows there is correlation evident between the slope (colour banding) direction of AUSGeoid09 and the step direction of the difference surface. This problem was with the supplied AHD data rather than the ellipsoidal data, due to transformation of the ellipsoid data to AHD using AUSGeoid09 at the one centimetre level. Stepping will always occur with this method of AHD production but may be reduced to the millimetre level if AUSGeoid09 is interpolated to that precision.

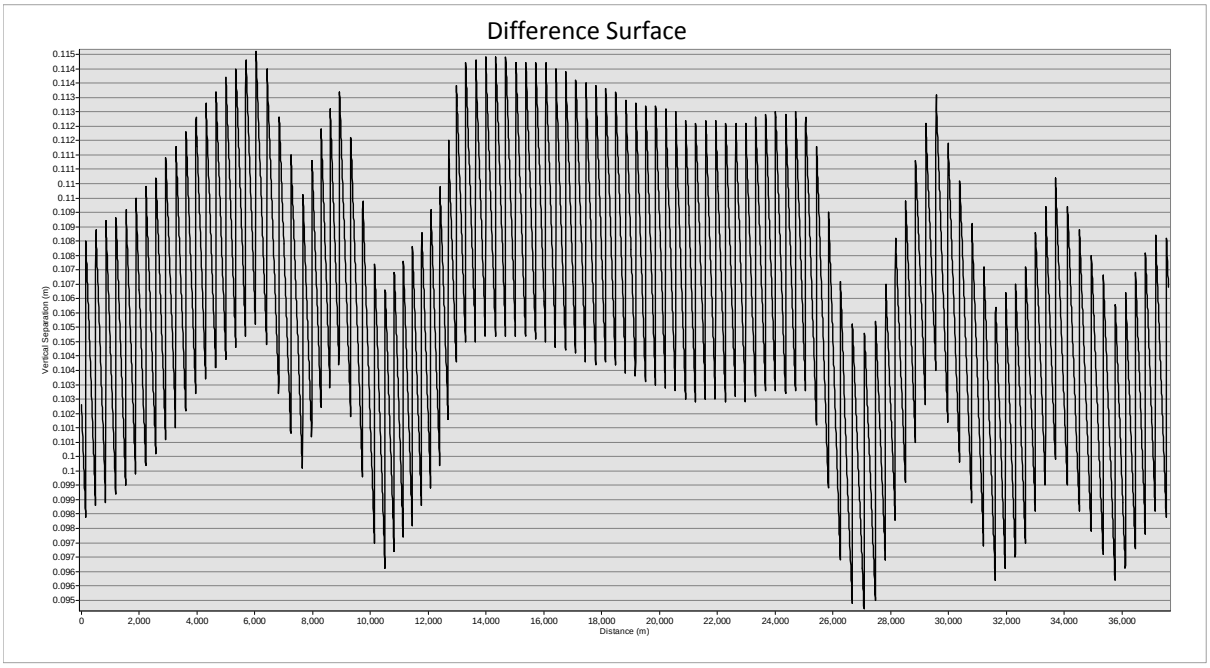


Figure 10. Profile of the vertical separation versus distance across the surface of difference between the Victorian Goulburn Broken Floodplains topographic LiDAR derived geoid model and AUSGeoid09.

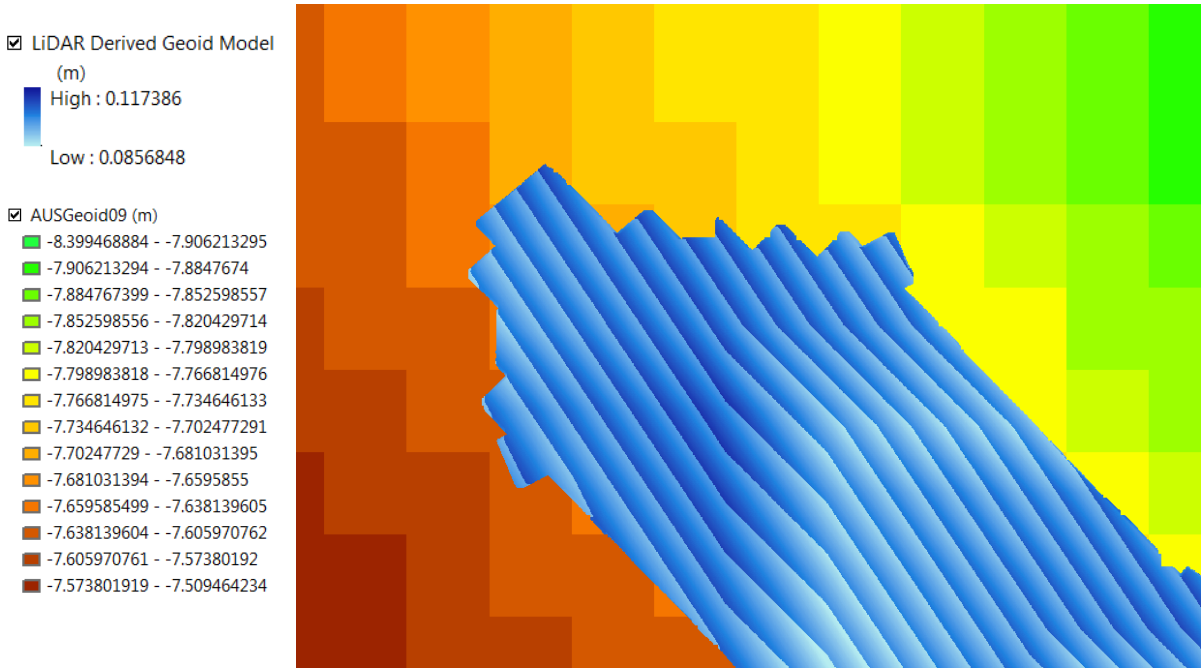


Figure 11. Topographic LiDAR derived geoid model (blue) overlayed on AUSGeoid09.

As with the previous research discussed in *Section 1.2*, Sunshine Coast bathymetric data exhibited systematic errors in the form of along flight line 'waves' and steps between adjacent flight lines (Figure 12). Unlike the WA research which concluded the problem was largely in the ellipsoidal data (using the old Fugro LADS Mk II system) (Seager, 2011b), this analysis determined that the issues were present to the same degree in AHD and ellipsoidal data (using the new LADS Mk 3 system). This is demonstrated visually in Figure 41 to Figure 44 in Appendix D.

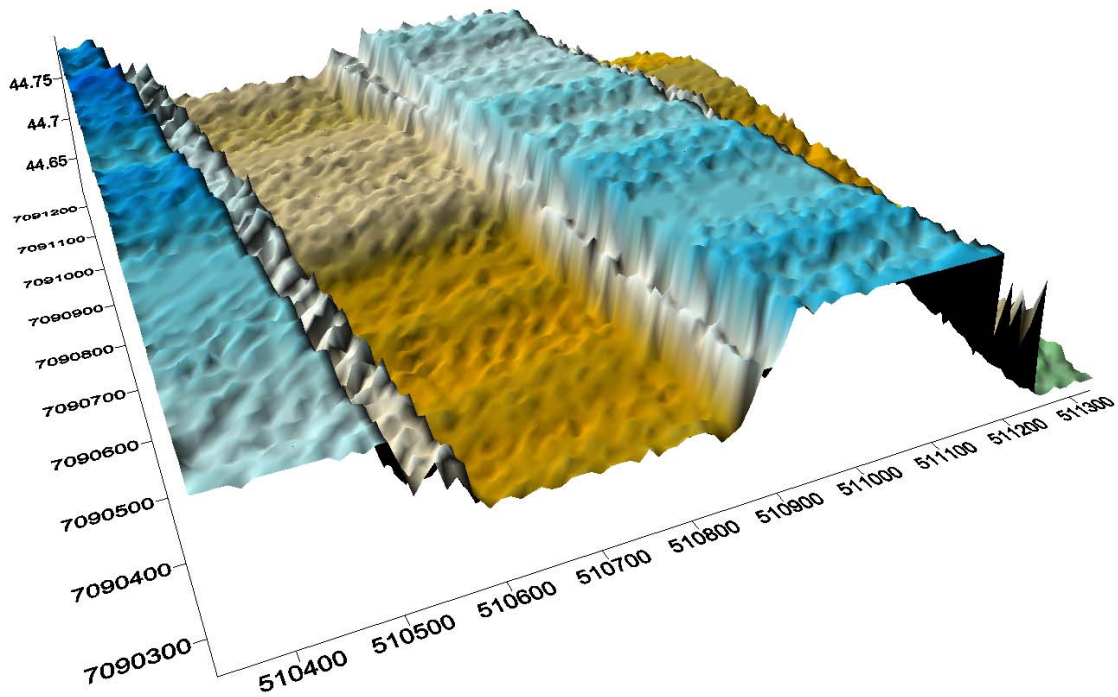


Figure 12. Stage 1 Sunshine Coast bathymetric LiDAR ellipsoid subtract AHD surface.

Although the difference between the LiDAR derived geoid model and AUSGeoid still ranges up to about 1.5m for the Sunshine Coast bathymetric data, the WA results showed mean differences across four blocks about five times the magnitude of that for Sunshine Coast (Table 5 and Table 6). The smaller mean difference for Sunshine Coast suggests that when combining AHD and ellipsoidal data to produce the LiDAR derived geoid model, the systematic errors in both datasets sometimes compound and sometimes cancel, bringing the mean closer to zero. In the WA case, the systematic error is primarily in the ellipsoid data which tends to compound the difference, pushing the mean away from zero in one direction.

Table 5. Sunshine Coast summary statistics for entire dataset showing the difference between the LiDAR derived geoid model and AUSGeoid09 in metres.

	Min	Max	Range	Mean	SD
Entire dataset	-0.86	0.64	1.49	0.10	0.15

Table 6. WA summary statistics for four randomly selected data blocks (1km x 1km) within the data showing the difference between the LiDAR derived geoid model and AUSGeoid98 in metres.

	Min	Max	Range	Mean	SD
Block 1	-1.40	-0.10	1.30	-0.76	0.31
Block 2	-0.69	-0.02	0.67	-0.28	0.11
Block 3	-1.31	0.14	1.44	-0.58	0.31
Block 4	-1.06	0.06	1.11	-0.34	0.15

Results show that the Fugro LADS Mk 3 system has improved the accuracy of bathymetric ellipsoidal LiDAR data to the same level as corresponding AHD data, both of which are within required tolerances (typically ≤±50cm @ 95% CI). However, because AHD and ellipsoid bathymetric data are produced using independent methods, the errors within each surface do not necessarily coincide, resulting in the large range of difference values between the LiDAR derived geoid model and AUSGeoid09. As Sunshine Coast bathymetric data are within the required accuracy tolerances specified through the data acquisition process, the data will be used in the Demonstration Tool. The Sunshine Coast topographic data will also be utilised although it would be preferable, from a purely computational perspective, to have the ellipsoidal height data supplied at millimetre resolution to reduce the size of the steps and thereby avoid any need to smooth the steps in the developed transformation process.

7 Stage 2 - Vertical Datum Transformation

In order to develop a vertical datum transformation approach for Australia, an investigation was conducted into which vertical datums are of relevance to users of integrated coastal height products both onshore and offshore (discussed in *Section 3.2*). Understanding was required of how the relevant datums are typically defined and realised in a practical sense. The existing vertical datum models VDatm and VORF (*Appendix B*) were investigated to determine if any of their methods were suitable to contribute to the Australian case. From this background research, the transformation approach shown in Figure 7 was developed for Australia. This approach has only been implemented for the study area and requires extension around the remainder of the Australian coast which can be achieved following the process described in *Appendix J*. Although it would be possible to include EGM2008 and a MDT to allow additional paths of transformation, this has not been done for the Demonstration Tool. The Demonstration Tool allows five transformations in either direction using grids of separation between: ellipsoid-AHD, ellipsoid-MSL, ellipsoid-LAT, ellipsoid-MHWS, and ellipsoid-HAT. The development of the gridded separation surfaces which make possible these transformations is described in the following sections.

7.1 Ellipsoid to Australian Height Datum

AUSGeoid09 (described in *Section 4.5*) provides the transformation between GRS80 ellipsoid heights (realised as GDA94) and AHD heights. The vertical datum transformation concept requires these transformations be applicable offshore as well as on land. However, it is well known that AUSGeoid09 is not as effective at the coast and offshore due to the lack of underlying gravity data. Therefore, an analysis of the performance of AUSGeoid09 in the coastal zone was conducted. The Sunshine Coast LiDAR derived geoid model developed in Stage 1 of the project was subtracted from AUSGeoid09 which in theory should produce a surface without slope, with an average value of zero, and a standard deviation within project accuracy tolerance. However, if AUSGeoid09 does degrade offshore, taking into account errors in the LiDAR data, an offshore trend showing an increase in the difference may be expected. Figure 13 shows an example profile across the difference surface (AUSGeoid09 subtract LiDAR derived geoid model) beginning from the coast and heading in an offshore direction.

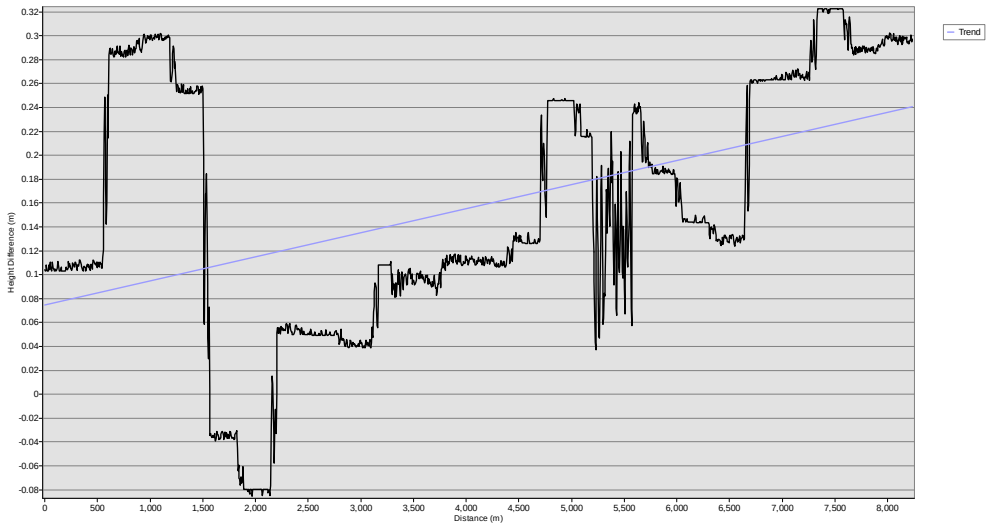


Figure 13. Example profile of AUSGeoid09 minus the Sunshine Coast LiDAR derived geoid (vertical separation versus distance) shown in black, and the trend across the profile in purple.

The steps and noise in the example difference profile in Figure 13 are due to the errors present in the Sunshine Coast bathymetric LiDAR data (steps between adjacent flight lines) discussed in *Section 6* and shown in Figure 12. The errors do not stem from AUSGeoid09, as profiles across it are smooth. Given the amount of variation in the above profile relative to the trend line, conclusions are unconvincing. However, the trend line shows an increase in the difference in an offshore direction and hence may indicate degradation in AUSGeoid09 offshore. Nine profiles were produced across the dataset, six in the south where the extent of offshore data was the greatest, and three towards the north of the dataset. The statistics for these profiles can be found in *Appendix E*. All profiles showed offshore degradation in AUSGeoid09. There was little variation in the magnitude of this degradation across the dataset with southern profiles showing an average degradation of 1.47cm/km (R^2 = 0.147), and northern profiles 1.71cm/km (R^2 = 0.162). Overall the profiles revealed an average degradation of 1.59cm/km (R^2 = 0.155). R^2 is a measure of the global fit of the trend line to the profile. The closer R^2 is to zero, the less successful the trend line is at explaining the variation of the data. R^2 = 0.155 shows a weak positive linear relationship.

However, there is not enough data for results to be conclusive and more testing would be required to confirm the trend. It is possible that the bathymetry is less accurate in deeper water therefore the derived geoid is also less accurate, leading to a growing divergence from Ausgeoid09. It is also possible that results are affected by decorrelation in the tide between the gauge and each LiDAR point measured. Only one bathymetric LiDAR dataset (Sunshine Coast) was available for testing and it is known to contain systematic errors so the apparent trend cannot necessarily be attributed to the degradation of AUSGeoid09 offshore. The Sunshine Coast LiDAR data also only extends to a maximum of about 11.5km offshore, whereas the offshore extent of the study area ranges from about 30-100km from the coast. Testing at best a third of the offshore extent of AUSGeoid09 as used in the Demonstration Tool, was not a particularly robust analysis. Although AUSGeoid09 was used in the Demonstration Tool, further testing of its effectiveness offshore should ideally be completed when additional bathymetric data is available, before use in a practical transformation tool. If AUSGeoid09 is proven to be inaccurate and unreliable offshore, other methodologies would need to be investigated. For example, transformation to AHD could occur through LiDAR derived geoid models.

7.2 Ellipsoid to Mean Sea Level

Conversion from ellipsoidal to MSL heights required an ellipsoidal MSS (or a geoid and MDT). For the Demonstration Tool, an integrated MSS grid was developed which used tide gauge data to enhance the satellite altimetry derived DTU10 MSS in the coastal zone. Before integration, the data was required to be referenced to a common datum, a common epoch, and the same permanent tide system. If the geoid and MDT transformation was used, the spectral content would also need to be considered.

The common datum chosen for the MSS was GDA94 MGA Zone 56 based on the GRS80 ellipsoid, as GDA94 is Australia's national datum. The epoch selected was 1992-2011, as this is the current NTDE for Australia and the epoch tide gauge data were supplied relative to. A tide-free permanent tide was the common system for this integration (discussed in *Section 12.6)*.

The tide gauge information included latitudes and longitudes relative to GDA94, MSL heights above LAT and ellipsoid (GRS80) elevations *below* LAT for the NTDE 1992-2011. As the tide gauge ellipsoid elevations were collected with GNSS they are considered to be in a tide-free system (discussed in *Section 12.6*). The permanent tide does not affect ocean tide observations at tide gauges (Liebsch, 2012) so to convert MSL relative to LAT, to MSL relative to the GRS80 ellipsoid (realised as GDA94), Equation 2 was applied. In Equation 2, heights are given above the subscript reference surface. As ellipsoid height was given below LAT, this is equal to LAT above the ellipsoid.

$$MSL_{Ellipsoid} = MSL_{LAT} - (-Ellipsoid_{LAT}) = MSL_{LAT} + LAT_{Ellipsoid} \qquad \text{Equation 2.}$$

The DTU10 MSS is available in the mean-tide system, relative to the Topex/Poseidon ellipsoid, and the epoch 1993-2009. For the purposes of the Demonstration Tool, this epoch was considered the same as the NTDE used for the tide gauge data. The two epochs are similar and are centred over the same period. The DTU10 MSS required conversion of its ellipsoid and tide system to the common systems chosen. The GUT software (described in *Section 5.3*) was used to accurately convert the ellipsoid and tide system.

The below GUT command line functions were used as a step by step workflow to achieve the two conversions. Following the GUT conversions, the netCDF output file was imported into ArcGIS and projected to GDA94 MGA Zone 56.

1. gut changeellipse_gf -InFile MSS_DTU_10_2M.nc -Ellipse GRS80 -OutFile MSSDTU10_GRS80.nc
2. gut changetide_gf -InFile MSSDTU10_GRS80.nc -OutFile MSSDTU10_GRS80_TF.nc -T tide-free

The following sections discuss the four elements of the integrated MSS which are;

- A tide gauge derived coastal ellipsoid-based MSS extending 4km offshore
- The satellite altimetry derived DTU10 MSS extending from 22km offshore to the open ocean extent of the study area
- Interpolation across the 4-22km offshore satellite altimetry zone of caution between the tide gauge MSS and the DTU10 MSS, rejecting low accuracy (error >0.03m) altimetry data as defined by DTU10ERR
- Extrapolation of the tide gauge MSS from the coastline to 20km inland

7.2.1 Tide Gauge Derived Mean Sea Surface

As mentioned in *Section 12.3*, Deng *et al* (2002) conducted a study of the contamination of satellite altimetry data close to the coast of Australia. They recommended that data be used with caution for distances less than about 22km from the coastline, and rejected altogether within 4km. Following these recommendations, only the coastal tide gauge ellipsoidal MSL data was used within 4km of the coastline. The UK also based their zone of exclusion of altimetry data on the work of Deng *et al* (2002). VORF resolved to use only tide gauge data within 14km of the coast, purely satellite altimetry outside a 30km buffer of the coast, and a combination of the two in between (Iliffe et al, 2007). For this project, in order to ensure satellite altimetry data has no influence within its zone of exclusion, the tide gauge data were first interpolated/extrapolated into a surface extending from the coastline to 4km offshore. This gave the tide gauge data equal weighting to the altimetry in the latter

interpolation across the 4-22km zone of caution and resulted in a smoother integrated MSS than if only the individual tide gauge points were used.

Before interpolating the tide gauge data, the behaviour of the sea surface along the east coast was analysed. Values of EGM08 at each tide gauge location were subtracted from the tide gauge ellipsoidal MSL to produce GPS-geoid MDT point values. Figure 14 and Figure 15 show a linear regression of the GPS-geoid MDT as a function of latitude for the tide gauges along the east coast of Australia. The regression line in Figure 14 has a slope of 49mm/degree of latitude and an R^2 value of 0.2962. The removal of two outliers (perhaps due to errors in MSL or ellipsoid height) results in Figure 15, with a slope of 25mm/degree and an R^2 value of 0.5668. The limited sample of data indicates some degree of correlation between MDT and latitude, and a North-South slope in MDT, which has been shown by others such as Featherstone and Filmer (2012). It should be noted that this GPS-geoid method of calculating MDT is adversely affected by the limitations of geoid models in the coastal zone which can cause noise in the MDT values. Also, the tide gauge MSL values were not IB corrected for the MDT calculation. As mean atmospheric pressure tends to decrease towards the equator, it could account for some of the north-south slope in the MDT. However Featherstone and Filmer (2012) showed the IB influence to be -2.8mm/degree which is much smaller than the slope of MDT.

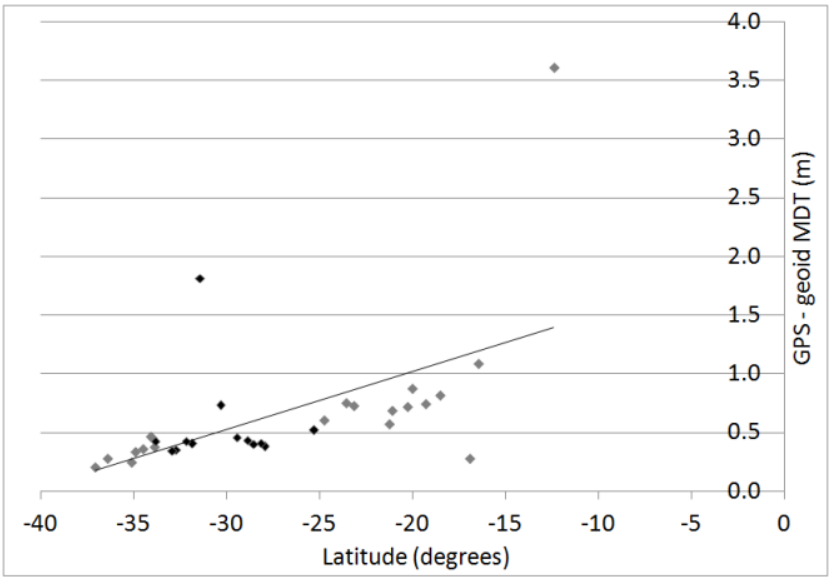


Figure 14. GPS-geoid MDT (metres) plotted against latitude (degrees) for all east coast tide gauges. Study area gauges shown in black.

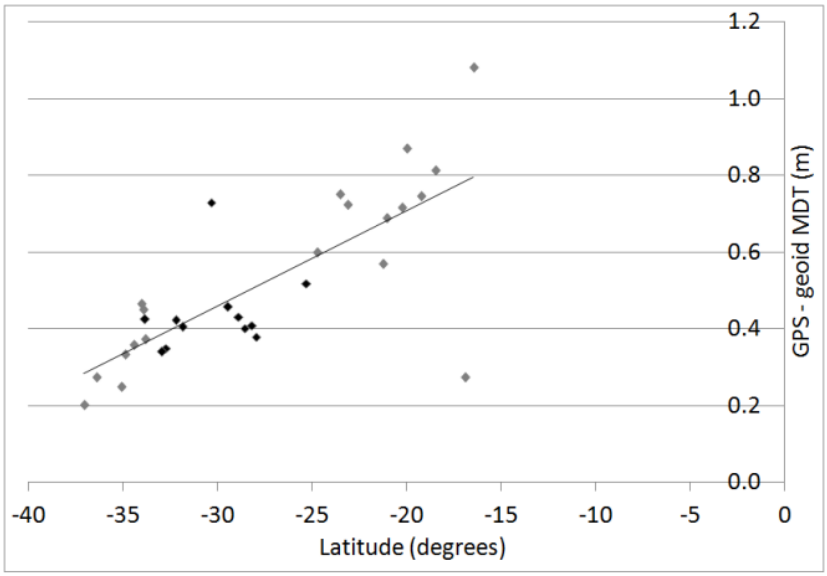


Figure 15. GPS-geoid MDT (metres) plotted against latitude (degrees) for east coast tide gauges: two outliers removed. Study area gauges shown in black.

A covariance analysis was also conducted for GPS-geoid MDT point values along the east coast. The test hypothesis was; as distance between tide gauges increases, the correlation between their MDT values will decrease. Distance between gauges was computed using a generalised outline of the coastline to provide distance over sea as opposed to straight line distance. Bin ranges of 20km were used to calculate the MDT covariance. Computing an empirical covariance function of MDT versus distance demonstrated that it was not possible to identify any significant levels of correlation with distance. This is most likely due to the linear tide gauge configuration along the east coast, as well as the limited number of tide gauges and the low accuracy and reliability of their data as discussed in *Section 16*. These tide gauge data issues lead to a high degree of random error which obscures any correlation that hypothetically may exist and is a significant problem for interpolation. This is in contrast to the work of Iliffe (2007) in which the data volume, configuration and availability of metadata to correct MSL observations, revealed a high degree of correlation between MDT (SST) and distance and allowed fitting of a trend line to estimate the size of the signal and random noise. These error statistics could then be used as weights in the data merging.

Australia's sparse, unreliable tide gauge data makes it impossible to conduct a meaningful statistical analysis of the behaviour of ellipsoidal MSL/MDT around the coast, and as such, the interpolation methods adopted are necessarily simplistic for the proof of concept. A number of interpolation techniques for extending Australian tide gauge data to 4km offshore were tested, including simple linear inverse distance weighting (IDW), ordinary linear kriging (similar to least squares collocation), and a minimum curvature technique called (regularised) spline, all with a variable search radius of two points. When compared to the input tide gauge data, on average all methods retained input values to better than one centimetre (Table 7).

To further test each method, one gauge at a time was removed and the surface re-interpolated. The original value for the tide gauge removed was then compared to its predicted value, the statistical results of which are shown in Table 8. From these results, Kriging was rejected based on its relatively large mean. The IDW technique has the lowest mean of -0.0209m however the -0.0316m mean for

spline is only one centimetre worse while the standard deviation is significantly better than for IDW. Visually, spline also produced the smoothest surface and aligned best with altimetry values in the offshore direction. Although the IDW technique would be acceptable, the spline method (also known as thin plate) was adopted. Spline is considered suited to generating gently varying surfaces such as elevation and water level heights and was implemented by the UK in modelling LAT below MSL (Turner et al, 2010). Further investigation into the validity of various interpolation techniques should be conducted if metadata and/or denser tide gauge data becomes available.

Table 7. Statistical results of the differences between actual and predicted values for tide gauge ellipsoidal MSL in metres, using three interpolation techniques.[9]

	IDW	KRIGING	SPLINE
Mean	0.0000	-0.0049	-0.0029
Std Dev	0.0003	0.0095	0.0182

Table 8. Statistical results of the differences between actual and predicted values using the removal test for tide gauge ellipsoidal MSL in metres for the three interpolation techniques.[10]

	IDW	KRIGING	SPLINE
Mean	-0.0209	-0.1539	-0.0316
Std Dev	1.0264	0.9233	0.6787

This interpolation does not account for the presence of islands or the shape of the coast but rather interpolates continuously across such features as if they were water. Future improvements may be made by the incorporation of a function which determines the correlation of tide gauge data by the distance over water, using a polygon of the coastline to include the effects of islands and bending shorelines. Improvement using this approach would be optimal with increased density of tide gauges to better define variation in MSL along the coast. Other methods could also be considered such as that of Broadbent (2012a) which involves the creation of a 'coastal thread' or hydrodynamic 'stream line'. This is a line drawn at varying offset from the coast so that its direction is that of the predominant motion of the water. The thread is assigned the value of each tide gauge using lines normal to the thread that pass through each gauge. Interpolation or hydrodynamic modelling could then be performed.

7.2.2 Satellite Altimetry Derived Mean Sea Surface

As mentioned above, purely satellite altimetry was used outside a 22km buffer of the coastline. The two MSS obtained were investigated to determine which aligned best with Australian tide gauge data. The DTU10 and CLS11 MSS were first converted to the tide-free system, and relative to the GRS80 ellipsoid using GUT. Their values at each tide gauge location around Australia were then extracted and compared to the actual tide gauge ellipsoidal MSL values. Table 9 shows the results of these comparisons for tide gauges with available ellipsoid heights. Statistics have been computed for all Australian gauges and study area gauges.

[9] Table containing extended dataset available in Appendix F.
[10] Table containing extended dataset available in Appendix F.

Table 9. Statistics of the differences between tide gauge MSL and satellite altimetry derived MSS referenced to tide-free GRS80 ellipsoid in metres.[11]

	Tide gauge MSL versus DTU10 MSS	Tide gauge MSL versus CLS11 MSS
Mean (all gauges)	0.3804	0.3009
Std Dev (all gauges)	1.4438	1.4622
Mean (study area)	0.0660	-0.0373
Std Dev (study area)	0.3971	0.4617

The statistical results are reasonably similar for the two MSS with CLS11 on average about 8cm closer to tide gauge values across the country and about 3cm across the study area. The DTU10 MSS has slightly larger mean values for both calculations but slightly smaller standard deviations. On average, for the study area, the DTU10 MSS sits lower than tide gauges, while CLS11 is slightly higher. As mentioned in *Section 2.1*, differences between tide gauge and altimetry could be attributed to hydrological and oceanographic effects, as well as the poor quality of tide gauge data. Although CLS11 appears to be a slightly better fit in the study area and for Australia, DTU10 was chosen for the Demonstration due to its use of EGM2008 values over land (as EGM2008 was selected as the geoid if the MDT surface was to be created, plus an MDT already exists using DTU10 MSS and EGM2008). The DTU10 MSS was clipped to an area from 22km offshore to the open ocean extent of the study area. If a vertical datum transformation tool is created in the future with improved tide gauge data, it will require a MSS that matches the epoch of the tide gauge data.

7.2.3 Interpolating Across the Zone of Caution

To fill the satellite altimetry zone of caution between the 4km offshore extent of the tide gauge data and the altimetry derived MSS at 22km offshore, interpolation was required. Limited analysis was conducted into the optimal combination method for the two datasets as the poor quality of tide gauge data meant there was little benefit in developing complex interpolation techniques which may not apply to future datasets. An interpolation method that produced a smooth result and remained true to the original data was selected for the demonstration. Point values of the MSS with an error ≤0.03m were extracted from the DTU10 MSS dataset in the 4-22km zone using the associated error surface, DTU10ERR. The tide gauge 0-4km surface and the MSS 22km-2000m depth surfaces were also converted to points and the three were combined into a single point data file. This dataset was then re-interpolated onto a one minute grid using ordinary kriging technique with a linear semivariogram and a variable search radius limited to four points (due to the linear configuration of tide gauge data).

The surface resulting from the Kriging interpolation is the final integrated MSS. Validation of this surface was carried out by comparison to the input tide gauge values and the original purely altimetric DTU10 MSS. This analysis only serves to evaluate the accuracy of the interpolation process. There is no other known integrated tide gauge and altimetric MSS available that covers the study area for the comparison of results. Table 10 displays the results of the analysis. The final integrated MSS has a mean difference to tide gauge data of -0.0028m compared to 0.0660m for the DTU10 MSS. This shows that the final integrated MSS is more closely aligned with tide gauge values than the DTU10 MSS and in theory should be a more accurate MSS.

[11] Table containing extended dataset available in Appendix G.

Table 10. Analysis of the difference between tide gauge ellipsoidal MSL and corresponding integrated MSS values (in metres).[12]

	Tidal gauge MSL subtract MSS	
	DTU10 MSS	**Final Integrated MSS**
Mean	0.0660	-0.0028
Standard Deviation	0.3971	0.0213

The final form of the MSS within the study area is shown in Figure 16. The surfaces are similar although the finer resolution of the integrated MSS is apparent, along with a different height pattern as a result of the assimilated tide gauge data. There are two notable differences. Firstly, between the Marine Operations Base Southport gauge just south of South Stradbroke Island and the Urangan Storm Tide gauge at the northern extent of the study area, there is a different spatial pattern of heights when compared to the DTU10 MSS. As there are no tide gauges between these locations (an approximately 300km linear distance), the form of the integrated MSS in this area cannot be relied upon. Additional tide gauge data is required to improve the accuracy of the integrated MSS in this region.

The second major disparity is in the region centred on the Port Macquarie gauge where higher values in the integrated MSS dip further south than in the DTU10 MSS. When considering the study area gauges, the difference between ellipsoidal MSL and the DTU10 MSS for Port Macquarie is significantly higher than for any other gauge, with a value of 1.2635m compared to the mean of 0.0660m (*Appendix G*). This difference is most likely because the Port Macquarie gauge is protected from some of the general ocean effects due to its position just south west of Lady Nelson Wharf and may also be highly influenced by the Hastings River. As mentioned in Table 1, hydrological and oceanographic effects such as these can explain differences between tide gauge and satellite altimetry data. As these issues can't generally be corrected for, gauges experiencing these kinds of effects could have a weighting applied to limit their influence on the interpolation. Alternatively, such gauges could be removed from the interpolation if temporary gauges could be established in nearby open coast locations, or fixed to the sea floor offshore outside the range of shallow water effects. As the Demonstration Tool is simply a proof of concept, the Port Macquarie gauge was not removed from the integrated surface. Ultimately, increased density of tide gauge data in this region would prevent the influences of this tide gauge due to its position, from being propagated beyond the area it directly affects. This would improve the accuracy of modelled MSL.

[12] Table containing extended dataset available in Appendix H.

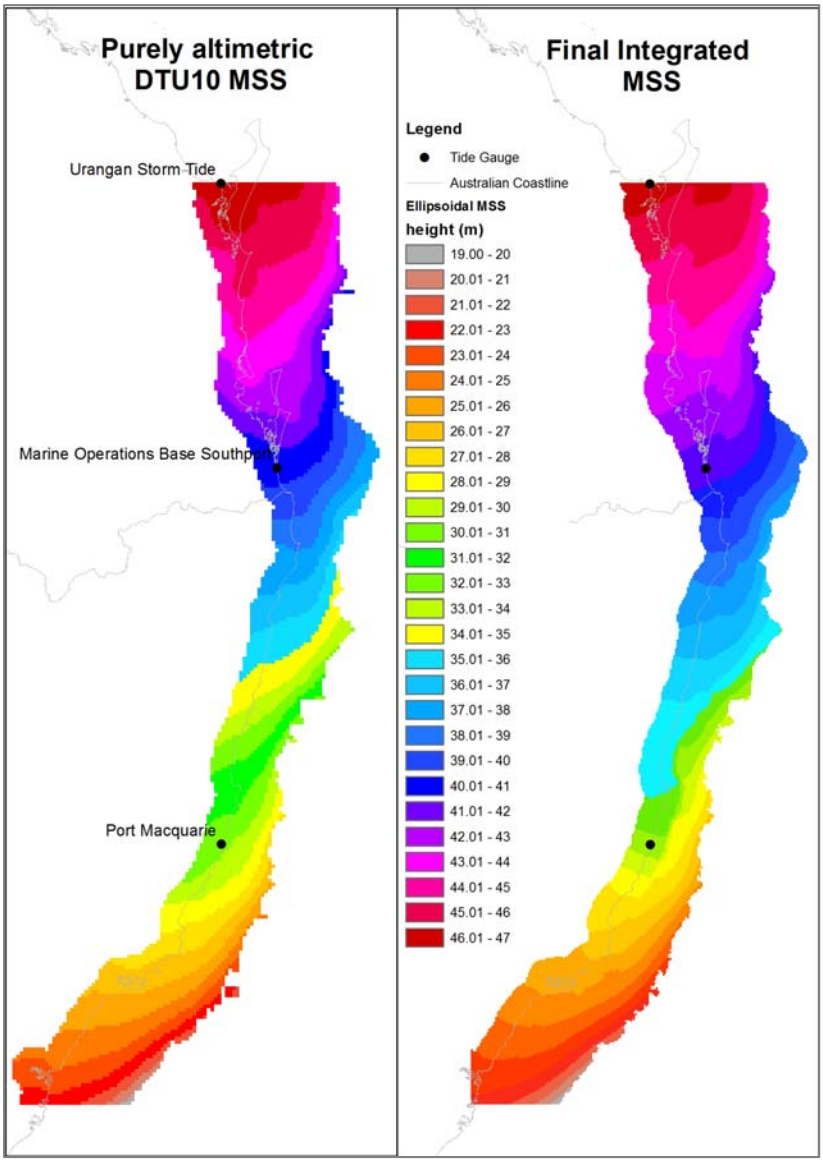


Figure 16. Height of the DTU10 and Integrated MSS solutions above the GRS80 ellipsoid.

The integration could be improved when better tide gauge data and metadata are available as these would permit meaningful analysis of the spatial behaviour of MSL between tide gauge data and satellite altimetry and hence enhance the quality of the integration. Methods used by other projects which may advise future methods for Australia are briefly described as follows. VORF used a combination of least squares collocation and specific algorithms based on coastal topology to interpolate between tide gauge and altimetry data, rejecting altimetry measurements with an error >0.03m using the associated error surface (Iliffe et al, 2007). The French BATHYELLI project conducted surveys to measure MSL relative to the ellipsoid using GNSS in the gap between tide gauge and altimetry data and then interpolated the three datasets using a least squares method (Pineau-Guillou and Dorst, 2011). Other examples of merging altimeter and tide gauge sea level observations include a multivariate regression model used by Deng *et al* (2011) in a study in South Eastern Australia, and temporal and spatial covariance functions used by Deng *et al* (2010).

7.2.4 Onshore Extrapolation

As the vertical datum transformation tool is intended to facilitate the integration of topographic and bathymetric data, the vertical transformations need to extend onshore. Although tidal datums have no physical meaning onshore, they do become relevant for example if the land is inundated by floods or tides in the case of storm surge or seal level rise, or for the processing of LiDAR data to determine shorelines. The VORF project did not extend onshore, as navigational objectives drove and funded the work. The US did extrapolate their tidal datums inland to a distance of 1-2km, and plan to enhance VDatum by extending these further inland (NOAA, 2011). For the Demonstration Tool, MSL has been extrapolated to a distance of 20km inland to enable inundation modelling. The generally accepted elevation extent for coastal inundation modelling in Australia is ten metres above MSL. Although the 20km distance selected is conservative, it should encompass the majority of the Australian coast within the ten metre elevation extent.

The extrapolation was achieved as part of the kriging process discussed in *Section 7.2.3* by defining the extent as a 20km inland offset from the coastline. As no sea level data exists between the coast and this 20km offset, technically extrapolation occurred in this region. For the demonstration, kriging was deemed an acceptable extrapolator, with other methods tested returning very similar results. GEMS is capable of modelling over land (for the purpose of inundation), so the other tidal datums were simply offset from MSL without the need for extrapolation.

There are a number of issues with extrapolating tidal datums inland. Spatial variations in tidal datums near the shore can influence the method of approximating their extension inland. For example, in Figure 17 the locations starred in red present potential problems because they are close to two different bodies of water for which different heights may represent the same tidal datums. This issue could be addressed by using breaklines and/or an algorithm for distance over sea. However if tidal datums are spatially uniform, extrapolation can usually be done by assuming an average constant datum difference or by using an interpolation method. In Australia's case (as discussed in *Section 7.2.1*), the variability of tidal datums along the coast and between different coastal regimes (e.g. river, bay, ocean, tidal flats, etc.) is smooth enough to allow interpolation to be used as an extrapolator for the Demonstration Tool. Closer investigation of the validity of using interpolation methods to extrapolate tidal datums inland for the Australian coast should occur in the future when denser tide gauge data are available.

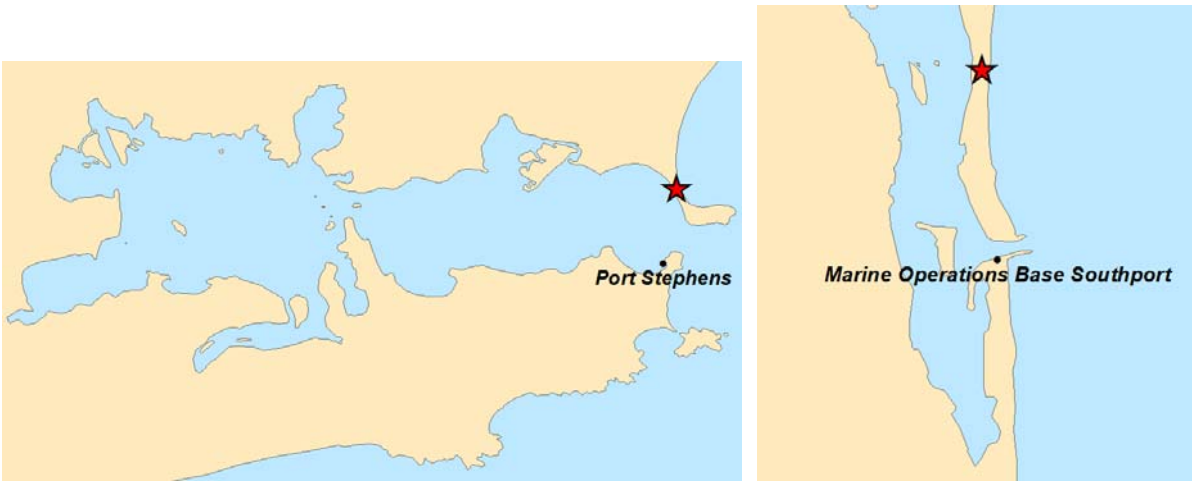


Figure 17. Locations starred in red that are potential problems for inland tidal datum extrapolation.

7.3 Ellipsoid to Tidal Datums

Transformations to the tidal datums LAT, MHWS, and HAT were achieved via the GEMS hydrodynamic model discussed in *Section 5.4*. The GEMS model was tested against current tide gauge data by running the tide gauge coordinates through GEMS. Before GEMS results could be compared to tide gauge values of LAT, MHWS, and HAT, the tide gauge data had to be converted so they were relative to MSL rather than LAT. Equations 3-3.2 were used, where the subscript is the reference surface that heights are relative to.

$$LAT_{MSL} = -MSL_{LAT} \qquad \text{Equation 3.}$$

$$MHWS_{MSL} = MHWS_{LAT} - MSL_{LAT} \qquad \text{...3.1}$$

$$HAT_{MSL} = HAT_{LAT} - MSL_{LAT} \qquad \text{...3.2}$$

Table 11 shows the results of these comparisons for tide gauges with available tidal datum heights. Statistics were computed separately for all gauges and study area gauges. Three possible outliers can be seen in *Appendix H* highlighted in pink, all of which are in Queensland, north of the study area. It is known that GEMS has not been properly calibrated in northern Queensland but as this is outside the study area, it has no impact on the Demonstration Tool. When compared to current tide gauge data across Australia, GEMS performed best for LAT, with a mean of -13cm. On average GEMS results put LAT and MHWS below tide gauge values and HAT above. Statistics for study area gauges are similar to the statistics for all gauges for the datums HAT and LAT, while results for MHWS are significantly better with a study area mean of -2cm. The reason for this is not clear although, it is perhaps linked to GEMS not being calibrated in some places outside the study area which may affect MHWS more than HAT and LAT as it is an average value as opposed to an extreme. GEMS generally produces results within 10-20cm of current tide gauge values. Although the GEMS tidal model may be able to be improved and updated with more recent bathymetry in some areas, it performs reasonably well when compared to current Australian tide gauge information and hence was utilised in the demonstration vertical datum transformation tool.

Table 11. Differences between tide gauge tidal datums relative to MSL & GEMS results in metres. [13]

	Tidal gauge datum values subtract GEMS results		
	HAT	**LAT**	**MHWS**
Mean (all)	0.21	-0.13	-0.15
Standard Deviation (all)	0.46	0.46	0.39
Study Area Mean	0.22	-0.15	-0.02
Study Area Standard Deviation	0.32	0.22	0.21

To develop the ellipsoidal tidal datum separation surfaces, a point grid with one kilometre spacing was generated for the study area. Ideally this point spacing should be closer to 100m to capture all coastal variation in the tidal datums however to save time and processing, a larger value was selected given the MSS grid has only been developed at one minute resolution (~1-2km). The grid of point 'stations' was run through GEMS to produce MSL to LAT, MHWS and HAT offsets for each point. These offsets were interpolated into gridded surfaces using the spline minimum curvature technique as used for the coastal MSL interpolation. Each tidal surface was then individually added to the final integrated MSS to produce three gridded ellipsoidal tidal datum separation surfaces to the centimetre level for use in the transformation tool. As GEMS is capable of producing output over

[13] Table containing extended dataset available in Appendix I.

land (for the purposes of inundation modelling), no extrapolation of the tidal surfaces was required. By producing these separation surfaces, the GEMS model does not have to be integrated into the Demonstration Tool which saves significant time in the transformation process, as GEMS executes slowly.

The results for the HAT tidal datum are shown in Figure 18. The interpolated output from GEMS is on the left, and interestingly, reveals a pattern of circles along the coast. These circles are centred on tide gauges which suggests that, contrary to the information available, GEMS has a statistical model component which matches to the tide gauges as opposed to purely being a physical model which uses boundary conditions to replicate the tidal behaviour within the area of applicability. A pure physical model would not take tide gauge data as direct input, but use it only for calibration. The pattern produced by GEMS, aside from the circles, is strange and can only be attributed to the inner workings of the model itself. The same pattern was found for the LAT and MHWS results and carries through to the final separation surfaces. GEMS has been used for the Demonstration Tool but these results provide further impetus to source an improved model/s for any future vertical datum transformation tool.

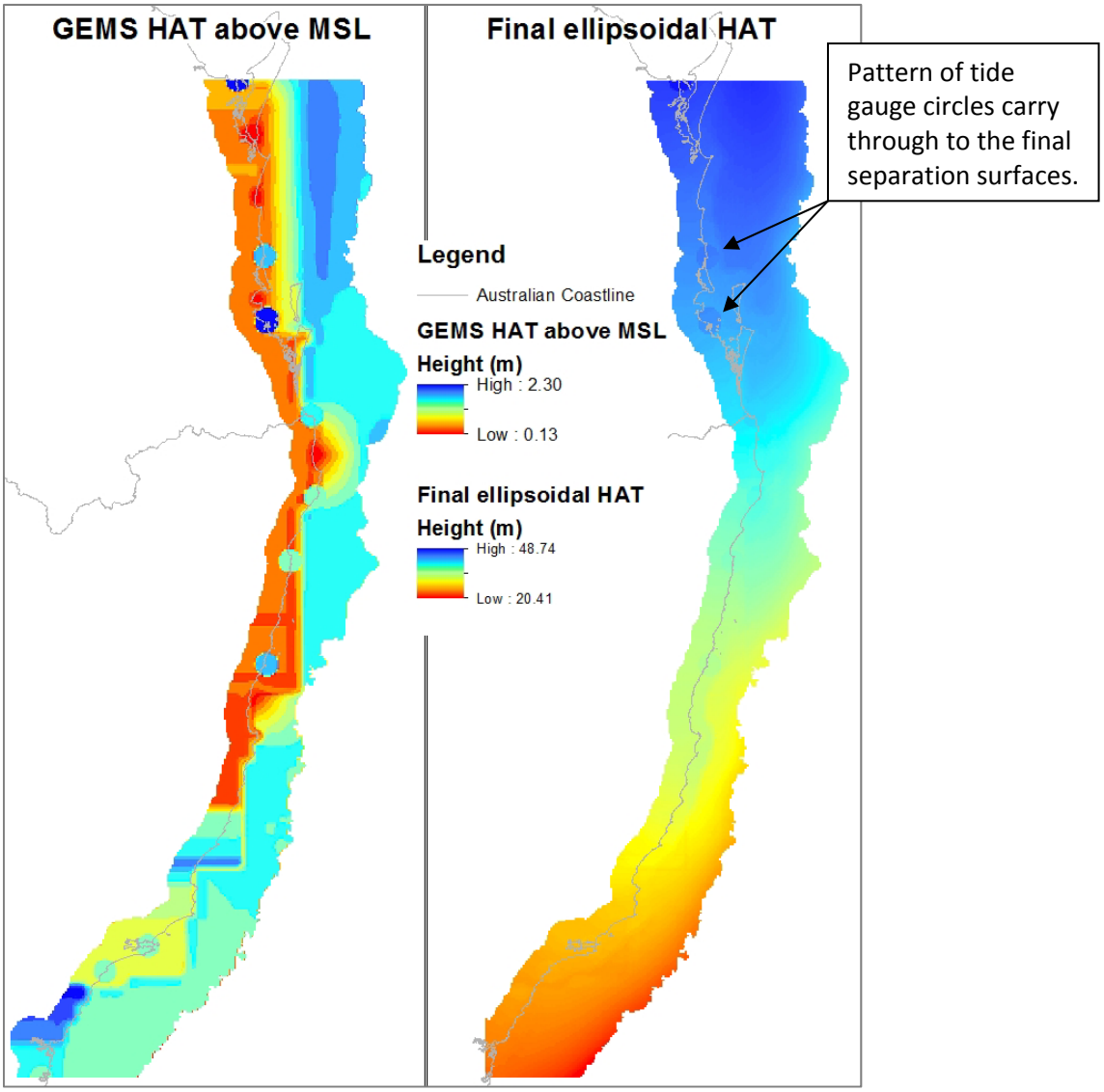


Figure 18. Results for HAT. The left image is the interpolated GEMS HAT above MSL output, and the right image is the final separation surface HAT relative to the GRS80 ellipsoid (in metres).

7.4 The Demonstration Tool

The Demonstration Tool was developed in the Python 2.5 programming language and runs as an ArcToolbox geoprocessing script with an ArcInfo license of ArcGIS 10.0 or with the Spatial Analyst and 3D Analyst extensions. A package of data and tools are required for the operation of the tool, and must all be located within one folder and named exactly as described in inverted commas below. A sample of this data for the project study area is supplied however the user can supply data for other areas of Australia which can be produced following the steps in Appendix J. The folder location of this data or Demonstration Tool Data Package (DTDP) is an input requirement for the tool and must contain;

- The ESRI GRID format vertical separation surfaces (sample data supplied was developed as part of the project for the MGA Z56 study area discussed in *Section 7*)
    - ellipsoid-MSL – "integmss"
    - ellipsoid-LAT – "ell_lat"
    - ellipsoid-MHWS– "ell_mhws"
    - ellipsoid-HAT – "ell_hat"
    - ellipsoid-AHD – "ausgeoid09"
- A polygon shapefile describing the extent of the transformation surfaces named "StudyArea_bound.shp" (sample data supplied)
- The LAStools; "lasboundary.exe", "lasclip.exe" and "lasmerge.exe". These are not supplied with the sample DTDP as may require licensing as discussed in *Section 5.1*. They must be obtained to use the tool.

Also supplied with the sample DTDP is an example input LAS file ("SunshineBathy2011-C2-ELL_5137053_56_0001_0001.las") and an ESRI GRID raster DEM file ("e513705201005") with which to test as input to the tool. Rasters of other formats can also be used as input. These files are both in MGA Z56. The LAS file is relevant to the ellipsoid and the raster to AHD. The tool is provided "as-is" and is licensed under 'Attribution-ShareAlike 3.0 Australia (CC BY-SA 3.0)' meaning users are free to copy, distribute, display, and perform the work, to make derivative works, and to make commercial use of the work. However, if users alter, transform, or build upon this work, they may distribute the resulting work only under a licence identical to this one and must give the original author credit.

If problems are experienced with the tool, some issues to be aware of are as follows. The use of LAStools may mean there is a limit to the size of LAS files that can be processed (you may receive warnings during processing). The spatial reference of rasters must be defined using the ESRI convention for the MGA projection otherwise the tool will fail. It may be best to avoid spaces and long path names for the tool and input files. When a raster file is input, the process may produce a lock file that cannot be removed until the software is exited (an ESRI bug). If the tool claims it cannot create an output, exit ArcMap, then re-open it to re-run the tool. This unfortunately means the tool cannot be run in batch mode for raster files. It can however be run in batch mode for LAS files.

Figure 19 outlines the transformation process applied by the tool. The majority of Australian elevation data exist in MGA projected coordinates and the study area falls within MGA Zone 56. Therefore the Demonstration Tool requires the horizontal coordinates of input data to be in GDA94 MGA Zone 56 unless the user is providing their own separation surfaces in another MGA Zone. In the unlikely scenario that data are not in an MGA Zone, pre-transformation to this system is required. A tool that covers the entire Australian coast would ideally be capable of accepting either GDA94 or MGA coordinates, to deal with projects that cross zones or to avoid horizontal transformation of data which is in one zone before input.

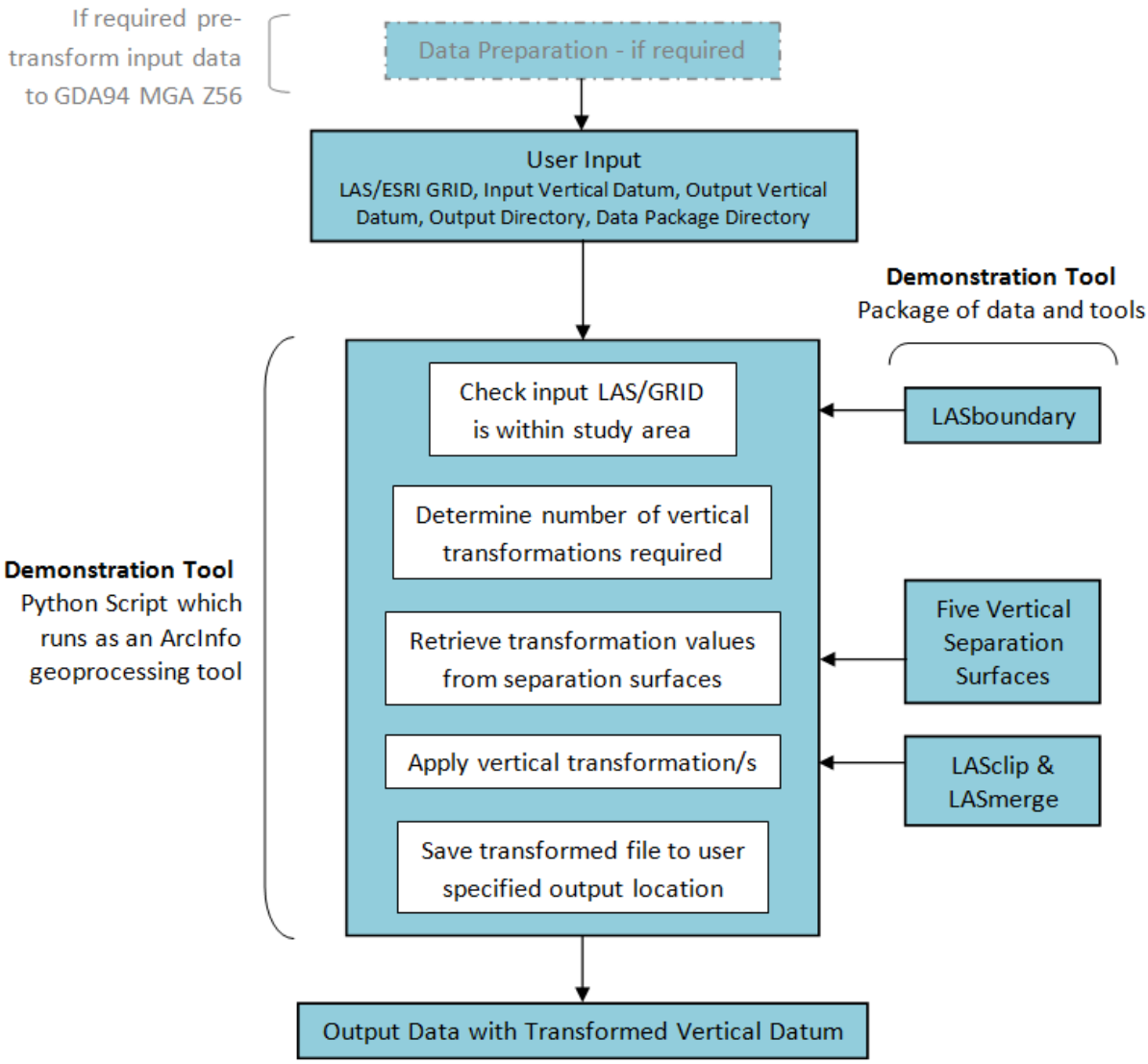


Figure 19. Overview of the Demonstration Tool vertical datum transformation process

Figure 20 shows the transformation tool's interface. Six inputs are required to perform the transformation. The user must provide either a LAS file or raster file in one of the first two input boxes. When one of these files is selected, the other box is disabled. The tool then requires the user to enter the MGA Zone of input data (56 if using the supplied DTDP), the vertical datum of the input data (which must be one of the relevant six), as well as the desired output vertical datum (which also must be one of the six). As these must be different, the vertical datum selected as input is excluded from the output datum options. The user is also required to identify two directories. These include where to save the transformed file, and the location of the DTDP. In this mode the tool only transforms one LAS or GRID file at a time however it can be run in 'Batch' mode (for LAS files) as with other geoprocessing tools to process multiple files. In this way the tool can be run once for a project containing many tiles.

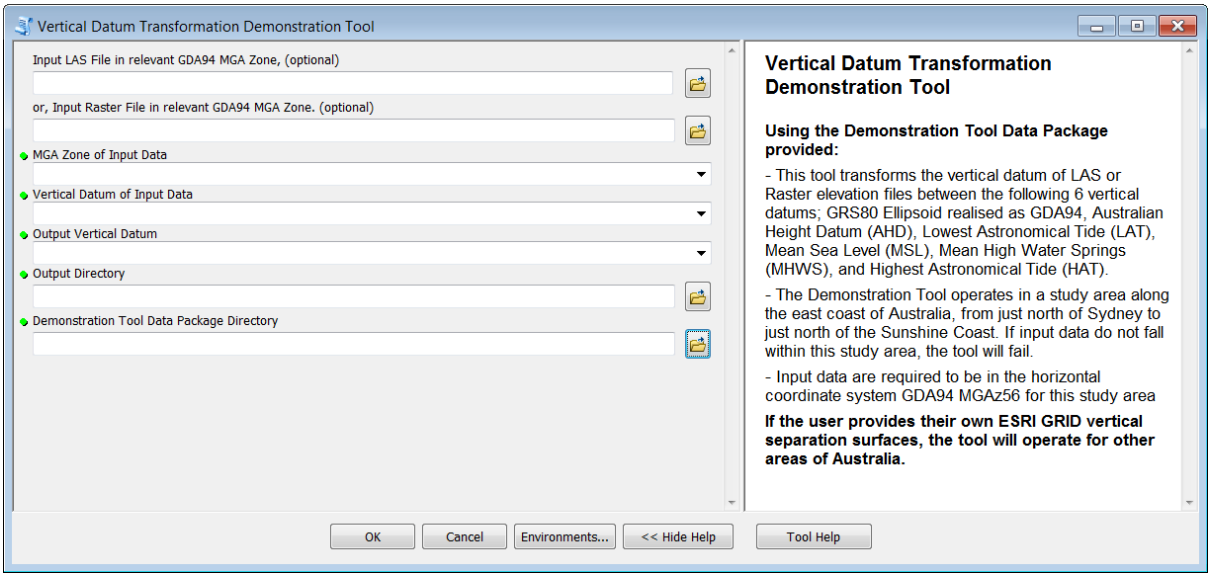


Figure 20. Demonstration Tool interface and example input.

The average processing times for the Demonstration Tool are shown in Table 12. The tool performs efficiently for raster files with little increase in processing time when two transformations are required. The processing times for LAS files are longer as they are not a native ArcGIS format and require more complex scripting. When a LAS file requires two transformations, the processing time almost doubles. This could be reduced using alternate scripting methods but was not necessary for the Demonstration Tool which simply proves the concept. Although the Demonstration Tool has a number of limitations (discussed in *Section 8*), it can be considered functional in areas close to the tide gauges that were used in its development, where the tidal regime does not change significantly from that at the tide gauge.

Table 12. Average processing times of the Demonstration Tool using a 1x1km bathymetric LiDAR data tile (average 5m point spacing which is about 40,000 points per tile) for both LAS and GRID files.

Input Data Type	Number of Transformations	Average Processing Time
LAS	1	15 seconds
LAS	2	30 seconds
ESRI GRID	1	5 seconds
ESRI GRID	2	6 seconds

8 Discussion

8.1 Demonstration Tool Considerations

An accurate and effective vertical datum transformation tool cannot be produced for the Australian continent with the currently available tide gauge data. A Demonstration Tool has been produced for a study area in MGA Zone 56. The problems with using coastal tide gauge data to enhance an altimetry derived MSS for Australia are primarily associated with; the limited number of gauges around the coast available to accurately describe ellipsoidal MSL, the number of existing gauges which are missing MSL data and/or direct GNSS observed connections to GRS80, and the lack of metadata to determine the reliability and accuracy of available tide gauge records. In addition, gauge records are of different vintages and gauges have operated for various periods of time from one, up to about one hundred years. However this is potentially less of an issue, as Iliffe *et al* (2007) have demonstrated that by modelling spatial-temporal correlation of MSL, tide gauge observations over short epochs and of various vintages can be reliably corrected to the current epoch.

Although there are currently only 67 gauges with the required data available to this project, Jayaswal (2012) indicated that thousands of additional secondary tide gauges exist nationally. The number of gauges available to the work currently underway by Broadbent (2012a) for the Queensland Climate Change Centre of Excellence (QCCCE) exhibits this. The Centre is undertaking a project to improve coastal mapping for climate change response which involves identifying and prioritising coastal locations for the collection of tidal, bathymetric and storm tide information, as well as modeling HAT. Approximately 700 gauges were available along the Queensland coast, but only about 200 of these had sufficient precision for the purposes of the project. Figure 21 shows the approximately 200 tide gauges in Queensland with HAT elevations being used by the QCCCE project. As there is no central repository for Australian tide gauge data, this data was not available to this project. It is highly likely that most of these gauges do not have ellipsoid heights or adequate metadata. Despite having access to about 700 gauges, the Queensland project has identified large sections of the coast which require additional tide gauge information to accurately model HAT (Figure 22). The requirement for additional data was based on priorities assigned for the vulnerability of the coastal communities and lands to inundation by the sea.

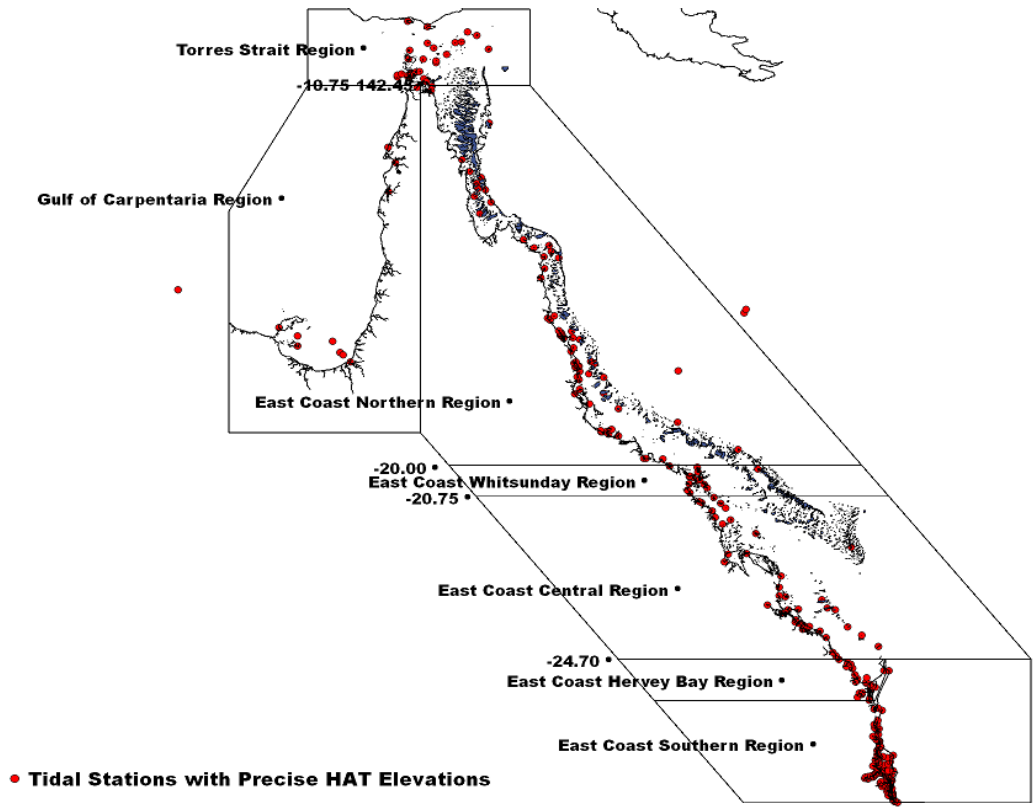


Figure 21. The approximately 200 tide gauges (red) with HAT values used in the QCCCE project (Broadbent, 2012a).

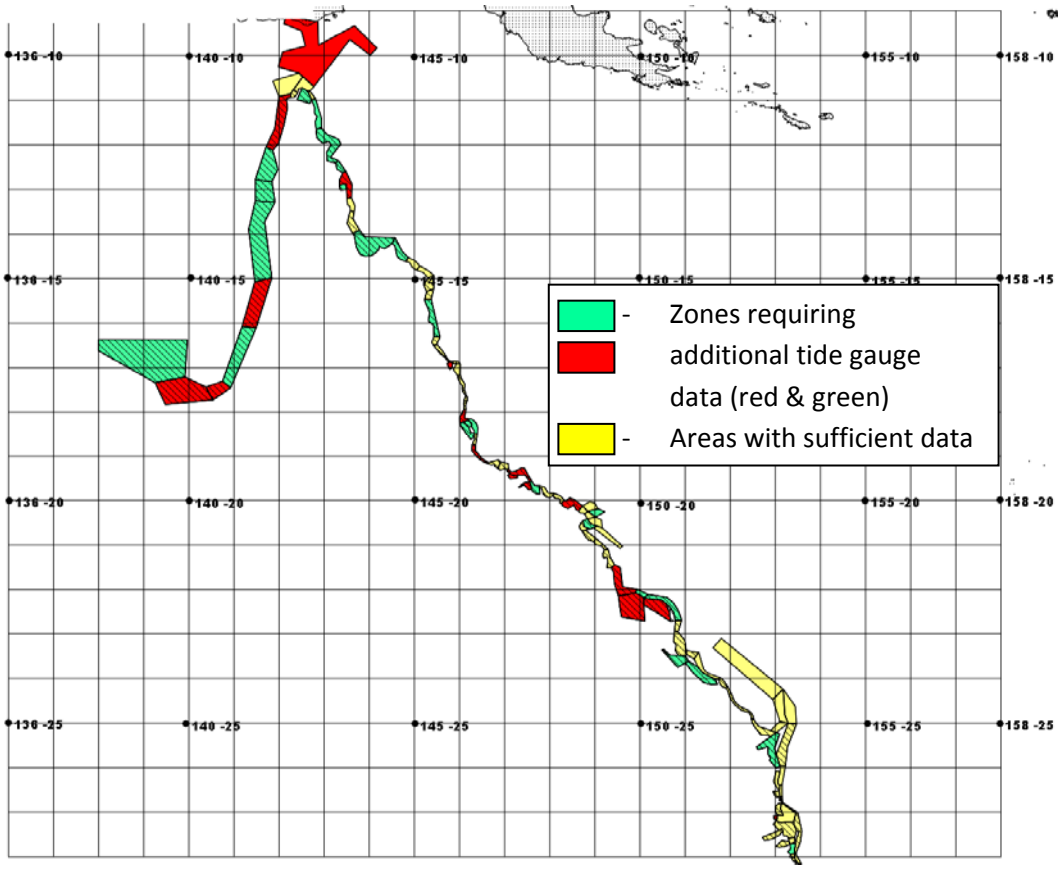


Figure 22. The areas of Queensland coastline requiring additional tide gauge readings - highlighted in red and green. Yellow areas are deemed to have sufficient data (Broadbent, 2012a).

If denser tide gauge data with the required ellipsoidal and MSL heights and metadata was available, it would be possible to develop comprehensive methods for interpolation, integration, and extrapolation of the enhanced MSS. Denser coastal tide gauge records would also allow meaningful statistics to be derived for the spatial behaviour of coastal MSL and hence more accurate coastal interpolation methods could be developed. If detailed metadata was available for each tide gauge, corrections could be applied for issues in Table 1 such as vertical land movement. Metadata would also enable accuracy statistics for ellipsoid and MSL heights to be derived and used as weightings to better represent MSL in coastal interpolation, especially with increased density of gauges. Improved gauge data may also permit meaningful analysis of the spatial behaviour of MSL between tide gauge data and satellite altimetry and hence enhance the integration process.

As the current accuracy of tide gauge data is unknown and there is no other known integrated tide gauge and altimetric MSS available that covers the study area for the comparison of results, the accuracy of the final MSS used in the Demonstration Tool cannot be readily determined. Results have been compared to the original tide gauge values and these compared to the difference between the satellite only MSS and tide gauge values, but this analysis only serves to evaluate the accuracy of the interpolation process. The accuracy of the final MSS near the coast is dependent upon the accuracy of the input data. Given the issues identified with Australian tide gauge data including that gauge accuracies are currently unknown (*Section 2.1)*, the final integrated MSS is only considered suitable for the proof of concept. It will be necessary to ensure that the epoch of the altimetric MSS employed in any future tool aligns with the NTDE of improved tide gauge data. If a MSS of equivalent epoch is not freely available, one may have to be commissioned or produced by someone with the necessary experience. The UK for example, commissioned the DNSC06 satellite altimetry derived MSS from the DTU especially for the VORF project (Iliffe et al, 2007).

The GEMS tidal model used in the Demonstration Tool would not be suitable in its current form as part of an effective vertical datum transformation tool. GEMS study area results indicate that it is statistically forced to match tide gauge values as opposed to being a more accurate physical hydrodynamic model (*Section 12.2*). Physical models replicate known tidal behaviour based on the physical laws of fluid dynamics. They use boundary conditions (constraints at the limits of the model) to model water flow inwards from the boundaries. Tide gauge data are not usually input but are used to calibrate these models. Hence the circular tide gauges pattern resulting from GEMS indicates it is not a pure physical model. GEMS performance is also limited in bays with a narrow entrance, where the bathymetry and tidal flow are not adequately represented, as GEMS only has a maximum resolution of 1km. Furthermore, the tidal model has not been completely calibrated in the northern part of Queensland and Western Australia. For a future transformation tool it may be necessary to update GEMS or acquire another tidal model/s with improved currency, accuracy, and resolution which are preferably pure physical models. For example, Luciano Mason from the Australian Maritime College has developed three hydrodynamic models that cover the entire coast of Queensland (Broadbent, 2012b). It is unknown whether local models exist to cover the remainder of Australia. There is also a NTC Australian regional model (ORSOM) that could be investigated.

Although the application of hydrodynamic models is potentially the most accurate approach to determining tidal datums, in practice they are typically very expensive and require a long time (months to years) to develop to the required accuracy for vertical datum transformations (refer to

Section 12.2). Where high accuracy hydrodynamic models are unavailable and unfeasible to develop, it may be necessary to consider alternative methods. For example, the coastal thread method of Broadbent (2012a) (refer to *Section 7.2.1*), or the TCARI method of spatial interpolation used by the VDatum project which was developed so that existing gauge and historical data could be utilised rapidly (in the order of months) (refer to *Section 12.8*).

8.2 Additional Considerations

The Demonstration Tool produced is a proof of concept which requires data and software improvements before it can be considered an accurate vertical transformation tool. For the production of effective vertical datum transformation software there are a number of additional considerations. The resolution of the transformation grids needs to be fine enough to represent the coastal features in complex regions of the coast. For example, a narrow barrier island may have tidal datum values on the ocean side quite different to those on the landward side. If the grid resolution is greater than the width of the island, the required detail would be lost. Although high resolution may be required in areas of complex coastal topography, it is unnecessary in the open ocean. When choosing grid resolution, it is also necessary to consider the overall size of datasets and the required processing time as this can be significant. In computing the final sea surface topography (SST – referred to as MDT in this project) over the whole UK continental shelf, it took the equivalent of 150 desktop machines 12 hours (Iliffe et al, 2007). Therefore, to balance these factors, creating grids of variable cell size should be considered. For example, the resolution of VORF's grids is 0.008 degree with patches of 0.003 degrees where there is complex coastal topography.

Accounting for the effects of complex coastal topography and near shore islands or reefs should also be considered when interpolating/extrapolating tide gauge values. Currently, the Demonstration Tool does not specifically account for the presence of islands or the shape of the coast but rather interpolates/extrapolates continuously across such features. Using a polygon of the coastline to determine the correlation of tide gauge data by the distance over sea only, may improve results by including the effects of islands and bending shorelines. For example, VDatum's TCARI used a set of weighting functions to quantify the local contributions from each of the tide gauges in a manner that considered distances between stations by over-water paths only and thus included the effects of land. VORF also found an improved pattern of correlation between tide gauges using distance over sea only as opposed to straight line distance (which could cross land). Interpolation taking into account land, may only be feasible for Australia with a denser network of tide gauge data to better represent the coastal MSS, as with currently available data, gauges can be thousands of kilometres apart.

A number of Australia's tide gauges are quite a distance up rivers. For example, the Perth Swan River, Yarra River, Gateway Bridge and Port Office Brisbane River gauges are tens of kilometres inland from the coast. If the vertical datum transformation approach is applied around Australia, care should be taken in using the data from gauges so far from the coast. None of the gauges mentioned currently have both ellipsoid and MSL values so their behaviour in comparison to coastal gauges has not been analysed. However, MSL will behave differently in a river when compared to the open sea so it may be appropriate to prevent gauges a certain distance inland from the coast from propagating their values outside the mouth of the river. For example, the UK excluded points

more than two kilometres from the open sea from contributing to ocean MSL (Iliffe et al, 2007). This is a sensible approach that could be adopted for Australia.

An important component of an effective transformation tool is the associated accuracy of the transformations it performs. If an application requires a common vertical reference for the integration of elevation data, its accuracy requirement is innately high. Therefore transformations must not introduce significant errors. Errors may arise from inaccuracies in the gridded separation surfaces used in the datum transformations (e.g. AUSGeoid09), in the scripted method of applying the transformations, in the source data used to create the separation surfaces (e.g. tide gauge data), as well as measurement errors in user input elevation data. The only transformation that currently has an associated error is ellipsoid to AHD as it has been determined that AUSGeoid09 has an accuracy of 0.03m across most of Australia (GA, 2012). As the other four separation surfaces incorporate tide gauge data which currently has no metadata or associated errors, the accuracy of these transformations cannot be determined. If tide gauge accuracies were available, the cumulative uncertainties of the separation grids could be determined using; the error surface provided with the DTU10 MSS, by testing GEMS (or any tidal model) against tide gauge data (with known errors), and by estimating errors in interpolation/extrapolation and application of transformations. This would allow the approximation of spatially varying errors across the study area. It is important to provide a vertical accuracy statement with transformed data so the user is aware of limitations.

Even if a common vertical reference is accurately established for datasets before integration into a seamless elevation surface, vertical datum reconciliation will not solve all the problems of data integration. Users should be aware of other issues causing data mismatches such as differences in collection sensor used, horizontal coordinate system, the season of collection, the dates of collection and whether any significant events have occurred between collection dates to alter elevations, the vertical and horizontal accuracy requirements of the various datasets, the density of elevation data in the various datasets, and the extent of overlap of the datasets (NOAA, 2007). Most of these issues can be partially or fully resolved using appropriate data preparation and gridding techniques that suit the application. For detailed information around the integration of multi-resolution DEMs, recent research by Ravanbakhsh and Fraser (2012) can be consulted.

Caution must also be applied when using tidal datums that have been extrapolated inland for flooding or sea level studies. If, subsequent to production of a vertical datum transformation tool, sea level changes in a region, the tides will also change due to new areas being flooded or dried. The local tide patterns used to construct the tidal datums may then no longer be completely applicable if significant changes occur. This provides impetus for the update and maintenance of a vertical datum transformation tool however caution would still be required between reviews. The ellipsoid to MSL separation surface would require update upon change to the NTDE used for tide gauge data. Hence the other tidal surfaces would require update as a change to the NTDE would signify a sea level change and consequently a change to the coastal tidal regime. The transformation from ellipsoid to AHD would need to be updated if further updates are made to AUSGeoid. However, if the intention to move Australia to a dynamic version of GDA in 2020 with the associated ellipsoidal height datum replacing AHD is carried out, the transformation tool would need to accommodate the change.

9 Conclusion

A broad approach has been developed for Australia, which will enable the transformation of ellipsoid height related data to other vertical datums of user interest (and vice versa), and hence facilitate the creation of seamless height datasets across the Australian littoral zone. However, the tide gauge data and metadata available in Australia are not adequate for a project such as this when compared to those in the US and UK. This hinders the determination of a detailed and comprehensive transformation approach as well as its immediate implementation for the entire Australian coastline. The general approach identified for vertical datum transformation in Australia requires:

- Horizontal coordinates of input data in the applicable GDA94 MGA Zone
- Input data in any of the six relevant vertical datums
- Ellipsoid based MSL heights at tide gauges to enhance satellite altimetry derived MSS
- Modelling of other tidal datums through hydrodynamic modelling
- Using AUSGeoid09 to transform to AHD from the GRS80 ellipsoid

The results from Stage 1 of the project illustrate that although Australian LiDAR data providers are consistently producing both topographic and bathymetric ellipsoidal and AHD data to satisfy project specifications, there remain systematic errors in the data collection and processing techniques which impact the topographic and bathymetric data products. As the collection and processing procedures for topographic LiDAR are different to those of bathymetric LiDAR, the form and magnitude of the errors vary. However, because the data are within the required accuracy tolerances, current techniques are accepted. Users of the vertical datum transformation tool should be aware that any errors present in input ellipsoidal LiDAR data will carry through to outputs when transforming the vertical datum.

The major hindrance to developing a vertical datum transformation approach for Australia is the available tide gauge data and metadata. The main issues are:

- The limited number of gauges around the coast available to accurately describe coastal ellipsoidal MSL.
- The number of existing gauges which are missing MSL data and/or direct GNSS observed connections to GRS80.
- The lack of metadata to determine the reliability and accuracy of available tide gauge records.

For the above reasons, an accurate and effective vertical datum transformation tool cannot be readily produced. For a tool to be considered ‘accurate’, it would need to retain the original accuracy of the input data or maintain it to a degree quantifiable within acceptable tolerances. To be considered ‘effective’, a tool requires a dense network of tide gauges which accurately represent the spatial behaviour of coastal MSL. The issues of grid resolution in complex coastal regions, and the effects of such complex coastal topographies, near shore islands, reefs and rivers on the interpolation/extrapolation of MSL should also be addressed in detail. Although not considered ‘accurate’ or ‘effective’, the Demonstration Tool developed proves the concept, with gridded separation surfaces created for the study area allowing five transformations between: ellipsoid-MSL, ellipsoid-LAT, ellipsoid-MHWS, ellipsoid-HAT, and ellipsoid-AHD and vice versa.

10 Recommendations

The recommendations for future research and development of a high accuracy vertical datum transformation tool in Australia are as follows;

- Collate all existing tide gauge data and metadata.
- Create a central repository for Australian tide gauge data and metadata which would implement standards for the detail of data and metadata required. Failing a national repository, state/territory centralised repositories are recommended.
- Conduct a survey of the ellipsoid height of all tide gauges with GNSS and obtain missing MSL values.
- Establish a denser network of tide gauge data (new gauges only require a month of data before utilisation if seasonal variation is corrected for and a method applied to align them with the required epoch).
- Produce a satellite altimetry derived MSS matching the NTDE of tide gauge data.
- Undertake further testing of AUSGeoid09 at the coast and offshore.
- When improved tide gauge data is available, perform analysis to determine the best methods for aligning the epoch of tide gauge MSLs, coastal tide gauge interpolation, integration with satellite altimetry, and onshore extrapolation.
- Develop improved hydrodynamic model/s and/or alternative interpolation methods for modelling tidal datums.
- Raise the level of awareness amongst the spatial, coastal, and hydrographic industries in Australia of the importance of tide gauge data for vertical datum transformation.

If the above mentioned recommendations are implemented, it will be possible to develop a more accurate and effective vertical datum transformation tool for the Australian coast using the approach developed by this project.

* Discussions with the ICSM PCTMSL revealed there is a lack of funding and resources available to achieve the above mentioned recommendations. However, the ICSM PCTMSL supports ongoing development and recommended the production of a coarse vertical datum transformation tool using currently available data (an outcome from PCTMSL 45th meeting held in Adelaide October 2012). Such a tool will initially provide national coverage at a coarse level which will then enable improvement in high priority areas via focused efforts to collect additional data. A coarse vertical datum transformation tool is currently in development through the CRCSI and ICSM PCTMSL and will be available via the ICSM webpage around mid 2013.

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12 Appendices

Appendix A - Overview of Relevant Concepts

12.1 Tides, Analysis & Prediction

Tides are the periodic rise and fall of sea level. The rise and fall is actually the horizontal movement of tidal waves with very long periods (24.8 or 12.4 hours) and wavelengths of thousands of kilometres (Park, 1999). Their crest is high tide, their trough low tide, and the horizontal component is known as the tidal current. The vertical distance between high and low tide, or the height of the wave, is known as the tidal range which varies from place to place and over time from almost zero to many metres. The three basic types of tides are semidiurnal, mixed, and diurnal (Figure 23). When there are two high and two low tides each tidal day that are approximately equal in height, the tide is semidiurnal. When the difference in height between the two high and/or low tides of each tidal day is relatively large, the tide is mixed. When there is only one high tide and one low tide each tidal day, the tide is diurnal (CO-OPS, 2006). Although tides are most recognised as a coastal phenomenon, they affect the oceans as well as shallow coastal waters. They are fundamentally the result of the gravitational attraction of the Moon and the Sun on the Earth (NOAA, 2010; CO-OPS, 2006; Park, 1999).

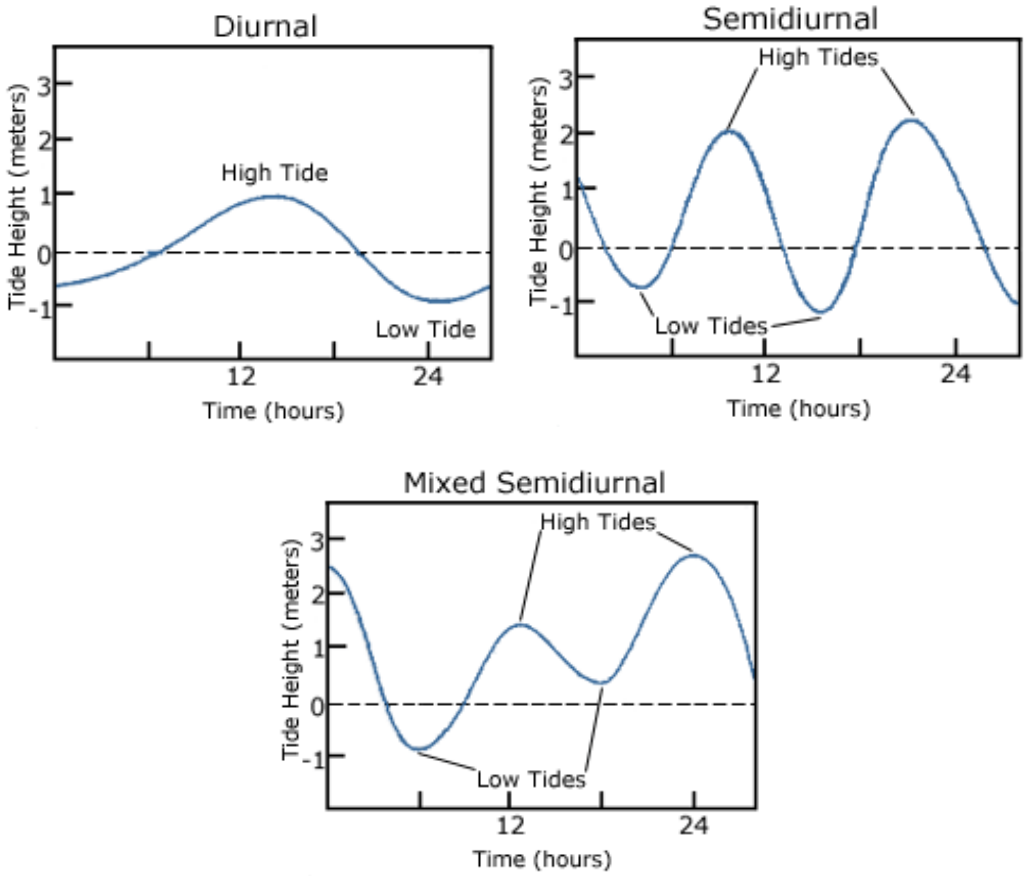


Figure 23. Examples of Diurnal, Semidiurnal and Mixed Semidiurnal tidal cycles (NOAA, 2010).

Both the Moon and Sun affect the tides, but as the Moon is much closer to the Earth it has more than twice the effect of the Sun, even though it is much smaller (NOAA 2010; CO-OPS, 2006). The Earth and the Moon revolve together around their common centre of mass. The gravitational attraction between the two bodies is balanced exactly, at the centre of mass of the individual bodies, by the centrifugal force produced by their individual revolutions around their common centre of mass. However, the forces are not balanced on the Earth's surface. The centrifugal force has exactly the same magnitude and direction at all points on the Earth's surface, whereas the gravitational force exerted by the moon varies in magnitude with distance from the moon, and direction as it points towards the moons centre of mass (Park, 1999). The result is known as the tide-producing force and is demonstrated in Figure 24. On the side of the earth facing the moon, a tide-producing force acts in the direction of the moon's gravitational attraction, while on the side of the earth directly opposite the moon, the tide-producing force is in the direction of centrifugal force, or away from the moon, creating an ellipsoidal tidal potential envelope. This theory is known as equilibrium tidal theory and assumes a water covered Earth with no land masses.

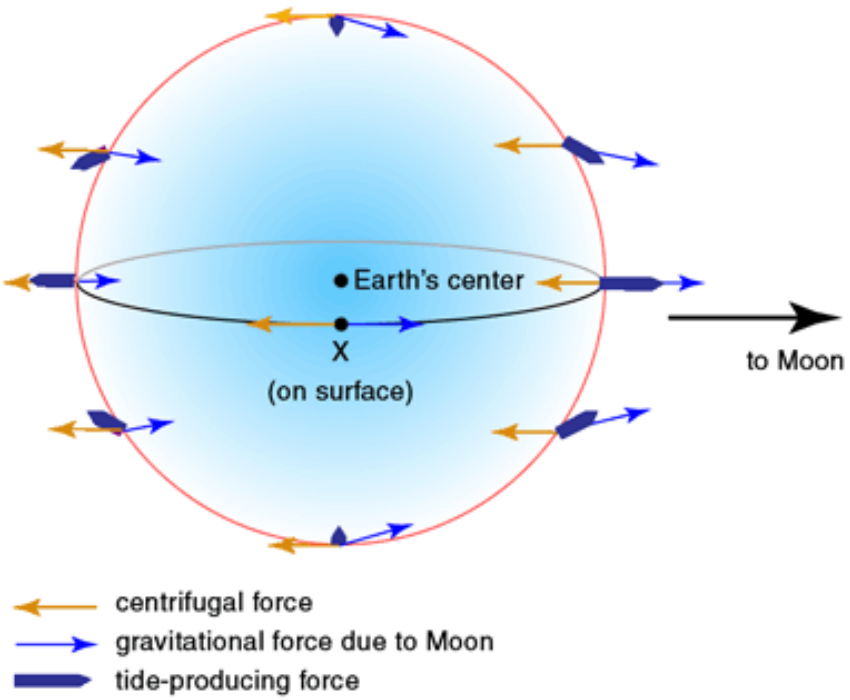


Figure 24. An example of the tide-producing forces (not to scale) for a hypothetical water-covered Earth (Park, 1999).

The relative positions and orientations of the Earth and Moon (and Sun) vary according to a number of regular cycles and cause variations in the tide. Two important variations are caused by the Lunar Declination Effect, and Lunar Phase Effect. The Lunar Declination Effect results in the three basic types of tide as demonstrated in Figure 25. The plane of the Moon's orbit is at an angle to the Earth's equator which is called the declination. If the moon is over the equator, as in the dotted lines, the height of the tide at A would be the same as at A' 12 hours later (semidiurnal), but if the moon is at high declination, differences between the heights of two daily tides of the same phase begin to occur. This can be seen in the different magnitude of the arrows at B and B' resulting in a mixed tide, and the fact that C' is outside the tidal potential envelope resulting in a diurnal tide. The Lunar Phase Effect results in Spring and Neap tides. When the Earth, Moon and Sun align, the solar tide has an additive effect on the lunar tide creating maximum high tides and minimum low tides both known as Spring tides. A week later when the Sun and Moon are at right angles, the solar tide partially cancels the lunar tide creating moderate tides known as neap tides (Park, 1999; NOAA, 1998).

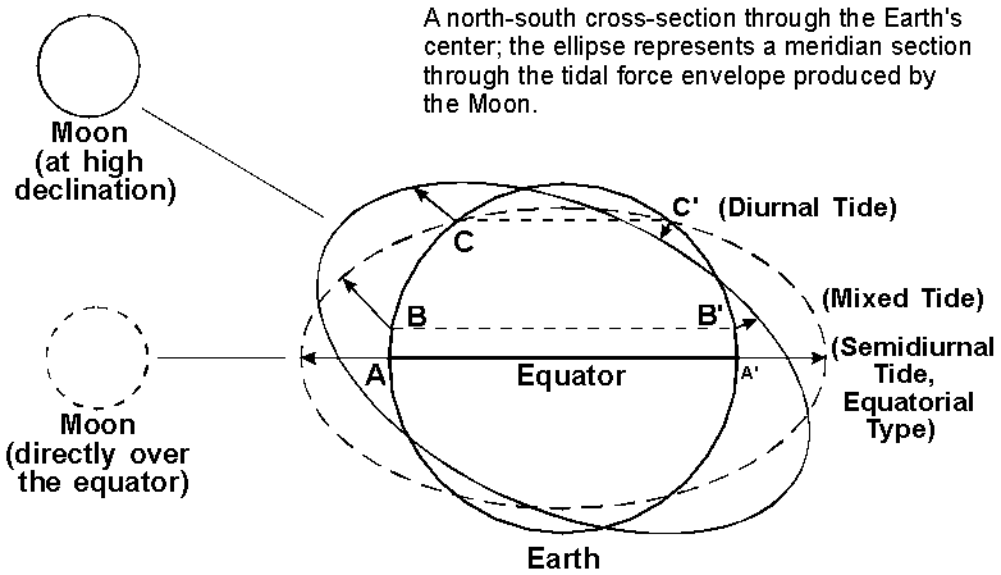


Figure 25. The Moon's declination effect (NOAA, 1998).

Tides are one of the most accurately predictable natural phenomena. Their fundamental cause, the astronomy of the Earth-Moon-Sun system, is known very accurately, and oceanographers have developed a detailed understanding of wave dynamics and the response of the ocean to the tide-generating forces. However, the observed tide at gauges differs from the theoretical equilibrium tide as the observed tide cannot be entirely described by the fundamental forces of the Moon and Sun. Although gravity between the celestial bodies provides the driving force for tides, the rotation of the Earth, interaction of tidal waves, the size and shape of the ocean basins (bathymetry), bottom friction, turbulence, viscosity of the water, and local coastal circumstances such as weather and the shape of the coastline, play an important role in altering the tidal range, interval between high and low water, and times of arrival of the tides (CO-OPS, 2006; NOAA, 1998). These factors can create complex tidal patterns that vary spatially and temporally. Every location has unique circumstances, so every location has a unique tidal pattern. Therefore the equilibrium theory is not sufficient for predicting tides; a dynamic model is used (Park, 1999).

The dynamic theory of tides was developed in the eighteenth century by Pierre-Simon Laplace and others. The model describes the tide in terms of the influencing factors, of which there are as many as 390, including the fundamental forces and factors of local control. Each factor is called a partial tide or harmonic constituent and for any coastal location has a particular amplitude and phase (Park, 1999), described by Figure 26. Harmonic analysis (tidal analysis) is the practical application of the dynamic theory of tides and is the process of breaking down a complex wave form as observed at a tide gauge, into its sinusoidal components or harmonic constituents. The four harmonic constituents defined in Table 13 are the most important and dominant (PCTMSL, 2011). Given a set of amplitudes and phases determined via tidal analysis for a location, tidal predictions of the height and time of arrival of the tide can be made for that location using the constituents. The computations for the tidal predictions are much simpler than for the tidal analysis that created the amplitudes and phases.

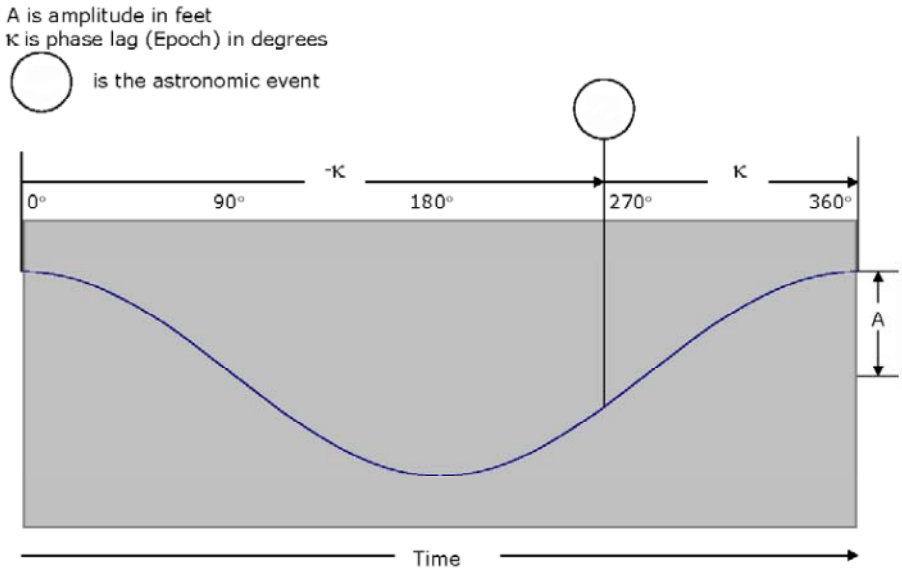


Figure 26. Phase lag and amplitude for a particular harmonic constituent (CO-OPS, 2006).

Table 13. Major tidal constants or harmonic constituents of the tide (PCTMSL, 2011).

Constant	Definition
Major Diurnal Constants	
O^1	Principal Lunar diurnal constituent
K^1	Principal Lunisolar diurnal constituent
Major Semi-Diurnal Constants	
M^2	Principal Lunar semidiurnal constituent arising from the Earth with respect to the Moon
S^2	Principal Lunisolar semidiurnal constituent arising from the Earth with respect to the Sun

This section has provided a brief general overview of tides. Much more can be learnt about tides, tidal analysis and prediction from sources such as Our Restless Tides[14], by the National Oceanographic and Atmospheric Administration (NOAA), and the Australian Tides Manual[15] by the PCTMSL which also provides links to many other sources of information.

[14] NOAA Our Restless Tides: http://www.co-ops.nos.noaa.gov/restles1.html
[15] PCTMSL Australian Tides Manual: http://www.icsm.gov.au/tides/SP9_Australian_Tides_Manual_V4.1.pdf

12.2 Tidal Datums & Models

For marine applications, the sea surface is used as the vertical datum from which to measure height and depth. However, as the sea surface moves through space and time, each vertical datum must be statistically defined. This is done for a particular phase of tide, for example MHWS, by extracting the observed MHWS values of each tidal day from the continuous water level records of a tide gauge, and averaging the values for the NTDE (for the datums LAT and HAT the values are the extreme of the phase rather than an average). The result is a value for the tidal datum MHWS that is relevant at the specific tide gauge location and for the NTDE. In order to make a datum stable, the observed data must cover a time period in which meteorological, oceanographic, and hydrologic variability as well as all significant tidal periods are averaged out (CO-OPS, 2006). The tidal datum epoch is the interval recommended for the calculation of datums. It is normally longer than 19 (18.6) years, in order to include a full lunar nodal cycle and capture all variability. The PCTMSL (2011) recommend a 20-year NTDE, 1992-2011 inclusive, be adopted in Australia.

Tidal datums are used by mariners for navigation to determine e.g. the minimum depth of water that could occur in an area at any point, or the minimum clearance under a bridge at high tide. Tidal datums are also the basis for establishing cadastral and maritime boundaries. Table 14 gives the observation-based definitions and purposes of Australian tidal datums as defined by the AHS tidal glossary. Variations may apply in state legislation but the below definitions are used in this project.

Table 14. Observation-based definitions of tidal datums (PCTMSL, 2011).

	Purpose	Definition
HAT	- Landward limit of the tidal interface. Chart datum for high tide (clearances). - Limit of landward extent of tidal water under normal atmospheric circumstances.	- Highest Astronomical Tide: The highest level of water which can be predicted to occur under any combination of astronomical conditions.
MHWS (and MHHW)	- Tidal datum for cadastral (boundary) purposes for some jurisdictions (eg New Zealand, Queensland).	- Mean High Water Springs (MHWS): The average of all high water observations at the time of spring tide over a period time (preferably 19 years). Applicable in semi-diurnal waters only. - Mean Higher High Water (MHHW): The mean of the higher of the two daily high waters over a period of time (preferably 19 years). Applicable in mixed and diurnal waters.
MHW	- Common law datum for cadastral (land boundary) purposes. Used in Australia unless amended by legislation (as in Queensland for example). - Frequently used as the coastal limit on topographic mapping.	- Mean High Water (MHW): The average of all high waters observed over a sufficiently long period.
MSL	- Average limit of the tides.	- Mean Sea Level (MSL): The arithmetic mean of hourly heights of the sea at the tidal station observed over a period of time (preferably 19 years).
MLWS (and MLLW)		- Mean Low Water Springs (MLWS): The average of all low water observations at the time of spring tide over a period of time (preferably 19 years). Applicable in semi-diurnal waters only. - Mean Lower Low Water (MLLW): The mean of the lower of the two daily low waters over a period of time (preferably 19 years). Applicable in mixed and diurnal waters.
MLW	- Has been used as the limit of Australian States as the definition of 'low water'.	- Mean Low Water: A tidal level. The average of all low waters observed over a sufficiently long period.
LAT	- Chart low water datum. - Baseline for the purposes of defining Australia's maritime boundaries in compliance with the UN Convention on the Law of the Sea.	- Lowest Astronomical Tide (LAT): The lowest tide level which can be predicted to occur under average meteorological conditions and under any combination of astronomical conditions.

Tidal datums can also be described using harmonics, as the observed tide is the sum of a number of harmonic constituents. The set of tidal harmonics Equations (4 - 4.7) below, are from the ANTT and can be considered convenient simplifications as they only use the four constituents described in Table 13. To derive tidal datum heights at locations other than tide gauges, modelling is required.

In the following harmonic descriptions of tidal datums from the ANTT, Z_0 represents MSL, and the other symbols are the major harmonic constants Table 13.

For semi-diurnal ports:

Mean High Water Springs: MHWS = $\mathbf{Z_0 + (M_2 + S_2)}$ Equation 4.

Mean High Water Neaps: MHWN = $\boldsymbol{Z_0 + (M_2 - S_2)}$ ...4.1

Mean Low Water Springs: MLWS = $\boldsymbol{Z_0 - (M_2 + S_2)}$ ...4.2

Mean Low Water Neaps: MLWN = $\boldsymbol{Z_0 - (M_2 - S_2)}$ ...4.3

For diurnal ports:

Mean Higher High Water: MHHW = $\boldsymbol{Z_0 + (M_2 + K_1 + O_1)}$ ...4.4

Mean Lower High Water: MLHW = $\boldsymbol{Z_0 + (M_2 - (K_1 + O_1))}$ ...4.5

Mean Higher Low Water: MHLW = $\boldsymbol{Z_0 - (M_2 - (K_1 + O_1))}$ ...4.6

Mean Lower Low Water: MLLW = $\boldsymbol{Z_0 - (M_2 + K_1 + O_1)}$ ...4.7

There are two main options for modelling tidal datums. The first, statistical modelling, involves mathematical interpolation/extrapolation of tidal datum heights derived from measurements at tide gauges (e.g. tidal zoning or datum transfer). This method is generally acceptable in the vicinity of primary tide gauges. However, in areas without tide gauge observations and with factors of local control such as rivers or bays, statistical modelling is generally unreliable. In such cases, complex hydrodynamic modelling is required. A hydrodynamic model is a physical model able to represent the motion of water. Harmonic analysis and fluid dynamics form the mathematical basis for the development of hydrodynamic models which take input such as bathymetry to derive the height of the water level at any point within the model area (NOAA, 2012). The accuracy of a model is limited by the quality of data available as input. Detailed, high precision hydrodynamic models are costly to build and validate. Although they are becoming more commonly available, there are very few models in existence (Todd et al, 2004).

12.3 Satellite Altimetry

Altimetry is the measurement of height. Satellite radar altimetry measures the time taken for a radar pulse to travel from the satellite to the surface and back to the satellite. This time measurement is first corrected for errors associated with signal propagation, geophysical parameters, surface factors, and instrument issues (Rosmorduc et al, 2011). It is then converted to a *range* measurement by applying the speed of light. The *altitude* of the satellite above a reference ellipsoid is known to within one or two centimetres via precise knowledge of its orbit. The *surface height* above the reference ellipsoid can then be determined to the same accuracy via Equation 5. The result is the instantaneous sea surface height which is made up of the geoid and the dynamic topography (refer to *Section 12.5*). Figure 27 demonstrates the concept and elaborates on the corrections applied. A lot of other information for a wide variety of applications can be extracted from the radar return signal in altimetry, such as wave height, wind speed, and surface roughness. This project is only concerned with sea surface height. More precisely, the project requires a gridded MSS, which is a secondary product of satellite altimetry.

$h = S - R$ Equation 5.

Where;

h = sea surface height above the ellipsoid

S = *satellite height or altitude above the ellipsoid*

R = r*ange* (corrected time of flight multiplied by speed of light)

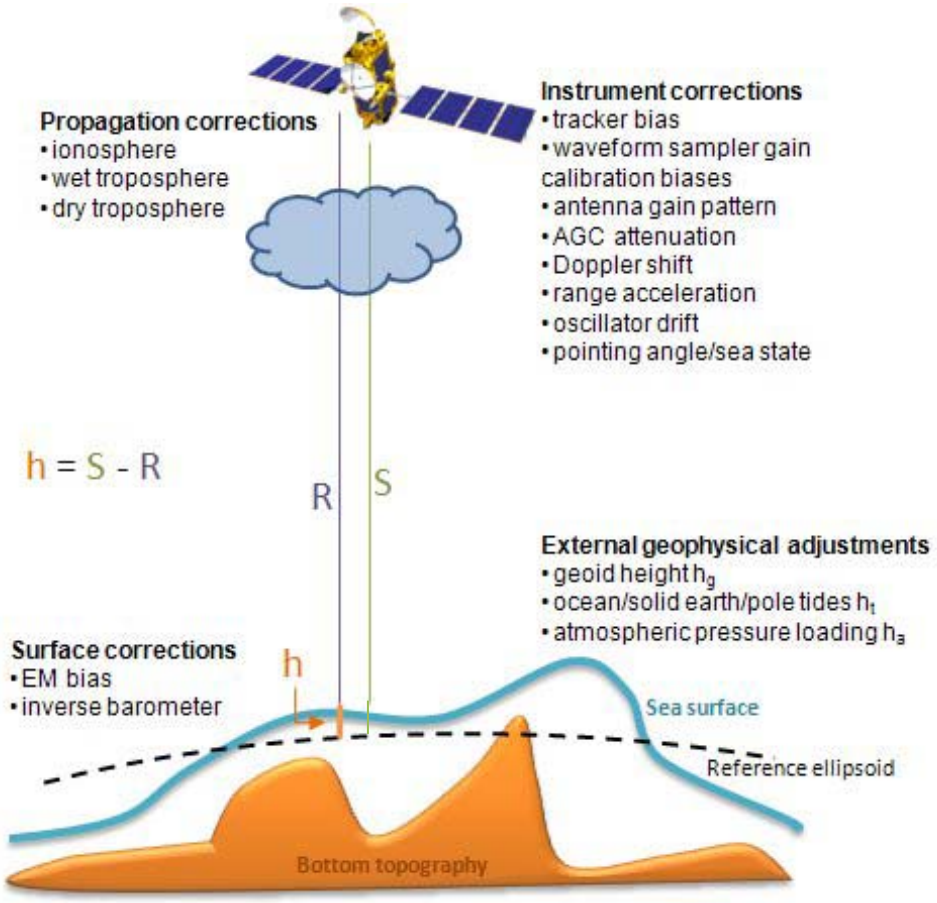


Figure 27. Satellite altimetry range measurements, corrections, and surface height calculation. (Rosmorduc et al, 2011).

Early altimeter missions included Seasat in 1978 and Geosat in 1985 by the US, followed by a number of missions including Topex/Poseidon, a combined US and French mission, to current missions such as Jason-2. These missions produced large volumes of along-track (orbit) data of surface height for the particular instant of measurement. There are different processing levels of data as well as auxiliary products. Each new level takes longer to deliver to the user from acquisition but is increasingly accurate. When the data is acquired, it is raw telemetry or level zero data that is down-linked to ground stations. Telemetry is processed to obtain level one data which is timed and located, expressed in the appropriate units, and checked for quality. Instrument, atmospheric, surface and geophysical corrections are applied to level one data, as well as precise orbit determination to achieve the highest accuracy. At this stage data are level two: Geophysical Data Records (GDR). These are validated using precise quality controls and monitoring of instrument drift, to produce level three along-track data (Rosmorduc et al, 2011).

A mission orbit (track) is a compromise between spatial and temporal resolution. Satellite ground tracks can be 40-300km apart and may only pass over the same spot tens of days apart. To fill in the gaps between ground track data and allow complete and accurate mapping of the ocean, data from multiple satellites can be combined (AVISO, 2012; Rosmorduc et al, 2011; Andersen and Knudsen, 2009). Cross-calibration between satellites produces level four multi-mission gridded data. Level three and four data can be used to generate science products and distributed to users. Auxiliary products include datasets such as MSS and MDT. Complex data processing is required to turn mono-mission along-track surface height datasets into a multi-mission, gridded MSS product over a certain epoch and referenced to a specific ellipsoid. A number of organisations have computed global MSS products which are publicly available. These have been used in this project and are further discussed in the *Section 12.4*.

An issue with current standard altimeter products is that they cannot provide precise sea surface heights in coastal areas. The waveform of the pulse reflection from an ocean surface has a characteristic shape which can be described analytically (AVISO, 2012). Figure 28 shows real waveforms from over the ocean and from over land from the Topex altimeter. The basic waveform is similar to the waveform over the ocean, while that over land has a different configuration which makes it difficult to process. The different waveform shapes over and near land are due to contamination of the signal by noisier radar returns from land surfaces and rapidly varying coastal sea states (Deng et al, 2010; Deng and Featherstone, 2006; Deng et al, 2002). Improvements to altimeter data in coastal areas and reduction of the contamination distance can be achieved by reprocessing (called re-tracking) the raw measurements. This has been tested for Australia with about ten to fifteen kilometre shoreward improvement (Deng and Featherstone, 2006). Deng *et al* (2002) investigated the coastal contamination of satellite altimetry around Australia and recommended that data be used with caution for distances less than 22km from the coastline, and rejected altogether within 4km.

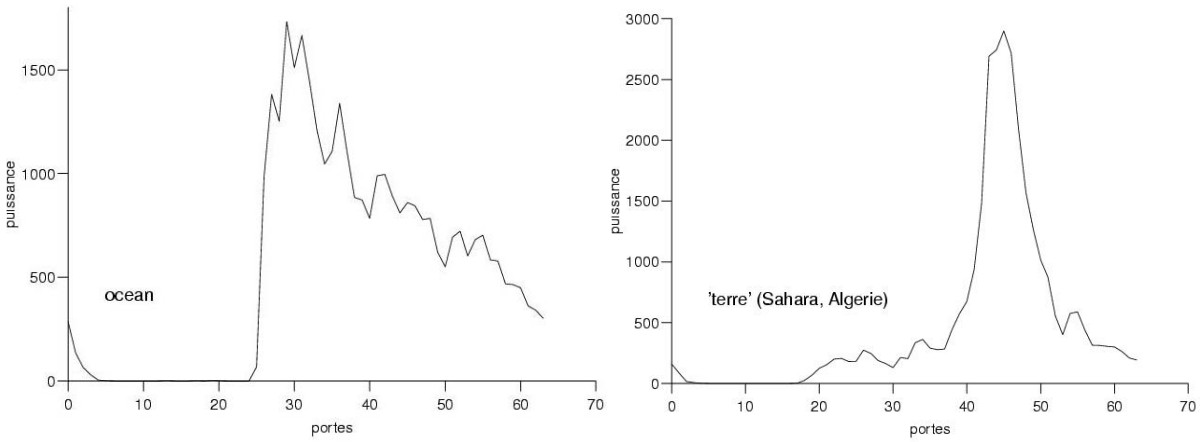


Figure 28. Real waveforms from the Topex altimeter left plot is over the ocean, right plot is over land (AVISO, 2012).

A major source of altimetry data is the Archiving, Validation and Interpretation of Satellite Oceanographic data[16] (AVISO) website. They distribute along-track mono-mission products including GDRs, and multi-mission along-track and gridded products from a number of satellites, as well as auxiliary products mostly in NetCDF format via FTP for free on application. There are also other online sources of altimetry data. An excellent source of information about satellite altimetry is the Radar Altimetry Tutorial[17] produced by the French Collecte Localisation Satellites (CLS) under contract to the ESA and the French government agency Centre National d'Etudes Spatiales.

12.4 Satellite Altimetry Derived Mean Sea Surface

To a tide gauge operator, MSL is the 'still water' level measured relative to fixed benchmarks on land, with wind waves and tides averaged out over a period of time. To a geodesist, MSL is the local height of the global MSS relative to an ellipsoid. The value of MSL varies between locations and over time as the MSS varies spatially and temporally. As mentioned in *Section 12.3*, a global MSS can be computed as a secondary product from satellite altimetry data, by averaging data over a period of time to remove annual, semi-annual, seasonal, and false sea surface height signals (Rosmorduc et al, 2011). Sophisticated interpolation techniques are used to produce a gridded surface with spacing consistent with the altimeter and other data used in the generation of the grid values. An example of a MSS is shown in Figure 29. The MSS over the oceans represents the sea level due to constant phenomena and comprises the geoid and the MDT (refer to *Section 12.5).*

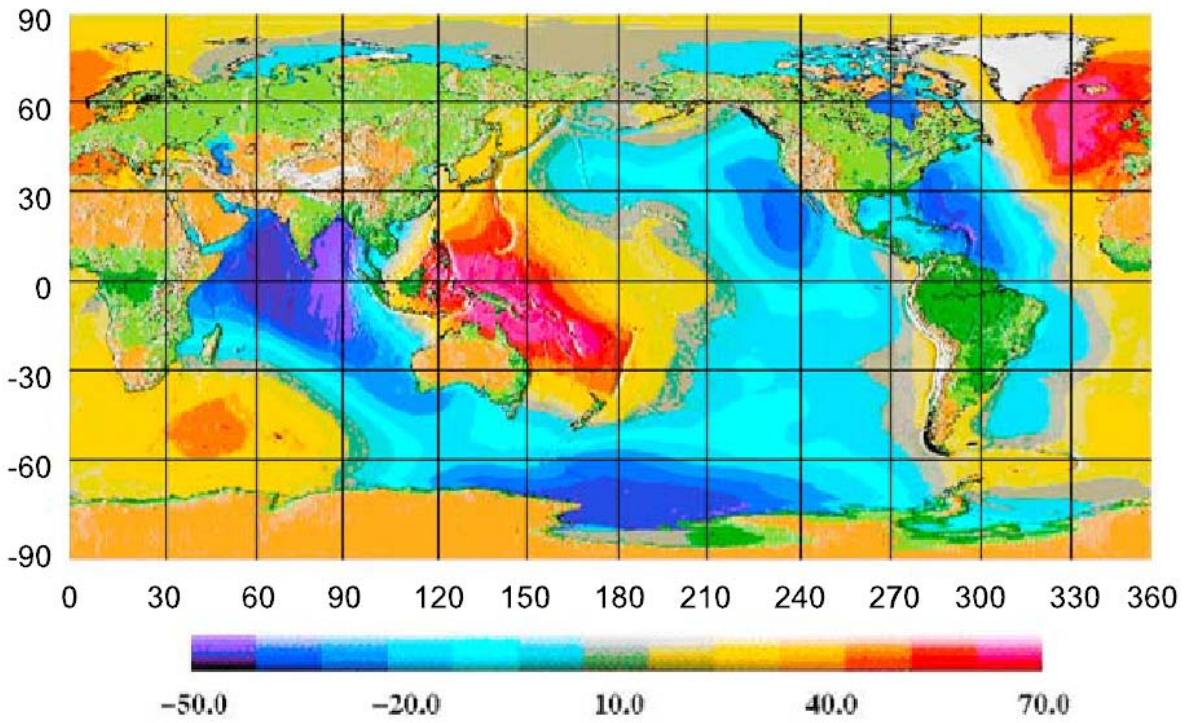


Figure 29. Example of a MSS, scale in metres (Andersen and Knudsen, 2009).

[16] AVISO: http://www.aviso.oceanobs.com/
[17] CLS Radar Altimetry Tutorial: http://www.altimetry.info/

Methodologies to compute global MSS vary, but most involve a "remove-restore" procedure designed to map the different spatial scales in a MSS. Long-wavelength signals in the MSS tend to be mapped first and then shorter wavelengths, sometimes using information from a geoid (Andersen et al., 2006). Before merging data from multiple satellites, differences caused by reference frame offsets, different orbits, different applied range and geophysical corrections, and different time averaging periods and epochs must be removed (Andersen and Knudsen, 2009). Other issues to be resolved include uniform data coverage at the equator where the largest gaps between satellite ground tracks exist, determining the MSS at high latitudes where the number of satellites decreases along with the quality and quantity of data, and filling the polar gap where no altimetry is available. The accuracy of a MSS is degraded from the original one to two centimetre accuracy of altimetry sea surface height measurements, to around three to ten centimetres (worse at the coast) (Andersen, 2012), due to the additional data processing required to produce a MSS.

Two MSS products were acquired and investigated for this project (see *Section 12.4*). These were the CLS11[18] MSS produced by the French CLS Space Oceanography Division and distributed by AVISO, and the DTU10[19] MSS produced and distributed by the Danish National Space Centre (DNSC). Both products represent the MSS height of the world's oceans above the Topex/Poseidon reference ellipsoid, the parameters of which are slightly different to those of GRS80/WGS84 (Table 15). The minimum difference between these ellipsoids is 70.0cm at the equator, up to a maximum difference of 71.36cm at the poles. A simple conversion from Topex/Poseidon to GRS80/WGS84 is achieved by subtracting a constant value, for example 70cm, from the MSS. For a more accurate conversion, the change in elevation between ellipsoids for a particular latitude can be approximated using an empirically-derived formula (Equation 6), or for exact conversion, software programs such as the ESA GOCE User Toolbox GUT are available.

Table 15. The parameters of three relevant ellipsoids.

	Topex/Poseidon	WGS-84	GRS80
Equatorial radius (a)	6,378,136.300000	6,378,137.000000	6,378,137.00000
Polar radius (b)	6,356,751.600563	6,356,752.314245	6,356,752.31414
Reciprocal flattening (1/f)	298.25700000	298.25722356	298.257222101
Eccentricity (e)	0.081819221456	0.081819190843	0.0818191910435

*delta_h = h2 - h1 = - ((a2 - a1) * cos(phi)^2 + (b2 - b1) * sin(phi)^2* Equation 6.

where; *phi* is latitude.
h1 and *h2* are elevations for ellipsoids 1 and 2, respectively.
a1 and a2 are equatorial radii of ellipsoids 1 and 2, respectively.
b1 and b2 are polar radii of ellipsoids 1 and 2, respectively.

[18] AVISO CLS11 MSS: http://www.aviso.oceanobs.com/en/data/products/auxiliary-products/mss/index.html
[19] DNSC DTU10 MSS: http://www.space.dtu.dk/English/Research/Scientific_data_and_models/Global_Mean_sea_surface.aspx

When compared, the CLS11 and DTU10 MSS solutions vary up to about plus or minus nine centimetres in the open oceans, significantly greater in coastal areas and at high latitudes (Schaeffer et al, 2011). This variation is largely due to different averaging of large ocean signals, for example El Nino, the use of slightly different values for global average atmospheric pressure in the inverse barometer correction, and the better global coverage of DTU10 due to inclusion of additional data (Andersen and Knudsen, 2009). Table 16 shows the different parameters used in the two MSS.

Table 16. The parameters of the two global MSS datasets.

Name	CLS11	DTU10
Ellipsoid	Topex/Poseidon	Topex/Poseidon
Epoch	1993-2009 (17years)	1993-2009 (17years)
Domain	Global (80°S to 84°N). Ocean wide where altimetric data are available. EIGEN_GRACE_5C elsewhere.	True global (90°S to 90°N). Inclusion of Envisat and ICESat data near the poles. Independent of geoid model.
Resolution	Regular grid with a 1/30° (2min) spacing (~4km)	Available as a 1/60° = 1min (1-2km) or a 1/30° = 2min grid
Land Values	EIGEN_GRACE_5C geoid	EGM2008
Tidal System	Mean-tide	Mean-tide
Error estimate	Yes	Yes
Altimetric datasets	T/P 10 years mean profile; T/P tandem 3 years profile; ERS-1/2 8 years mean profile; ERS-1 1 year geodetic data; GFO 7 years mean profile; Jason-1 7 years mean profile; Envisat 7 years mean profile	T/P+Jason-1 12 years mean profile; ERS-2 8 years mean profile; T/P interlaced 2 years mean profile; GFO 4 years mean profile; ERS-1 0.9 years geodetic data; GEOSAT 1.5 years geodetic data; Envisat 2 years mean profile; ICESat 0.6 years

In principle, the MSS represent the same physical variable as tide gauge sea levels (Mitchum, 1998) so MSS and tide gauge data should agree well. Although, the atmospheric pressure (inverse barometer (IB) correction) state of the MSS must be considered before comparison. The difference between IB and NIB versions of MSS can range up to several decimetres (Rosmorduc et al, 2011). Ideally an IB corrected MSS should be used in the direct computation of MDT (*see Section 12.5*). However, for comparison to tide gauge sea surface heights, whether the MSS should be IB or NIB corrected depends on the observation length of the gauge data. Atmospheric pressure variations will average out over long periods (i.e. decades) and hence long term records do not require IB correction. Pressure can fluctuate significantly for short term datasets and affect the estimate of MSL, so an IB correction should be applied. However, to calculate MSL over the appropriate epoch from short term records, harmonic analysis is performed. The use of harmonics mean that the component frequency waves are used to produce the long term estimate of MSL and hence pressure fluctuations are eliminated and no IB correction is actually required (Mitchell, 2012).

Vinogradov and Ponte (2011) compared tide gauge measurements to satellite altimetry data from around the globe for the epoch 1993-2008 and found some of the best agreement to be along the west coast of Australia. Locations with the worst correspondence included eastern Australia. This poor correlation was attributed to the presence of rapid changes in coastal sea level due to low-frequency events like large river runoff. The extent of differences can also depend on the geometry of the continental slope. To select the most appropriate MSS for this project, the MSS parameters were considered, and the two MSS were compared to available Australian tide gauge data (refer to *Section 2.1*).

12.5 Mean Dynamic Topography

As stated in *Section 12.4*, a MSS comprises the geoid and the MDT, therefore a MSS can be used to derive a MDT using a geoid. The geoid is an equipotential surface that would coincide with the sea surface if the oceans were at rest. However, wind, atmospheric pressure, water temperature, salinity, and currents mean that there can be up to one or two metres of difference between the geoid and the sea surface globally (Bingham and Haines, 2006; Parker, 2002). This difference is referred to as (Absolute) Dynamic Topography (DT). As demonstrated by Figure 30, it is the instantaneous sea surface height with respect to the geoid and consists of a variable and a static component (Rosmorduc et al, 2011). MDT is the static component of DT, and is the MSS height with respect to the geoid. The variable component of DT is termed Sea Level Anomaly (SLA) and is the instantaneous sea surface height above the MSS. The SLA allows monitoring of ocean variability due to seasonal variations and climatic phenomena such as El Nino. The MDT represents the oceans circulation due to the major currents which is of interest to oceanographers, but in this project, MDT is significant as a vertical separation between surfaces. It is also referred to as Sea Surface Topography (SST) or Topography of the Sea Surface (TSS).

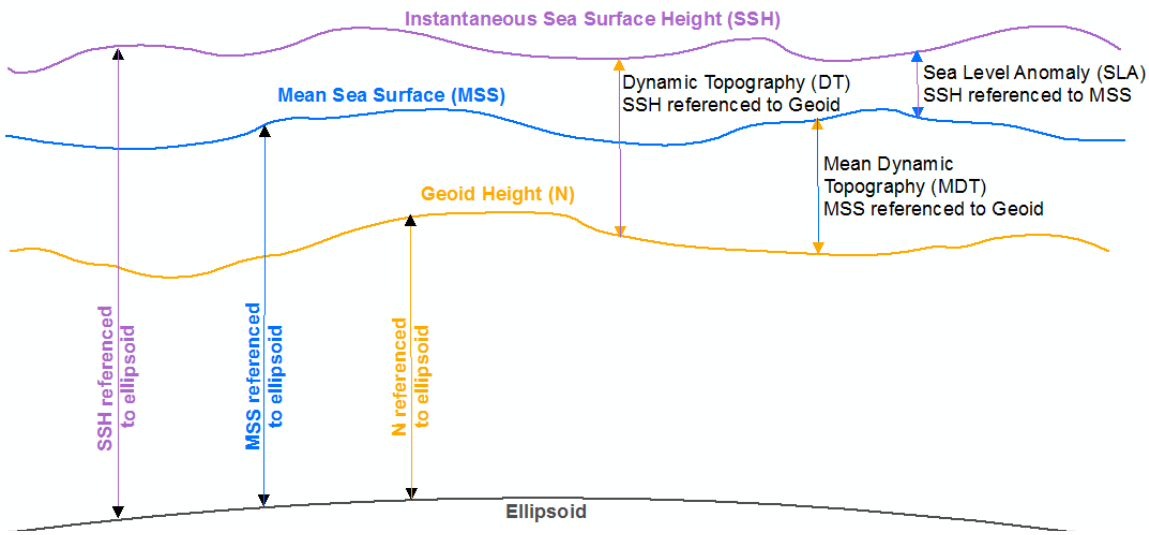


Figure 30. Oceanographic reference surfaces.

The direct method of determining MDT is to compute the difference between the geoid height and the MSS height obtained from satellite altimetry as follows (ESA, 2012; Rosmorduc et al, 2011; Bingham et al, 2010; Deng et al, 2009):

$$MDT = MSS - Geoid \qquad \text{Equation 7.}$$

This subtraction is either done in the geographical domain using grids or in the spectral domain using spherical harmonic constituents. MDT can also be computed using methods other than the above equation, including ocean climatology (Karimi and Ardalan, 2010). The direct method of computing MDT is not as straightforward as Equation 7 may imply. The spatial variations of the MSS and geoid are about two orders of magnitude greater than those of the MDT. The resulting MDT is therefore very sensitive to errors in the MSS or geoid, as even a very small error in either can lead to errors in the MDT that are the same size as the actual MDT values (Bingham et al, 2010).

There are four main issues which complicate the computation of MDT (ESA, 2012; Deng et al, 2009); reference ellipsoid, permanent tide system, spectral content, and time period. Altimetric MSS heights and geoid heights are given relative to a reference ellipsoid. To subtract one from the other and obtain an accurate MDT, both have to be relative to the same reference ellipsoid (referred to in *Section 12.4*). Geoid heights and MSS heights also differ depending on the permanent tide system used for the computation. Again, it is important, for the correct estimation of MDT that the geoid and MSS are in the same tide system (discussed in *Section 12.6*). Spectral content refers to spatial scale. If one dataset includes small-scale phenomena and not the other, the subtraction will neglect some information so it is necessary for the MDT to be filtered to remove noise (discussed in *Section 12.7*). One should also be aware that the time period, or epoch, of the MDT will be the same as that of the MSS used and needs to be comparable with other data in use e.g. tide gauge data.

An example of a MDT is shown in (Figure 31). The DNSC computed the DTU10 MDT using the DTU10 MSS and the EGM2008 geoid. The DTU10 MDT was computed using the direct method and is freely available. DNSC directly subtracted EGM2008 from the IB corrected DTU10 MSS, removed outliers from the result, and filtered the data using a 75km correlation length to smooth the MDT (discussed in *Section 12.7*).

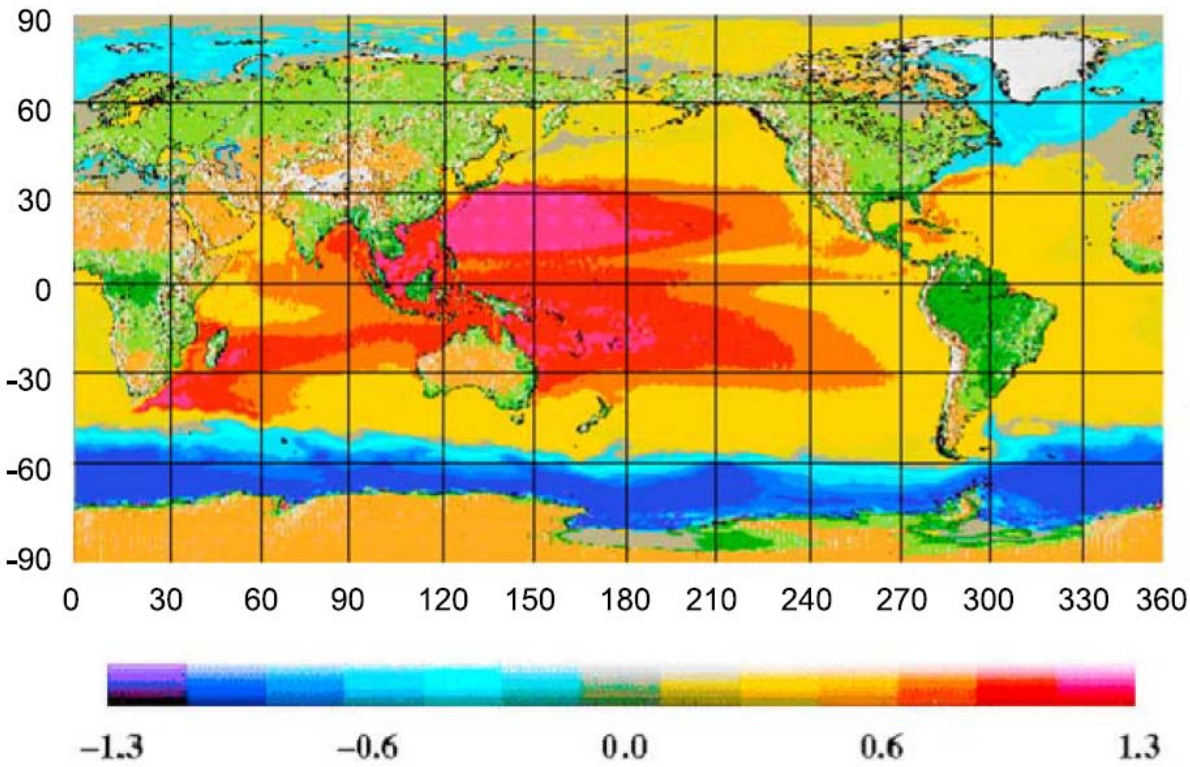


Figure 31. Example of a DNSC MDT, scale in metres (Andersen and Knudsen, 2009).

12.6 Permanent Tide System

The gravitational tide producing forces exerted on the Earth by the Moon and Sun do not average to zero. This non-zero average attraction results in ocean tides (*Section 12.1*) as well as what is called the permanent earth tide (or solid earth tide) (Milbert, 2012; Sideris et al, 2007). The permanent tide is the permanent tidal deformation of the Earth's crust which contributes to its equatorial bulge. Most of this bulge is due to the Earth's rotation, but part is created by the permanent tide. The permanent tidal deformation of the crust is unobservable but can be modelled. Table 17 shows the four parts of the tidal potential (forces). The periodic parts can be removed from geodetic measurements through averaging or modelling. Modelling of the permanent parts has led to the definition of three types of geoids, theoretically three analogous types of ellipsoids, and two concepts for the three dimensional shape of the Earth (crust) (Sideris et al, 2007; NASA, 1998);

Tide-free - All permanent effects (direct and indirect) are removed (also known as non-tidal).
Mean-tide - All permanent effects (direct and indirect) are retained.
Zero-tide - Direct permanent effects are removed and indirect permanent effects are retained. Therefore the topography or shape of the Earth's crust in a zero-tide system is the same as for a mean-tide system.

Table 17. Four Parts of the Tidal Potential (Smith, 1997).

	Periodic	Permanent Tide
Direct	Due to Moon/Sun masses	Due to Moon/Sun masses
Indirect	Due to deformation of the Earth's crust	Due to deformation of the Earth's crust

Permanent tide corrections were introduced to improve the precision of geodetic measurements. Gravity, normal gravity, GNSS heights, levelled heights, satellite altimetry derived sea surface heights relative to an ellipsoid, and geoid undulations are affected by the treatment of the permanent tide (Sideris et al, 2007; Smith, 1997). In combining such heights, they should first be reduced to a consistent permanent tide system to achieve the greatest precision (Ihde, 2007; Poutanen et al, 1996; Ekman, 1989). Equations to convert from one system to another for gravity values, levelled heights above the geoid, GNSS heights above an ellipsoid, and geoid heights above an ellipsoid can be found in Ekman (1989). The GUT software (*see Section 5.3*) can also be used to convert data to a different tide system. The equations for geoid heights are given below, where N_m is the mean-tide geoid undulation, N_n the tide-free, N_z the zero-tide, and k a variable called the Love number which depends on the mass distribution within the planet and also its rigidity and is usually taken as 0.3.

$$N_m - N_z = 9.9 - 29.6 \sin^2 \phi \ \ cm \qquad \text{Equation 8.}$$

$$N_z - N_n = k\,(9.9 - 29.6 \sin^2 \phi) \ \ cm \qquad ...8.1$$

$$N_m - N_n = (1 + k)\,(9.9 - 29.6 \sin^2 \phi)\ cm \qquad ...8.2$$

If the permanent tide is ignored, as can be observed in the examples in Figure 32 and Figure 33, differences between heights in the three systems can be up to about two decimetres depending on latitude and the variable values chosen for the model. Figure 32 and Figure 33 show the mean-tide and tide-free systems can differ vertically to about 25cm, while for mean-tide to zero-tide the vertical difference can be up to about 20cm, and for zero-tide to tide-free up to about 6cm (NASA, 1998). The permanent tide is an effect that is sometimes negligible, is unobservable, but is non-zero and imbedded in various reference systems so should be dealt with when combining heights to maximise precision.

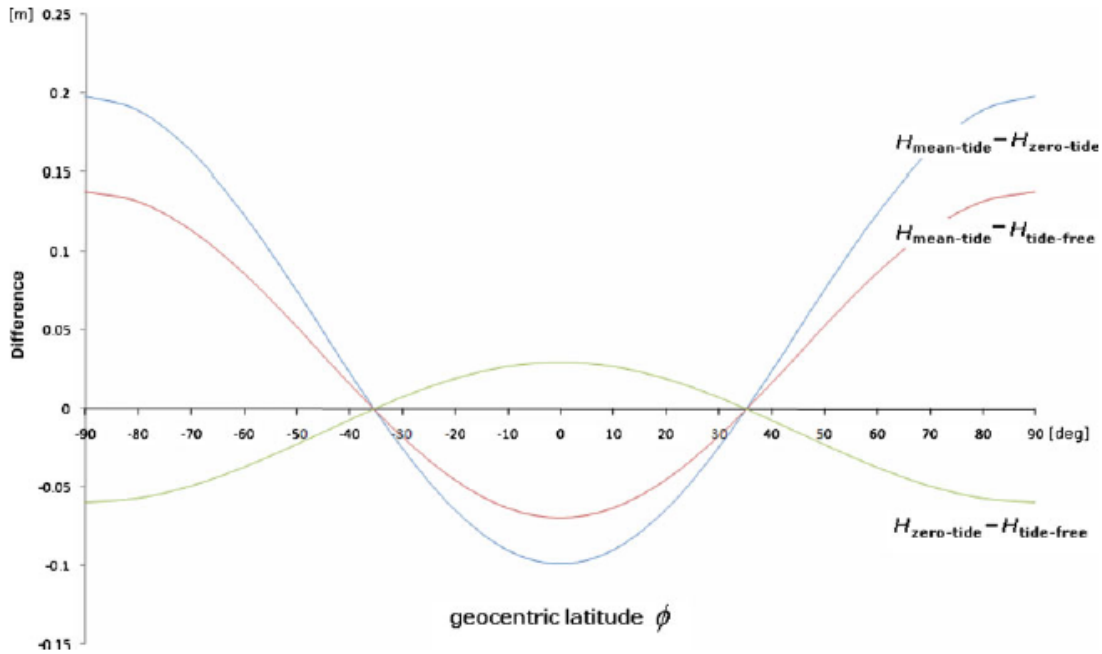


Figure 32. Global differences between heights defined in the three permanent tide systems (where k=0.3). (Tenzer et al, 2011).

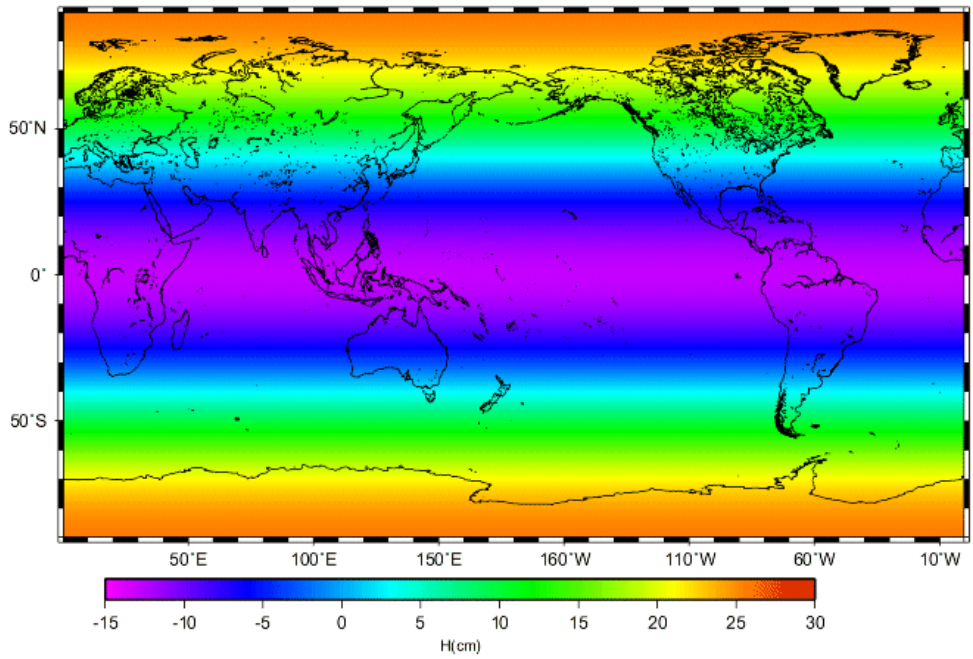


Figure 33. Height difference between the tide-free and mean-tide systems (ESA, 2012).

Different sources of height use different permanent tide systems. The following is summarised in Table 18. Gravity values tend to use zero-tide, although can be represented in any of the systems. The ITRF and hence its realisations use the tide-free system, which is therefore the system of GNSS ellipsoidal heights. Levelled heights are usually mean-tide although newer systems adopt zero-tide. Satellite altimetry derived sea surface heights relative to an ellipsoid must use the mean-tide system to give oceanographically relevant information. Any system can be applied for geoid undulations, but EGMs are usually provided as both tide-free and zero-tide. Regional geoids generally inherit their tidal system from the EGM used but should explicitly state the system - most often zero-tide (Makinen, 2008; Ihde, 2007; Sideris et al, 2007; Poutanen et al, 1996; NASA, 1991). As it is necessary to treat the permanent tide consistently when combining heights, it has been suggested that zero-tide be adopted for gravity, levelling and GNSS networks (Poutanen et al, 1996; Ekman, 1989).

It appears the issue of permanent tide is currently ignored or largely unidentified in Australia. It is not addressed in transformations between ellipsoidal and AHD heights via AUSGeoid09. The tide system of AUSGeoid09 is unclear, as although it is based on a zero-tide version of EGM2008, the system of the terrestrial gravity data is unknown. If gravity values are taken as zero-tide then it can be assumed AUSGeoid09 is zero-tide. The system of AHD is also unclear but can be assumed to be mean-tide, as according to Makinen (2008), Sideris *et al* (2007), and Ekman (1989) most countries with older height systems didn't correct for permanent tide in their determination and by default ended up with the mean-tide system. Zero-tide height systems are more recent than AHD e.g. 2005 (Makinen, 2008). This means it is common and accepted practice in Australia to combine all three systems by using a 'zero-tide' geoid to convert from tide-free ellipsoid heights to 'mean-tide' AHD heights.

Table 18. Summary of the permanent tide system of height data sources globally and in Australia.

	Height Data Source	Permanent Tide System
Globally	Gravity values	Zero-tide (can be tide-free or mean-tide)
	ITRF and hence GNSS ellipsoid heights	Tide-free
	Levelled heights	Usually mean-tide but newer systems zero-tide
	Satellite altimetry derived sea surface heights relative to an ellipsoid	Mean-tide
	Geoid undulations (EGMs)	Predominantly tide-free and zero-tide (can be mean-tide)
	Regional geoids	Most often zero-tide (can be any)
Australia	AUSGeoid09 - EGM2008 - Terrestrial gravity data	Unclear, assumed to be zero-tide - Zero-tide version - Unkown, assumed to be zero-tide
	AHD	Unclear, assumed to be mean-tide

Neither the UK's VORF or the US' VDatum (discussed in *Appendix B*) project documentation mention the permanent tide system issue. However after contacting representatives, it was discovered that for both projects, modelling was computed using a 'tide-free permanent tide-system where appropriate'. Despite the current lack of consideration for the permanent tide in Australia, the vertical datum transformation tool does address the permanent tide issue by also adopting the tide-free system. Assuming ellipsoidal data fed into the tool is tide-free as derived from GNSS, a tide-free MSS is applied. Alternatively, the tide-free EGM2008 could be applied followed by a MDT. Salvatore Dinardo from ESA confirmed that MDT is tide system independent as long as it is calculated correctly. If the MSS and geoid used to compute MDT have a consistent reference ellipsoid and permanent tide system, the effects of the permanent tide cancel so that the calculated MDT is independent of tide system. It is also understood that as the permanent tide does not affect ocean tide observations at tide gauges (Liebsch, 2012) tidal modelling is independent of tide system.

Although a consistent tide-free system has been adopted for this project, an issue arises in that sea surface heights relative to an ellipsoid are best expressed in the mean-tide system to give oceanographically relevant information. It is possible that after applying tide-free vertical transformations, the data could be converted into the permanent-tide system preferred by the user, however this has not been implemented for the Demonstration Tool. The tool is aimed at integrating topographic and bathymetric height datasets, and to do so precisely, they need to be in the same permanent tide system despite traditionally being used for different applications and ideally using different permanent tide systems.

12.7 Spectral Content

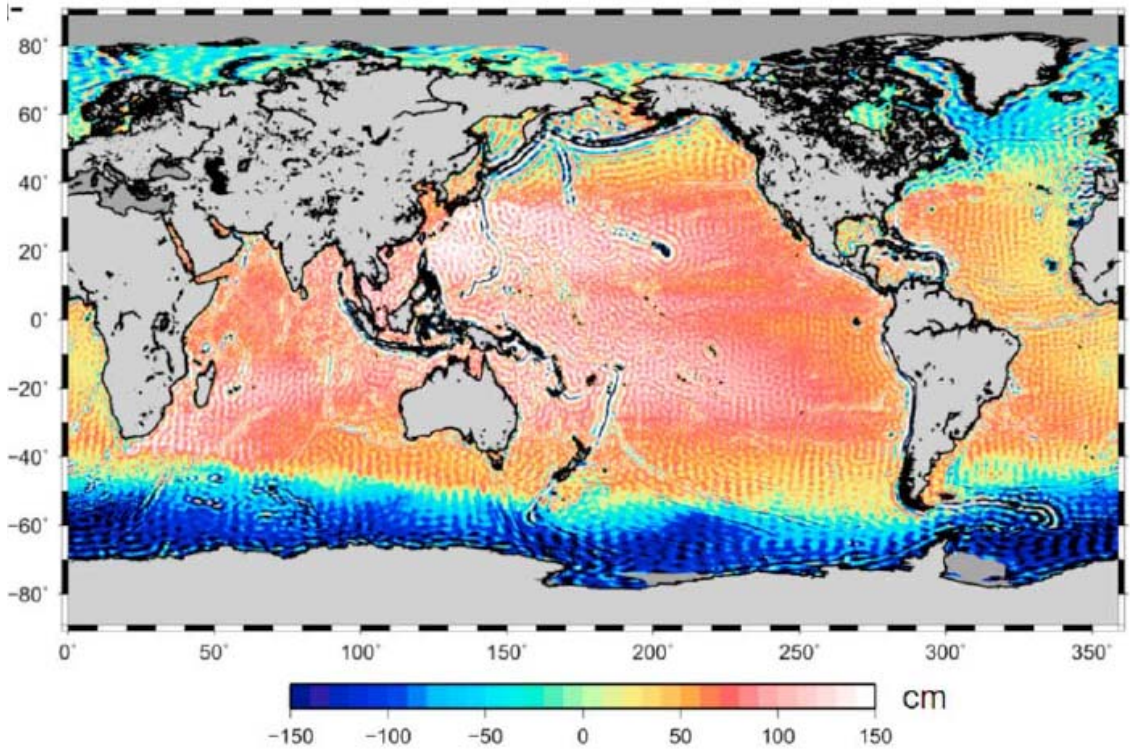
Spectral content refers to the information per wavelength (resolution) of data in the spectral domain (Featherstone, 1997). The term 'spectral' pertains to a signal that can be measured along a continuous variable. This includes concepts such as visible light (colour), the regular rotation of the earth, and as mentioned in *Section 12.1*, the motion of tidal waves and hence oceanographic signals such as MDT. In the geographical domain, this equates to the accuracy at a spatial scale or resolution (ESA, 2012). As mentioned in *Section 12.5*, MDT can be calculated in the geographic or spectral domains. Given a MDT produced by the spectral method retains more oceanographic information and is more realistic at coastlines (Bingham et al, 2010), technical literature tends to discuss the resolution of MDT in the spectral domain.

For a direct computation of MDT, the geoid is subtracted from a MSS. However, altimetric MSS and geoid models don't have the same spectral content. MSS are accurate to the centimetre level at scales of a few kilometres whereas the same accuracy on the geoid produced only from satellite data is achieved at scales down to around 100-200km (ESA, 2012) i.e. the geoid is smoother and doesn't contain high frequency/short-scale features. This is also referred to as geoid omission error due to the omission of small features from the geoid.

If one dataset includes short-scale phenomena and not the other, a direct subtraction will result in noise as demonstrated by Figure 34(a). Some form of filtering is required to remove this noise, the effect of which is demonstrated in Figure 34(b). Simple filters such as Gaussian or Hamming will suffice, however to remove as much noise as possible while retaining the true MDT signal, more complex filters may be used (Bingham et al, 2010; Rio et al, 2011). For example, Vianna *et al* (2007)

developed an adaptive filter, based on principal components analysis techniques. No matter which filter is used, the spectral content of satellite-only geoid models still limits the spatial resolution of the MDT computed through the direct method to scales longer than 100-200km (Hirt, 2011; Rio et al, 2011). However, different methods have recently been developed to estimate the MDT to scales shorter than 100-200km.

(a)



(b)

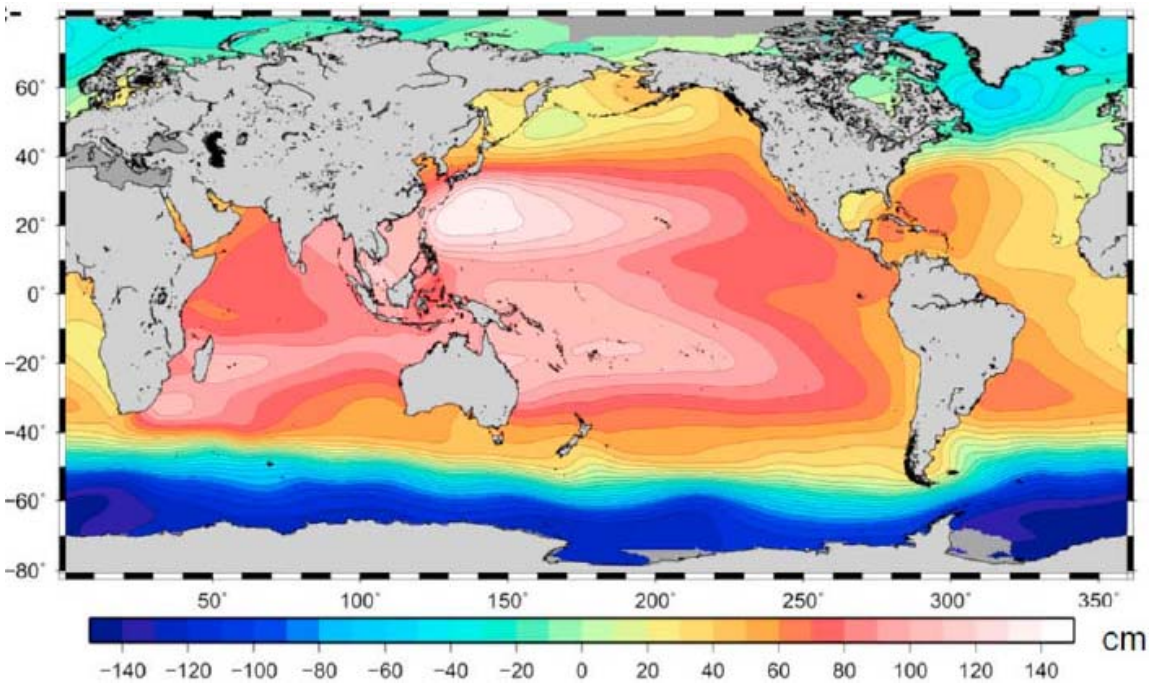


Figure 34. (a) MSS CLS01 minus EIGEN-GRGS.RL02 static geoid Model, (b) associated MSS CLS01 minus EIGEN-GRGS.RL02 filtered to remove scales shorter than 1000km (Rio et al, 2011).

A common approach is to improve the geoid resolution regionally using in situ gravimetric data, or globally using the shortest scale information from a MSS (Rio et al, 2011). This method results in what is known as a combined geoid model which has a higher resolution than satellite-only models. In terms of spherical harmonics, the combined model is developed to a higher degree and order. A second approach to estimate the MDT to scales shorter than 100-200km, is to initially compute a first guess long-scale MDT using the direct method and then improve it using external oceanographic data such as drifting buoy velocities, or hydrological profiles, to resolve the short scales (Rio et al, 2011; Maximenko et al, 2009; Rio et al, 2005; Rio and Hernandez, 2004). Another option is to combine all in situ and satellite measurements into a model and average the outputs to get an estimate of MDT for a certain period. Although progress has recently been made, further improvements are still required to achieve high resolution and high accuracy MDTs that use altimetric data to full potential.

A possible approach for this project was to use the DTU10MSS and the EGM2008 geoid to produce a MDT. The DTU10 MSS is valid up to degree and order 2190, and spatial scales down to about 15 kilometres (Andersen, 2012; Bingham et al, 2010; Knudsen et al, 2011). EGM2008 is a combined geoid; both in situ gravimetric data and short-scale MSS information have been used to compute the spherical harmonic coefficients of the gravity field up to degree and order 2159, and it is valid to spatial scales down to about nine kilometres (Hirt, 2011; Rio et al, 2011). As this geoid model is centimetre accurate down to about nine kilometres, it can be used in the direct method to compute a MDT with a spatial resolution better than the 100-200km previously achieved with satellite-only geoid models. Andersen and Knudsen (2009) used EGM2008, together with the DTU10 MSS to compute the global DTU10 MDT which they filtered to spatial scales upwards of 75km. It would appear from the relative spatial scales of the MSS and geoid, that a direct computation may be possible without any filtering. However, according to Andersen (2012), there is a problem.

The DNSC07 MSS (which is similar to DTU10 MSS) was used in the development of the EGM2008 geoid, along with a MDT up to degree and order 70. However for scales shorter than degree and order 70, nothing is used to represent the MDT in EGM2008. This means that the MSS and EGM2008 surfaces are not independent. From a certain degree and order, they become unrealistically close and some of the MDT is absorbed into them. Essentially, a filter is still necessary. Andersen (2012) suggested that perhaps the 75km Gaussian filter he used in creating DTU10 MDT was too severe and that investigation is required into the most suitable filter to apply. According to Ziebart (2012) of University College London (UCL) UK, the offshore MDT (SST) created for the VORF project was a direct subtraction of the Ordnance Survey Gravity Model 2005 (OSGM05) geoid from the DNSC06 MSS without any filtering performed. The reason for this is unclear. It is acknowledged that more research is needed into the best filter to apply (Andersen, 2012).

Appendix B – Review of International Projects

12.8 VDatum

VDatum[20] is the vertical datum transformation software tool of the US. It is developed jointly by NOAAs Office of Coast Survey/Coast Survey Development Laboratory (OCS/CSDL)[21], the National Geodetic Survey/Remote Sensing Division (NGS/RSD)[22], and CO-OPS[23]. The project was initiated as a pilot study in 2000 to support a seamless bathymetric-topographic digital DEM for Florida's Tampa Bay region. Following the pilot, NOAA continued developing VDatum around the US coast and the project is on-going. The current national coverage is shown in Figure 35. It remains in development for Alaska, Hawaii and some off-shore US territories. It is expected that by 2013 the software will provide seamless coverage for all of the US coastal areas from 1 or 2km inland of the MHW shoreline out to 25 nautical miles from land (46.3km). The resolution of the grid files used in transformations varies but an example uses a point spacing of 0.05 degrees in latitude and 0.025 degrees in longitude. The accuracy of VDatum is evaluated in terms of the standard deviations in both the vertical datums (i.e. source data) and the transformations between them for each VDatum region (NOAA, 2011). More accuracy information can be obtained from the webpage 'Estimation of Vertical Uncertainties in VDatum'[24].

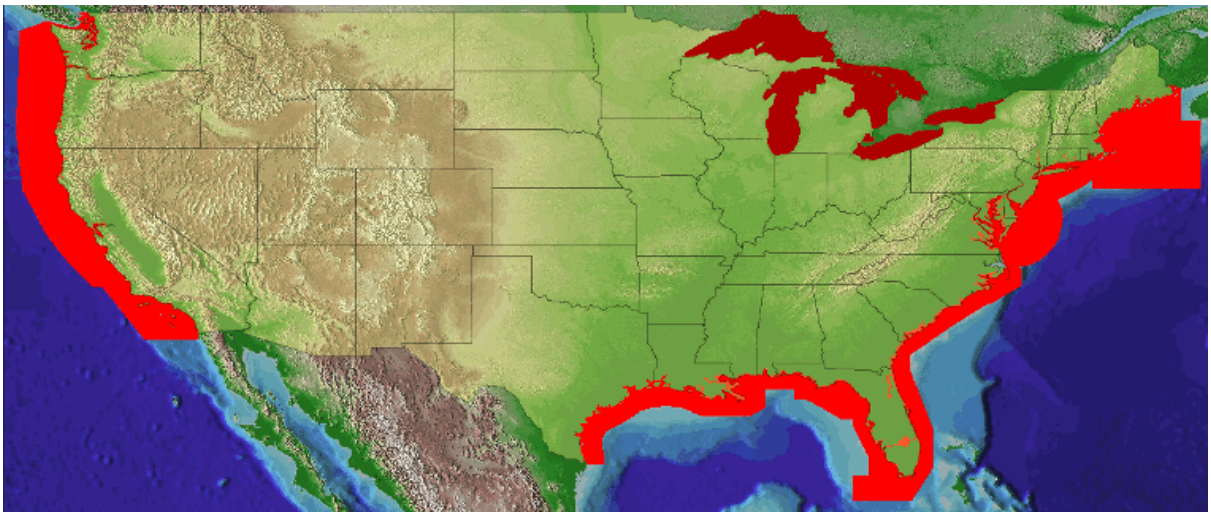


Figure 35. Currently available VDatum project areas highlighted in red (NOAA, 2011).

VDatum currently transforms between 36 different vertical reference systems within the classes of ellipsoidal, orthometric, and tidal (Figure 36). Each class has a principal member (highlighted by the blue ellipses) which must be traversed through to get from a datum in one class to a datum in another class. For example, referring to Figure 36, the transformation from WGS84 (G1150) to MLLW would be:

WGS84 (G1150) ----> NAD83 (NSRS2007/CORS96)) ----> NAVD88 ----> LMSL ----> MLLW

[20] NOAA, Vertical Datum Transformation: http://vdatum.noaa.gov/welcome.html
[21] NOAA, Office of Coast Survey: http://www.nauticalcharts.noaa.gov/
[22] NOAA, National Geodetic Survey: http://www.ngs.noaa.gov/
[23] NOAA CO-OPS Database: http://tidesandcurrents.noaa.gov/
[24] NOAA, VDatum uncertainties: http://vdatum.noaa.gov/docs/est_uncertainties.html

The transformations between ellipsoidal reference systems are provided by established 14 parameter Helmert transformations. Conversions between the North American Datum 1983 (NAD83) ellipsoidal datum (analogous to GDA94) and the NAVD88 orthometric datum (analogous to AHD) are calculated based on the existing GEOID[25] model of 2009. Conversions between the NAVD88 datum and NGVD29 (their old orthometric datum) are done by interpolating standard National Geodetic Survey VERTCON[26] vertical datum grids. Orthometric to tidal transformations between NAVD88 and Local Mean Sea Level (LMSL) are performed by interpolation of a TSS grid (which this project terms MDT) specially developed for VDatum. Finally, transformations between the tidal datums are generated from detailed hydrodynamic models where available, and otherwise using a spatial interpolation technique known as TCARI developed for VDatum (NOAA, 2011). Where appropriate, modelling was done using a tide-free permanent tide-system (Myers, 2012).

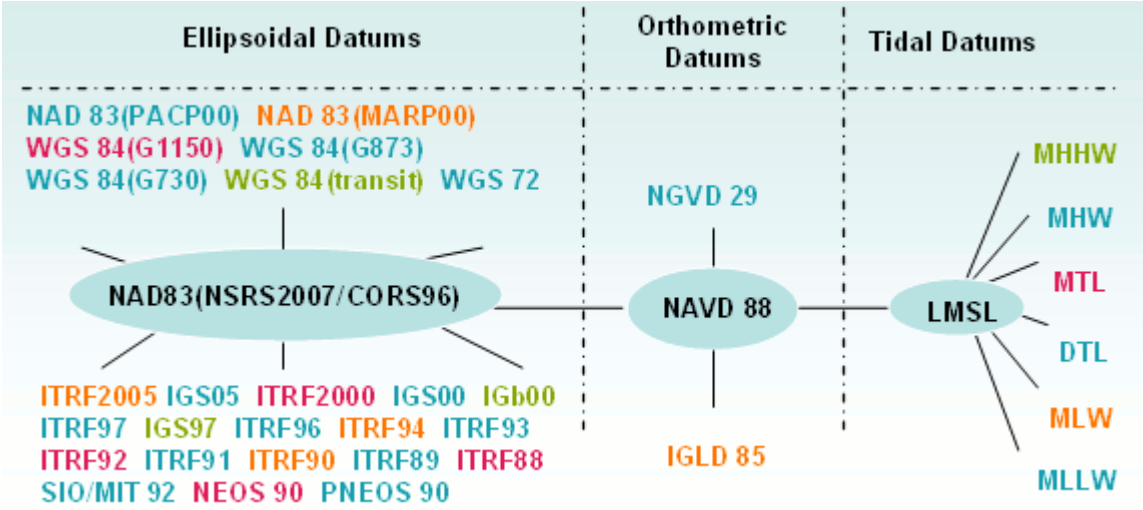


Figure 36. Reference systems supported by VDatum transformations (NOAA, 2011).

The hydrodynamic model used for Tampa Bay was a version of the Princeton Ocean Model previously developed by NOAA's National Ocean Service (Parker, 2002). Models incorporate digital shoreline data for MHW and MLLW obtained from the Coast Survey's Extracted Vector Shoreline project, bathymetric data, tidal datums and associated water level and benchmark data. The Tampa Bay model was also calibrated with inputs from seven rivers, winds and air temperature, and coastal salinity and temperature. Models are forced to match datums computed from observations and used to generate grids relating tidal datums to LMSL. The development of these hydrodynamic models is time and resource intensive and their accuracy depends on the quality of input data. A significant constraint is the density and accuracy of tidal benchmark information. In areas where a fully calibrated hydrodynamic model was not available, VDatum developed the TCARI technique for spatial interpolation between tide gauge data. It uses a set of weighting functions to quantify the contribution from each tide gauge, taking into account the effects of islands and complex shorelines (Parker, 2002). It should be noted that hydrodynamic tide models were primarily used to generate the initial tidal datum surfaces in VDatum. TCARI was used mainly for the interpolation of model-data differences which were used as corrections for the tidal datums. TCARI was only used in one situation (for the area of Puget Sound) to directly interpolate the tidal datums (Myers et al, 2008).

[25] NOAA, GEOID09: http://www.ngs.noaa.gov/GEOID/GEOID09/
[26] NGS, VERTCON: http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html

The TSS grid represents the vertical separation between the orthometric height system NAVD88 geopotential surface, and LMSL. The TSS grid was generated using tide gauge benchmark elevation information (NAVD88) and observed tidal datums, as well as hydrodynamically modelled tidal datums (NOAA, 2011). About 1,987 tide stations were used for the mainland US and the NTDE 1983-2001 (Myers, 2012). This information was readily accessible through the Tidal and Orthometric Elevations tool located in the CO-OPS database. Figure 37 visualises the TSS process. By differencing tide gauge data (labelled TBM*xxx*) and hydrodynamic model outputs (labelled VD*xxx*) for each tidal datum and averaging these results, initial estimates for TSS at each gauge were produced. These were then interpolated into a grid using the Surfer software's minimum curvature algorithm. A residual for each datum is then calculated as the difference between the observed tidal datum and the datum as computed by the initial TSS grid. If the residual is not less than 0.01 metres, adjustments are made to TSS values.

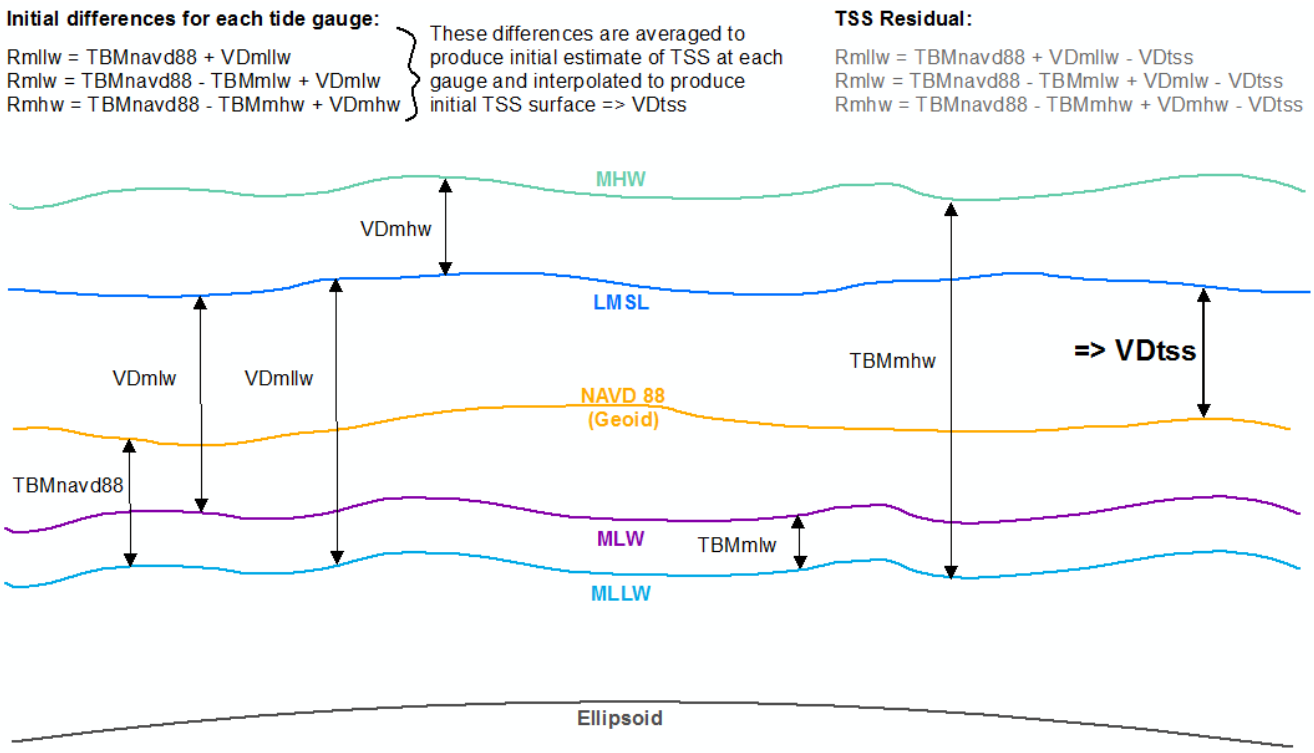


Figure 37. Visualisation of VDatum TSS process – diagram created by interpreting the description at NOAA (2011)

Future enhancements for VDatum include; supporting LiDAR LAS data format, supplying uncertainty estimates for the transformations, extending the datum transformation fields further inland, supporting State Plane Coordinates, and supplying standard metadata. More information can be obtained from the VDatum website.

12.9 VORF

The Vertical Offshore Reference Frames project (VORF) is the vertical datum transformation software tool of the UK. The project was sponsored by the UKHO[27] and led by UCL[28], with contributions from the Proudman Oceanographic Laboratory[29] (POL) and the DNSC[30]. Unlike VDatum which began in support of a seamless bathymetric-topographic DEM, navigational objectives drove and funded VORF, so it does not extend onshore. The project started in October 2005 and was completed successfully in early January 2008 (UCL, 2008). VORF covers the entire UK and Irish continental shelves (Figure 38). It is gridded at 0.008 degree intervals with patches of 0.003 degrees where there is complex coastal topography (Howlett, 2009), and has an accuracy of 10cm in coastal waters and 15cm in the open ocean (one standard deviation) (UCL, 2008).

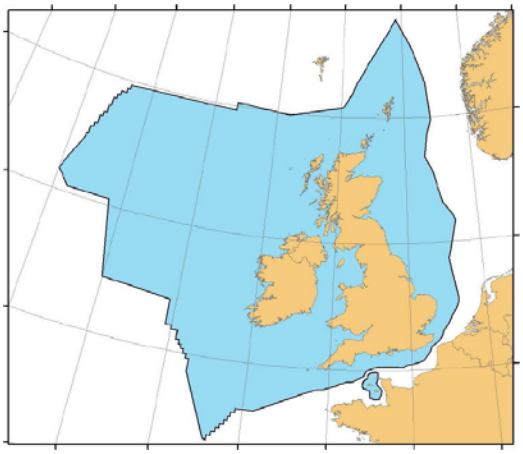


Figure 38. Coverage of VORF (Howlett, 2009).

VORF consists of a set of surfaces each of which defines the separation of one vertical datum from the WGS84/GRS80 ellipsoid which is realised as the ETRF89 in UK waters (Howlett, 2009). By combining surfaces, elevations can be converted from one vertical datum to another. There are two polygons for each surface and the area between these represents where that surface is applicable. Transformations are only allowed between surfaces that have overlapping areas of applicability. VORF transforms between 16 land datums, as well as the six tidal datums shown in Figure 39.

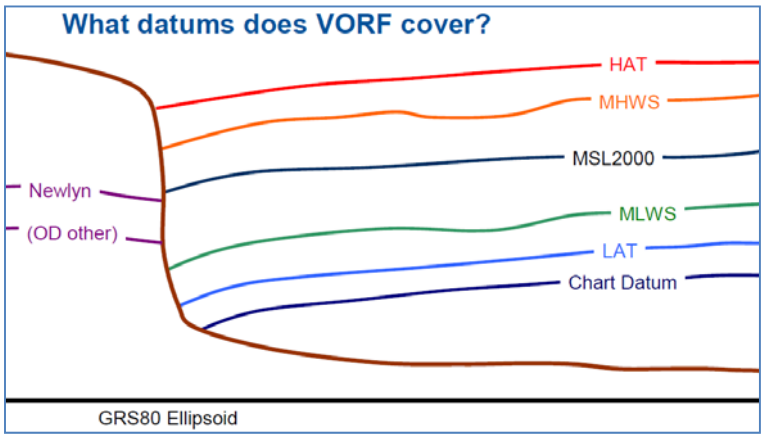


Figure 39. Vertical datums included in VORF (OD other – 15 other land datums) (Howlett, 2009).

[27] UKHO: http://www.ukho.gov.uk/
[28] UCL, VORF: http://www.cege.ucl.ac.uk/research/geomatics/vorf
[29] POL: http://www.pol.ac.uk/
[30] DNSC: http://www.space.dtu.dk/english.aspx

The process of developing VORF involved a number of steps:

1. Model MSL with respect to ETRF89 involving production of a SST
2. Use tidal modelling to determine MSL-LAT separation (& MSL-other tidal datums)
3. Use the MSL model and MSL-LAT separation to find LAT with respect to ETRF89
4. Use LAT to provide a continuous model of CD

The two most significant of these were (1) to determine MSL above the ellipsoid at the reference epoch (2000.0) and produce a SST (known as MDT in this project and TSS in VDatum), and (2) to determine LAT with respect to this (UCL, 2008). Modelling was done using a tide-free permanent tide-system where appropriate (Ziebart, 2011).

To model ellipsoidal MSL (methodology depicted in Figure 40), a DNSC one arc-minute grid resolution satellite altimetry derived MSS was used in the open oceans, and tide gauge data from 460 gauges near shore (Iliffe et al, 2007). The tide gauge data was of two types, long-term high accuracy Permanent Service for Mean Sea Level (PSMSL) data as well as short-term lower accuracy ATT data. The tide gauge data had to be brought into a common reference frame (ETRF89), and also a common epoch (2000.0). For gauges without GNSS connections, the OSGM02 national geoid model was used to convert heights above the mainland datums to ellipsoidal heights, or where levelling quality was poor, GNSS observations were commissioned. To achieve the common epoch, a spatial-temporal correlation model to correct first for sea level rise since the epoch of observation, and then for monthly variations in atmospheric, oceanographic and geological effects around the UK was developed, using long-term observations as control points. It was found that correlations between tidal stations were more strongly related to distance via the sea than straight line distance, so the model was refined using a generalized polygon of the coast as well as 'zones of de-correlation' (Iliffe et al, 2007).

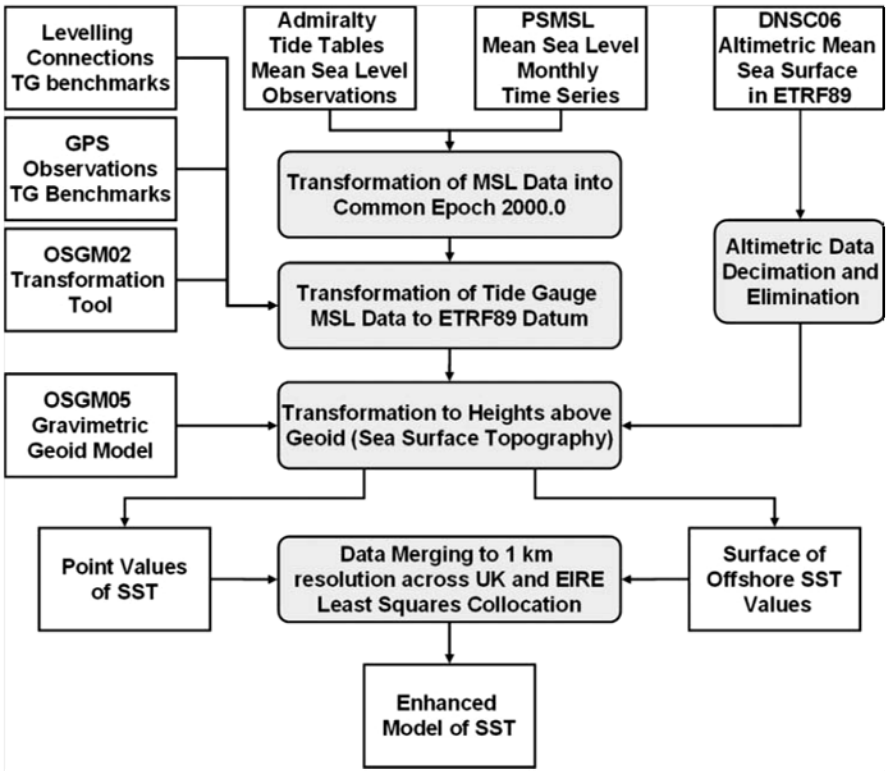


Figure 40. VORF methodology of steps 1 and 2 (Iliffe et al, 2007).

With all tide gauge data processed to MSL at epoch 2000.0 referenced to ETRF89, the OSGM05 geoid was then subtracted to produce on-shore point values of SST. OSGM05 was also subtracted from the MSS to create an offshore SST grid. No filtering of the offshore SST was performed to deal with spectral content. The reason for this is unclear. To cover the 20/30km gap between the offshore altimetry data and the on-shore tidal information a combination of least squares collocation and interpolation was developed with special algorithms created for different types of coastal topography based on a covariance function derived from the characteristics of the tide gauge and altimetry data (Iliffe et al, 2007). This resulted in an enhanced model of SST.

Determining LAT with respect to MSL allows the derivation of a modelled CD. The UK has over 700 definitions of CD which is an arbitrary local level used as the reference plane for both tidal predictions and marine chart depths (UCL, 2008). In the UK CD is considered to be identical or very close to LAT. To model LAT below MSL, an optimal combination of tide gauge tidal levels, hydrodynamic modelling, and satellite altimetry derived global ocean tide models was used. A thin plate spline method was employed for merging and interpolation of data which can deal with complex coastal morphology, retain 'true' coastal tide gauge values, and produce a smooth surface (Turner et al, 2010). Tide gauge data from 700 on-shore as well as 180 off-shore gauges was included, and four global tide models as well as a 3.5km resolution regional model were incorporated to produce a high-resolution model of LAT with respect to MSL (Turner et al, 2010). This tidal modelling also included the modelling of other tidal datums with respect to MSL. The model of MSL referenced to ETRF89 was then combined with the MSL-LAT separation to find LAT with respect to ETRF89 and thus to provide a continuous model of CD.

Appendix C - Australian Tide Gauge Data

Table 19. Available Australian tide gauge data supplied by the AHS (red and yellow shading denotes missing data).

Station Name	State/ Territory	Tidal Port Number	Latitude	Longitude	EH Datum below LAT	HAT	MHWS	MHHW	MHWN	MLHW	AHD	MLWN	MHLW	MLWS	MLLW	LAT	Source	Years for Sa/Ssa	Z00	Z0	O1	O1°	K1	K1°	M2	M2°	S2	S2°	Tide Ratio
Mawson	AAT	20080	67° 42′ 0.0000″	62° 51′ 59.9759"	27.27	1.66	0.97	1.34	0.91	1.28		0.75	0.37	0.91	0.31	0	NTC 1993 - 2009	See Source	0.83	0.81	0.25	8.41	0.23	22.60	0.03	47.82	0.11	189.26	3.36
Davis	AAT	20100	68° 27′ 0.0000″	77° 57′ 59.9760″	20.30	2.20	1.34	1.73	0.99	1.32		0.94	0.60	0.94	0.20	0	NTC 1993 - 2009	See Source	0.96	0.95	0.29	6.95	0.28	21.91	0.20	50.18	0.18	157.19	1.49
Casey	AAT	20120	66° 16′ 59.9879"	110° 31′ 59.9881"	- 17.35	2.24	1.43	1.79	1.10	1.21		0.85	0.74	0.85	0.16	0	NTC 1996 - 2008	See Source	0.98	0.96	0.26	345.42	0.26	4.15	0.29	13.95	0.17	79.04	1.15
Macquarie Island	AAT	65300	54° 30′ 0.0000″	158° 55′ 59.9879″		1.49	1.13	1.21	0.95	0.87		0.52	0.60	0.52	0.26	0	NTC 1995 - 2008	1912-2008 (17.7 yrs of obs)	0.74	0.72	0.08	337.73	0.09	8.70	0.31	317.82	0.09	358.33	0.43
Mornington Island	QLD	63540	16° 50'	139° 10'		3.94	2.18	3.17	2.12	2.89	2.00	1.90	1.13	1.90	0.85	0	MSQ 2007 - 2009	See Source	2.01	2.00	0.45	254.35	0.57	328.11	0.14	29.26	0.03	102.38	5.91
Karumba Bar	QLD	63580	17 29 07.49	140 50 18.82	49.70	4.97	2.34	3.83	2.28	3.46	2.18	1.97	0.79	1.97	0.42	0	MSQ 2009-2010	1985-2009	2.12	2.10	0.64	257.82	0.88	331.82	0.19	176.79	0.03	329.10	6.97
Weipa Storm Tide	QLD	63620	12 39 44.9988	141 50 59.9381	63.53	3.27	2.33	2.96	2.10	2.22	1.75	1.59	1.47	1.59	0.73	0	MSQ 1985 - 2009	1965-2009 (32.7yrs of obs)	1.85	1.84	0.30	158.40	0.44	216.46	0.37	147.22	0.11	209.53	1.54
Ince Point	QLD	58140	12 24 31.4730	143 22 20.0878	70.25	3.73	2.49	2.87	1.76	2.14	1.61	1.66	1.28	1.76	0.55	0	AMSA 1990 - 2009	1971-2009	1.71	1.69	0.26	149.44	0.53	208.98	0.37	41.87	0.41	341.45	1.02
Nardana Patches	QLD	58178	10° 30.2850'	142° 14.6290'	70.22	3.79	2.48	2.93	1.79	2.24		1.73	1.28	1.79	0.59	0	AMSA 2005-2009	See Source	1.76	1.75	0.28	146.86	0.55	207.43	0.34	59.13	0.38	341.13	1.15
Turtle Head	QLD	58180	-10.5217	142.2117	69.72	3.73	2.37	3.03	1.78	2.38	1.77	1.72	1.11	1.72	0.47	0	AMSA 1990 - 2009	1989-2009	1.75	1.73	0.34	146.35	0.62	206.43	0.32	100.43	0.29	330.66	1.55
Goods Island	QLD	58200	10 33 48.0412	142 08 47.8288	69.19	4.06	2.87	3.74	2.47	2.69	2.12	1.82	1.60	1.82	0.55	0	AMSA 1990 - 2009	1974-2009	2.15	2.13	0.40	137.23	0.67	200.50	0.52	132.61	0.20	302.19	1.47
Booby Island	QLD	58230	10° 36.1520'	141° 54.6080'	68.17	4.32	3.28	4.26	3.00	2.83		1.85	2.02	1.85	0.60	0	AMSA 1990 - 2009	1972-2009	2.43	2.41	0.42	131.64	0.69	194.65	0.71	131.63	0.14	262.85	1.31
Cooktown	QLD	58940	15 27 32.7106	145 15 03.2619		3.12	2.35	2.48	1.70	1.57	1.48	1.28	1.41	1.28	0.50	0	MSQ 1984-1985	See Source	1.49	1.43	0.15	153.20	0.31	191.10	0.53	277.40	0.33	248.00	0.53
Mossman	QLD	N/A	16° 26.15'	145° 24.19'												0													
Port Douglas	QLD	59040	16 28 49.3305	145 27 44.6059	62.08	3.35	2.50	2.62	1.83	1.71	1.58	1.37	1.50	1.37	0.58	0	MSQ 1992-2010	1987-2009	1.60	1.58	0.15	153.05	0.31	190.42	0.56	276.04	0.33	246.73	0.51
Cairns Storm Tide	QLD	59060	16 55 33.51	145 46 49.77	60.62	3.49	2.62	2.75	1.94	1.82	1.64	1.46	1.59	1.46	0.66	0	MSQ 1985-2010	1960-2009 (36.0 yrs of obs)	1.70	1.68	0.15	153.68	0.31	190.88	0.58	276.45	0.34	247.72	0.51
Mourilyan Storm Tide	QLD	59140	17 35 59.1142	146 07 15.4224		3.50	2.66	2.79	1.99	1.85	1.73	1.50	1.64	1.50	0.70	0	MSQ 1985-2010	See Source	1.74	1.72	0.16	153.55	0.32	190.02	0.58	277.35	0.33	248.59	0.52
Clump Point	QLD	N/A	17 51 00.51	146 06 17.88												0													
Cardwell	QLD	59185	18 16 04.0031	146 01 47.6985		4.13	3.12	3.18	2.25	2.19	1.86	1.63	1.69	1.63	0.70	0	QDOT 1994 - 1995	See Source		1.94	0.16	155.70	0.34	192.30	0.75	283.70	0.43	255.80	0.42
Lucinda Storm Tide	QLD	59200	18 31 39.8385	146 19 47.4513	57.53	3.95	2.99	3.08	2.19	2.09	1.84	1.61	1.70	1.61	0.71	0	MSQ 1985-2010	See Source	1.90	1.88	0.16	152.96	0.33	189.14	0.69	278.36	0.40	248.64	0.45
Townsville Storm Tide	QLD	59250	19 15 21.4763	146 49 18.7851		4.09	3.12	3.19	2.27	2.19	1.86	1.63	1.71	1.63	0.70	0	MSQ 1985-2010	1959-2009 (50.3 yrs fo obs)	1.95	1.93	0.16	152.15	0.34	188.09	0.74	278.13	0.43	247.63	0.43
Cape Ferguson	QLD	59260	19 16 37.9959	147 03 39.2418	56.95	3.84	2.89	2.99	2.10	1.99	1.70	1.48	1.59	1.48	0.59	0	NTC 1991 - 2009	See Source	1.79	1.68	0.16	151.24	0.33	187.07	0.70	277.44	0.40	246.19	0.45
Bowen Storm Tide	QLD	59320	20 01 21.9034	148 15 06.1660	55.59	3.70	2.84	3.04	2.21	2.01	1.78	1.32	1.52	1.32	0.49	0	QDOT 1986 - 2010	See Source	1.77	1.75	0.17	152.98	0.35	189.93	0.76	302.79	0.31	271.68	0.48
Laguna Quays	QLD	59404	20 36 11.5698	148 40 41.9620												0													

Shute Harbour Storm Tide	QLD	59410	20 17 36.4845	148 47 08.8855	55.43	4.31	3.31	3.48	2.58	2.40	1.91	1.27	1.45	1.27	0.36	0	MSQ 1987-2010	1982-2009 (22.5 yrs of obs)	1.92	1.90	0.18	152.06	0.36	189.81	1.02	315.05	0.36	297.58	0.39
Mackay Outer Harbour	QLD	59510	21 06 25.0654	149 13 30.0264	52.79	6.54	5.30	5.27	4.08	4.10	2.94	1.96	1.94	1.96	0.77	0	MSQ 1988 - 2010	1960-2009 (36.5 yrs of obs)	3.02	3.00	0.20	147.49	0.39	186.92	1.67	322.18	0.61	320.92	0.26
Half Tide Tug Harbour (HAY PT)	QLD	59511	21 16 25.1998	149 17 51.1052	51.96	7.08	5.81	5.74	4.49	4.56	3.34	2.26	2.19	2.26	1.01	0	MSQ 1985-2010	See Source	3.37	3.35	0.20	146.24	0.39	185.71	1.77	320.94	0.66	320.77	0.24
Dalrymple Bay	QLD	59511	21° 15.115'	149° 18.194'	51.96						3.34					0	QDOT 1996-1998	See Source											
Hay Point Offshore Port Beacon 2	QLD	59511	21 16 23.8429	149 17 49.2591	51.96						3.34					0	QDOT 1998	See Source											
Rosslyn Bay	QLD	59670	23 09 51.9572	150 47 28.2980	48.90	5.12	4.24	4.20	3.25	3.28	2.36	1.61	1.58	1.61	0.66	0	NTC 1993 - 2010	See Source	2.43	2.42	0.16	119.77	0.30	160.17	1.31	270.28	0.49	277.16	0.25
Port Alma	QLD	59690	23 35 01.1264	150 51 42.6637	47.74	5.90	4.93	6.31	3.83	3.36	2.85	1.98	2.45	1.98	-0.50	0	MSQ 1986-2010	See Source	2.91	2.89	1.62	122.45	0.31	163.63	1.48	274.21	0.55	283.79	0.95
South Trees Wharf Gladstone	QLD	59742	23° 51.230'	151° 18.820'												0													
Auckland Point, Gladstone	QLD	59750	23° 50'	151° 15'		4.81	3.96	3.95	3.11	3.13	2.27	1.57	1.55	1.57	0.74	0	MSQ 1985-2010	1978-2009 (30.3yrs of obs)	2.34	2.32	0.14	119.42	0.26	160.78	1.20	266.02	0.43	278.68	0.25
Bundaberg Port	QLD	59820	24 46 17.2347	152 22 57.5042	46.13						1.69					0													
Bundaberg (Burnett Heads)	QLD	59820	24 45 27.4195	152 24 04.6800	46.13	3.62	2.89	2.93	2.30	2.26	1.69	1.15	1.19	1.15	0.52	0	MSQ 1985-2010	1966-2009 (41.2 yrs of obs)	1.72	1.70	0.12	118.19	0.22	158.50	0.87	245.61	0.29	258.80	0.29
Bundaberg Beacon #2	QLD	N/A	24° 46'	152° 26'												0													
Urangan Storm Tide	QLD	59850	25 17 37.5523	152 54 25.1469	44.43	4.26	3.50	3.51	2.80	2.79	2.04	1.38	1.39	1.38	0.67	0	MSQ 1986-2009	See Source	2.09	2.07	0.12	123.43	0.24	163.79	1.06	255.62	0.35	273.35	0.25
Mooloolaba	QLD	59950	26 41 00.1687	153 08 01.2423		2.18	1.67	1.80	1.34	1.21	0.99	0.59	0.72	0.59	0.13	0	MSQ 1987-2009	1979-2009 (23.8 yrs of obs)	0.97	0.95	0.10	118.86	0.19	154.83	0.54	235.43	0.16	253.28	0.42
Caloundra Headland	QLD	59960	26° 47.9'	153° 09.1'		2.12	1.64	1.79	1.32	1.18		0.58	0.72	0.58	0.11	0	QDOT 1988 - 1989	See Source		0.95	0.11	116.40	0.19	152.90	0.53	234.40	0.16	251.20	0.44
Brisbane Bar	QLD	59980	27 21 34.1900	153 10 24.4792		2.72	2.18	2.31	1.79	1.65	1.24	0.76	0.90	0.76	0.24	0	MSQ 1985 - 2009	1957-2009 (37.6 yrs of obs)	1.28	1.26	0.12	131.42	0.21	171.13	0.71	274.90	0.19	302.10	0.37
Gateway Bridge Brisbane River	QLD	N/A	27° 25.9'	153° 00'												0													
Port Office Brisbane River	QLD	60000	27° 28.4'	153° 01.8'		2.78	2.21	2.34	1.85	1.71	1.24	0.78	0.91	0.78	0.28	0	QDOT 1995 - 1996	See Source		1.31	0.11	139.40	0.21	180.10	0.71	292.60	0.18	320.30	0.35
Marine Operations Base Southport	QLD	60050	27 56 17.6882	153 25 38.3985	39.62	1.92	1.42	1.56	1.14	1.00	0.76	0.40	0.54	0.40	-0.02	0	QDOT 1993 - 1999	See Source	0.77	0.77	0.10	104.44	0.18	145.13	0.51	236.94	0.14	256.34	0.43
Norfolk Island	NSW	57700	29° 3′ 59.9760″	167° 57′ 0.0000″		1.96	1.63	1.61	1.32	1.33		0.58	0.56	0.58	0.28	0	MHL 1994 - 2009	See Source	0.95	0.93	0.04	136.92	0.10	185.55	0.53	239.26	0.16	292.63	0.21
Lord Howe Island	NSW	57720	31° 30′ 59.9760″	159° 3′ 59.9760″		2.37	1.89	1.93	1.54	1.50		0.69	0.73	0.69	0.30	0	NTF 1995 - 2009	See Source	1.12	1.10	0.08	104.81	0.14	150.90	0.60	246.58	0.18	274.76	0.28
Tweed Heads Regional	NSW	60071	28 ° 10 ' 6.87463 ''	153 ° 33 ' 0.01979 ''	38.82	1.91	1.44	1.56	1.18	1.06	0.86	0.54	0.66	0.54	0.16	0	PWD NSW 1989 - 1990	See Source		0.86	0.09	108.22	0.16	148.52	0.45	238.20	0.13	257.66	0.44
Brunswick Heads	NSW	60080	28 ° 32 ' 18.33581 ''	153 ° 33 ' 5.01682 ''	37.78	2.02	1.49	1.64	1.22	1.07	0.86	0.51	0.66	0.51	0.09	0	PWD NSW 1989 - 1990	See Source		0.86	0.10	109.57	0.18	148.22	0.49	240.11	0.14	262.44	0.45
Ballina	NSW	60090	28 ° 52 ' 30.01429 ''	153 ° 34 ' 51.75396 ''	36.63	1.91	1.39	1.54	1.13	0.98	0.86	0.46	0.61	0.46	0.05	0	PWD NSW 1989 - 1990	See Source		0.80	0.10	105.02	0.18	141.22	0.47	238.69	0.13	260.66	0.47

Yamba	NSW	60130	29° 25' 46.96271"	153° 21' 42.75167"	34.98	1.92	1.47	1.59	1.21	1.09	0.82	0.53	0.65	0.53	0.14	0	MHL 1989 - 2009	See Source	0.87	0.85	0.09	96.13	0.16	138.37	0.47	234.93	0.13	257.43	0.42
Coffs Harbour	NSW	60180	30 ° 18 ' 18.27338 "	153 ° 8 ' 44.17351 "	32.73	2.12	1.60	1.73	1.31	1.18	0.93	0.56	0.69	0.56	0.14	0	PWD NSW 1989 - 1990	See Source		0.93	0.10	90.20	0.17	133.85	0.52	234.24	0.14	257.98	0.41
Port Macquarie	NSW	60220	31 ° 25 ' 44.69173 "	152 ° 54 ' 34.98614 "	30.88	1.72	1.28	1.41	1.06	0.93	0.72	0.44	0.57	0.44	0.09	0	PWD NSW 2005 - 2008	See Source		0.75	0.09	102.30	0.15	139.21	0.42	247.16	0.11	270.67	0.45
Crowdy Head	NSW	60235	31 ° 50 ' 26.32526 "	152 ° 44 ' 59.03433 "	28.38	2.10	1.58	1.73	1.30	1.15	0.94	0.52	0.67	0.52	0.09	0	PWD NSW 1989 - 1990	See Source		0.91	0.11	86.16	0.17	129.56	0.53	235.45	0.14	258.04	0.43
Forster	NSW	60250	32 ° 10 ' 32.05136 "	152 ° 30 ' 25.49718 "	27.30	1.84	1.61	1.63	1.17	1.15	1.00	0.63	0.65	0.63	0.17	0	PWD NSW 1989 - 1990	See Source		0.90	0.08	81.69	0.16	128.92	0.49	235.90	0.22	258.57	0.34
Port Stephens	NSW	60290	32 ° 42 ' 57.29187 "	152 ° 10 ' 53.59387 "	25.40	2.11	1.59	1.73	1.33	1.19	0.94	0.57	0.71	0.57	0.17	0	PWD NSW 1989 - 1990	See Source		0.95	0.10	78.23	0.17	120.55	0.51	239.13	0.13	263.46	0.43
Newcastle Pilot Station	NSW	60310	32° 55' 26.4"	151° 47' 18.9"	24.69	2.12	1.65	1.78	1.40	1.27	1.01	0.64	0.77	0.64	0.26	0	MHL 1985-2009	1957-2009 (43.8 yrs of obs)	1.02	1.00	0.09	78.26	0.16	117.34	0.50	238.21	0.13	262.76	0.40
Middle Head Cobblers Bay	NSW	60359	33 ° 49 ' 38.49501 "	151 ° 15 ' 25.84978 "	21.91		1.55	1.68	1.30	1.18	0.87	0.54	0.66	0.54	0.16	0	PWD NSW 1989-1990	See Source		0.92	0.10	79.56	0.15	119.45	0.51	236.41	0.13	259.86	0.40
Fort Denison	NSW	60370	33° 51'16.8"	151° 13'32.8"	21.75	2.09	1.61	1.73	1.36	1.24	0.93	0.60	0.72	0.60	0.23	0	Sydney Ports 1985-2009	1914-2009 (93.7 yrs of obs)	0.98	0.96	0.10	79.65	0.15	119.63	0.50	237.02	0.12	260.72	0.39
Botany Bay	NSW	60390	33° 59'	151° 13'	21.36	2.02	1.53	1.66	1.29	1.16	0.87	0.54	0.67	0.54	0.16	0	NTC 1985 - 2008	See Source		0.91	0.10	79.52	0.15	121.51	0.50	238.16	0.12	262.34	0.41
Port Hacking	NSW	60400	34 ° 4 ' 36.88765 "	151 ° 8 ' 45.89713 "	21.06	2.00	1.53	1.67	1.28	1.14	0.81	0.52	0.66	0.52	0.13	0	PWD NSW 1989 - 1990	See Source		0.90	0.10	78.67	0.16	121.05	0.51	237.91	0.12	261.24	0.42
Port Kembla	NSW	60420	34° 29'	150° 55'	19.78	2.03	1.53	1.68	1.30	1.15	0.89	0.56	0.71	0.56	0.17	0	NTC 1985 - 2009	1957-2009 (31.6 yrs of obs)	0.93	0.91	0.10	73.91	0.16	118.89	0.49	237.36	0.12	260.45	0.44
Shoalhaven Heads	NSW	N/A	34 ° 51 ' 40.44621 "	150 ° 44 ' 29.94590 "												0													
Crookhaven Heads	NSW	60434	34 ° 54 ' 24.18249 "	150 ° 45 ' 33.18501 "	18.41		1.40	2.36	1.16	1.45	0.79	0.48	0.19	0.48	-0.72	0	PWD NSW 2002	See Source		0.82	0.94	60.58	0.15	105.72	0.46	232.77	0.12	256.01	1.88
HMAS Creswell Jervis Bay	NSW	60440	35 ° 7 ' 23.46320 "	150 ° 42 ' 15.12721 "	17.28	2.01	1.55	1.70	1.32	1.17	0.96	0.58	0.73	0.58	0.20	0	PWD NSW 1989 - 1990	See Source		0.95	0.10	66.39	0.17	109.16	0.49	237.00	0.12	261.38	0.44
Bermagui	NSW	60500	36 ° 25 ' 30.45057 "	150 ° 4 ' 10.06124 "	13.42	1.83	1.35	1.48	1.14	1.01	0.79	0.44	0.57	0.44	0.10	0	PWD NSW 1987 - 1988	See Source		0.79	0.10	76.24	0.14	118.49	0.45	240.71	0.10	263.99	0.43
Eden Boat Harbour	NSW	60530	37 ° 4 ' 25.17661 "	149 ° 54 ' 27.86128 "	11.02	2.08	1.57	1.76	1.36	1.17	1.07	0.62	0.81	0.62	0.23	0	MHL 1989-2009	1966-2009 (22.8 yrs of obs)	0.99	0.97	0.11	66.61	0.18	110.81	0.47	238.60	0.10	261.01	0.51
Corner Inlet, Port Welshpool	VIC	60590	38° 41' 00"	146° 16' 48"	0.97	2.92	2.54	2.76	2.17	1.94	1.60	1.00	1.23	1.00	0.41	0	GIPSSLAND 2001 - 2009	See Source	1.58	1.57	0.16	69.86	0.25	107.44	0.77	4.69	0.19	198.36	0.43
Corner Inlet, Port Franklin	VIC	60600	38° 42' 03"	146° 27' 47"	2.07		2.84	3.03	2.41	2.22	1.51	1.15	1.34	1.15	0.53	0	VCA 2001 - 2002	See Source		1.78	0.16	71.81	0.24	106.85	0.85	4.71	0.22	197.91	0.38
Stony Point	VIC	60710	38° 22' 23"	145° 13' 27"	1.85	3.34	2.86	3.01	2.41	2.26	1.69	1.07	1.23	1.07	0.47	0	VCA 1993 - 2009	1963-2009 (29.8 yrs of obs)	1.74	1.73	0.15	43.06	0.22	76.89	0.89	352.22	0.22	137.72	0.34
Western Port, Flinders Jetty	VIC	60712	38° 28' 39"	145° 01' 30"	1.38		2.55	2.71	2.14	1.98	1.60	0.97	1.13	0.97	0.40	0	NTC 1973	See Source		1.55	0.15	32.73	0.22	64.38	0.79	326.02	0.21	106.70	0.37
Sth Channel, Hovell Pile	VIC	60721	38° 19' 38"	144° 53' 55"			0.88	0.99	0.78	0.66	0.38	0.47	0.59	0.47	0.26	0	VCA 1993-2005	See Source	0.63	0.61	0.07	95.69	0.10	131.63	0.20	58.84	0.05	196.69	0.66
Pt Lonsdale Jetty	VIC	60730	38° 17' 25"	144° 36' 50"	1.33	1.84	1.52	1.64	1.26	1.14	0.97	0.63	0.75	0.63	0.25	0	VCA 1985 - 2009	1962-2009 (45.9 yrs of obs)	0.95	0.93	0.10	39.12	0.15	71.04	0.44	326.58	0.13	98.04	0.44
Port Phillip Ent, 1M SE of Shortland Bluff	VIC	60730	38° 17' 33.99"	143° 39' 53.51"												0													
Queenscliff Pilots Jetty	VIC	60732	38° 16' 13"	144° 39' 45"	1.79		0.98	1.10	0.83	0.71	0.63	0.46	0.58	0.46	0.20	0	VCA 1993 - 2009	See Source	0.65	0.63	0.08	61.18	0.11	92.32	0.26	33.34	0.07	110.92	0.59
West Channel Pile	VIC	60739	38° 11' 34"	144° 45' 24"			0.78	0.90	0.69	0.57	0.48	0.37	0.49	0.37	0.15	0	VCA 1993 - 2009	See Source	0.53	0.51	0.07	94.27	0.10	130.22	0.21	56.46	0.05	192.41	0.65
Corio Bay No 1. Pt Richards Channel	VIC	60757	38° 05' 09.4"	144° 38' 28.9"			0.87	0.98	0.75	0.63	0.47	0.37	0.49	0.37	0.14	0	VCA 1999 - 2009	See Source	0.57	0.56	0.07	95.08	0.10	131.38	0.25	59.05	0.06	194.69	0.56

Geelong Shell Refinery (GL)	VIC	60770	38° 05' 31.1"	144° 23' 35.7"		1.19	0.98	1.09	0.85	0.75	0.58	0.44	0.55	0.44	0.21	0	VCA 1990 - 2009	1965-2009 (36.3 yrs of obs)	0.65	0.63	0.07	97.07	0.10	133.99	0.27	63.09	0.07	199.75	0.51
Williamstown, Breakwater Pier	VIC	60780	37° 52' 03"	144° 54' 44"	4.08	1.04	0.88	0.99	0.77	0.66	0.48	0.41	0.52	0.41	0.19	0	VCA 1985 - 2009	1966-2009 (43.5 yrs of obs)	0.59	0.57	0.07	96.41	0.10	132.94	0.24	60.75	0.06	197.06	0.58
River Yarra, No 45 Bcn, SMC	VIC	N/A	37° 49' 27.23"	145° 54' 23.67"												0														
Lorne Jetty	VIC	60790	38° 32' 52"	143° 59' 15"	-0.26	2.66	2.31	2.47	1.91	1.75	1.29	1.08	1.24	1.08	0.53	0	NTC 1993 - 2009	See Source	1.51	1.50	0.15	25.92	0.21	56.43	0.61	318.35	0.20	87.14	0.44
Portland	VIC	61410	38° 20′ 38"	141° 36′ 55"	-4.13	1.34	0.92	1.10	0.67	0.84	0.60	0.65	0.47	0.67	0.22	0	VIC 1992 - 2009	1982-2009 (27.2 yrs of obs)	0.66	0.63	0.13	16.44	0.18	44.30	0.13	334.71	0.14	51.77	1.16
Burnie	TAS	60910	41° 03'	145° 57′	-3.47	3.63	3.27	3.40	2.98	2.84	1.96	0.96	1.09	0.96	0.54	0	TAS 1985 - 2009	1952-2009 (37.2 yrs of obs)	1.97	1.95	0.12	55.28	0.16	93.77	1.15	329.90	0.15	125.79	0.21
Devonport	TAS	60930	41° 11′	146° 22′	-3.32	3.64	3.28	3.42	2.99	2.85	1.99	0.95	1.09	0.95	0.52	0	TAS 1994 - 2007	1965-2007 (22.0 yrs of obs)	1.97	1.94	0.12	55.18	0.17	93.46	1.16	327.19	0.14	126.28	0.22
Low Head	TAS	60948	41° 03′ 52″	146° 47′ 41″	-2.93	3.56	3.22	3.37	2.94	2.79	2.02	0.93	1.08	0.93	0.51	0	TAS 2003 - 2008	See Source	1.94	1.93	0.12	58.13	0.17	96.14	1.14	329.75	0.14	132.58	0.22
Spring Bay	TAS	61170	42° 33'	147° 36′	-4.20	1.47	1.09	1.29	1.03	0.83	0.76	0.49	0.69	0.49	0.23	0	NTC 1991 - 2008	1968 - 2009 (24.1 yrs of obs)	0.76	0.74	0.09	48.39	0.14	85.91	0.30	238.96	0.03	262.02	0.70
Hobart	TAS	61220	42° 53′S	147° 20′	-4.55	1.70	1.16	1.52	1.14	1.02	0.83	0.66	0.78	0.66	0.27	0	TAS 1988 - 2009	1960-2007, 2009 (38.6 yrs of obs)	0.90	0.88	0.15	49.50	0.22	82.31	0.25	243.03	0.01	186.54	1.42
Victor Harbour	SA	61490	35° 33′ 44.9″	138° 38′ 07.4″		1.56	0.98	1.17	0.72	0.91	0.71	0.68	0.49	0.72	0.23	0	FP 1985 - 2009	1964 - 2009 (42.5 yrs of obs)	0.70	0.68	0.14	3.30	0.20	32.01	0.13	351.30	0.15	46.83	1.22
Cape Jervis	SA	61561	35° 36′ 22.6″	138° 05′ 36.9″		1.76	1.19	1.35	0.81	0.93	0.87	0.77	0.64	0.77	0.22	0	NTC 2003 - 2006	See Source	0.79	0.79	0.14	14.73	0.21	42.72	0.21	93.79	0.19	161.02	0.89
Port Stanvac	SA	61583	35° 06′	138° 28′		2.50	2.01	2.00	1.16	1.18	1.29	1.15	1.13	1.15	0.31	0	NTC 1993 - 2009	1992-2009 (17.4 yrs of obs)	1.17	1.15	0.17	20.45	0.24	47.72	0.43	103.39	0.43	171.65	0.48
Port Adelaide Outer Harbour	SA	61600	34° 46′ 47.14″	138° 28′ 50.62″		2.85	2.37	2.28	1.35	1.44		1.35	1.27	1.35	0.42	0	FP 1985 - 2009	1940-2009 (67.1 yrs of obs)	1.35	1.33	0.17	21.85	0.25	49.06	0.51	106.53	0.51	175.32	0.42
Outer Harbour Entrance Beacon	SA	61600?	N/A	N/A												0														
Ardrossan	SA	61650	34° 26′ 30″	137° 55′ 30″		3.41	2.83	2.64	1.58	1.75		1.56	1.39	1.58	0.50	0	MHSA 1951	See Source		1.57	0.18	19.30	0.27	46.60	0.62	105.20	0.63	173.70	0.36
Port Giles	SA	61685	35° 01′ 18.4″	137° 46′ 05.9″		2.57	2.09	2.07	1.23	1.25	1.52	1.22	1.20	1.22	0.38	0	FP 1994 - 2009	See Source	1.22	1.21	0.17	16.10	0.25	43.16	0.44	92.95	0.43	160.68	0.47
Wallaroo	SA	61780	33° 55′ 33.6″	137° 36′ 54.6″		2.04	1.30	1.69	0.97	1.35	1.25	0.97	0.59	0.97	0.25	0	FP 1985 - 2009	1976 - 2009 (25.8 yrs of obs)	0.97	0.95	0.22	33.13	0.33	61.02	0.17	134.13	0.16	187.13	1.66
Middle Bank South	SA	61785	33° 43′ 59.5″	137° 29′ 48.8″		2.22	1.41	1.76	1.04	1.39		0.97	0.62	1.04	0.25	0	HYDRO 2005	See Source	1.00	0.99	0.21	31.79	0.36	60.38	0.19	143.72	0.22	198.70	1.40
Port Pirie	SA	61800	33° 10′ 39.5″	138° 00′ 41.9″		3.49	2.74	2.92	1.75	1.93	1.93	1.68	1.50	1.75	0.51	0	FP 1985 - 2009	1941-2009 (66.3 yrs of obs)	1.72	1.69	0.28	48.58	0.43	76.27	0.49	198.92	0.53	258.10	0.70
Port Bonython	SA	61837	33° 00′ 45.4″	137° 45′ 55.7″		3.17	2.34	2.52	1.44	1.63		1.36	1.18	1.44	0.28	0	NTC 2006	See Source		1.40	0.29	38.55	0.39	70.72	0.45	188.77	0.49	248.47	0.72
Whyalla	SA	61840	33° 00′ 46.0″	137° 35′ 25.3″		3.26	2.50	2.74	1.63	1.87	1.77	1.57	1.33	1.63	0.47	0	FP 1984 - 2009	See Source	1.60	1.58	0.28	41.41	0.43	68.93	0.43	183.87	0.46	242.72	0.78
Port Lincoln	SA	61900	34° 42′ 57.2″	135° 52′ 12.0″		1.90	1.32	1.47	0.84	0.99	0.75	0.80	0.65	0.84	0.17	0	FP 1985 - 2009	1964-2009 (44.0 yrs of obs)	0.82	0.80	0.17	1.17	0.24	26.82	0.24	32.91	0.26	84.49	0.83
Thevenard	SA	62000	32° 10′	133° 40'		2.32	1.71	1.67	1.12	1.08	0.99	0.97	1.01	1.12	0.41	0	FP 1992 - 2009	1966 - 2009 (42.9 yrs of obs)	1.04	1.02	0.14	357.60	0.19	21.34	0.30	0.93	0.37	43.76	0.50
Esperance	WA	62080	33° 52'	121° 54′		1.38	0.88	1.06	0.67	0.85	0.54	0.61	0.43	0.67	0.22	0	FP 1985 - 2009	1965 - 2009 (43.2 yrs of obs)	0.64	0.62	0.13	313.71	0.18	336.27	0.11	319.92	0.14	334.19	1.31
Bremer Bay	WA	62110	34° 25′ 29.3″	119° 23′ 55.4″	-22.00	1.27	0.76	0.88	0.57	0.70	0.66	0.53	0.41	0.57	0.22	0	WADOT 1998 - 1999	See Source		0.55	0.10	231.88	0.14	307.59	0.09	216.79	0.11	331.06	1.14
Albany (Albany Port	WA	62120	35° 02′ 01.4″	117° 53′ 33.2″		1.40	0.87	1.10	0.72	0.95	0.65	0.66	0.43	0.72	0.28	0	WADOT 1985 - 2009	1960 - 2009 (43.4 yrs of obs)	0.69	0.67	0.14	306.70	0.19	328.68	0.08	332.42	0.11	329.88	1.85

Authority)																														
Busselton	WA	62180	33° 37′ 39.6″	115° 23′ 39.8″	-28.93	1.23	0.72	0.96	0.61	0.85	0.68	0.61	0.37	0.61	0.26	0	MHWA 1977 - 1978	See Source		0.61	0.12	286.70	0.18	300.25	0.06	298.72	0.05	300.73	2.74
Mandurah	WA	62186	32° 31′ 43.2″	115° 42′ 55.3″		0.78	0.38	0.55	0.33	0.50		0.33	0.17	0.33	0.11	0	WADPI 1994 - 1997	See Source		0.33	0.08	310.33	0.11	323.58	0.03	306.83	0.02	311.34	3.70
Peel Inlet Dawesville	WA	62187	32° 35′ 35″	115°42′ 50.4″	-32.88	0.65	0.27	0.41	0.25	0.39	0.26	0.24	0.11	0.24	0.08	0	WADPI 1994-1997	See Source		0.25	0.06	357.09	0.09	9.27	0.01	14.57	0.01	30.51	6.38
Bouvard – Dawesville Channel	WA	N/A	32° 36′ 05.8″	115° 37′ 47.9″												0														
Caddadup – Dawesville Channel	WA	N/A	32° 36′ 34.7″	115° 38′ 35.6″												0														
Harvey Estuary Dawesville	WA	N/A	32° 41′ 00.4″	115° 40′ 34.3″												0														
Bunbury	WA	62190	33° 19′ 24.4″	115° 39′ 35.9″		1.24	0.73	0.97	0.62	0.86	0.57	0.62	0.38	0.62	0.27	0	WADPI 1985-2009	1963-2009 (42.3 yrs of obs)	0.62	0.60	0.12	288.57	0.17	301.64	0.06	299.69	0.05	300.96	2.70
Mangles Bay	WA	N/A	32° 16′ 28.2″	115° 42′ 12.5″												0														
Fremantle	WA	62230	32° 03′ 56″	115° 44′ 53.3″	-33.54	1.37	0.87	1.11	0.78	1.00	0.56	0.77	0.54	0.77	0.43	0	WADPI 1985-2009	1897-2009 (102.6 yrs of obs)	0.77	0.75	0.12	289.86	0.17	305.98	0.05	291.75	0.05	303.17	2.86
Perth Swan River – Barrack Street	WA	N/A	31° 57′ 34.9″	115° 51′ 26.1″												0														
Hillarys	WA	62237	31° 49′ 12.0000″	115° 44′		1.16	0.79	1.04	0.70	0.93		0.68	0.45	0.68	0.35	0	NTC 1991 - 2009	See Source	0.69	0.67	0.12	286.87	0.17	302.99	0.05	287.96	0.05	298.02	2.95
Two Rocks Marina	WA	62240	31° 29′ 46.2″	115° 35′ 00.4″	-33.14	1.22	1.30	1.56	1.21	0.94	0.87	0.26	0.52	0.26	-0.10	0	PWD WA 1975	See Source		0.73	0.12	284.20	0.19	303.60	0.52	289.60	0.05	299.80	0.55
Lancelin	WA	62250	31° 00′ 52.9″	115° 19′ 38.4″	-32.15	1.09	0.58	0.81	0.49	0.71	0.73	0.48	0.26	0.48	0.16	0	PWD WA 1975	See Source		0.48	0.12	286.20	0.16	309.00	0.05	285.80	0.05	300.40	2.87
Jurien	WA	62270	30° 17′ 14.3″	115° 02′ 34.1″	-29.86	1.16	0.63	0.88	0.54	0.77	0.69	0.52	0.29	0.52	0.18	0	NTF 1981 - 1982	See Source		0.53	0.12	286.28	0.17	302.08	0.06	287.71	0.05	304.84	2.89
Geraldton (Geraldton Port Authority)	WA	62290	28° 46′ 33.5″	114° 36′ 06.8″		1.23	0.71	0.97	0.62	0.82	0.54	0.57	0.37	0.57	0.22	0	WADPI 1985 - 2009	1963-2009 (43.9 yrs of obs)	0.59	0.57	0.12	286.97	0.18	303.06	0.07	291.08	0.05	310.43	2.49
Useless Loop Loading Jetty (Shark Bay Salt)	WA	62345	26° 05′ 27.32″	113° 24′ 45.55″	-23.49	1.55	0.90	1.22	0.79	0.97	0.75	0.65	0.47	0.65	0.22	0	WADOT 1988 - 1989		0.72		0.15	326.04	0.23	344.85	0.13	35.30	0.05	100.48	2.10
Carnarvon	WA	62370	24° 53′ 55.3″	113°39′ 03.7″		2.02	1.51	1.73	1.23	1.10	0.95	0.87	1.00	0.87	0.37	0	WADPI 1985 - 2009	1965-2009 (35.8 yrs of obs)	1.05	1.03	0.14	276.45	0.22	293.59	0.32	306.78	0.14	14.55	0.80
Exmouth	WA	62435	21° 57′ 17.5″	114° 08′ 27.2″	-15.73	2.88	2.35	2.40	1.74	1.70	1.40	1.20	1.24	1.20	0.54	0	WADPI 1990 - 2009	See Source	1.47	1.46	0.14	278.91	0.21	297.33	0.58	310.98	0.31	24.96	0.39
Onslow (Onslow Salt)	WA	N/A	21° 37′ 35″	115° 05′ 48.1″												0														
Onslow – Beadon Creek	WA	62470	21° 38′ 58.8″	115° 07′ 53.5″	-12.20	3.07	2.49	2.51	1.85	1.83	1.49	1.31	1.32	1.31	0.64	0	WADPI 1986 - 2009	1985-2009 (24.2 yrs of obs)	1.58	1.56	0.13	275.66	0.21	293.50	0.59	301.29	0.32	12.28	0.37
Dampier, King Bay (Hammersley Iron, Woodside)	WA	62540	20° 37′ 25″	116° 44′ 56.6″	-9.72	5.09	4.41	4.13	3.11	3.38	2.65	2.18	1.90	2.18	1.15	0	WADPI 1985 - 2009	1982-2009 (26.8 yrs of obs)	2.64	2.62	0.15	271.71	0.23	291.56	1.12	302.88	0.65	12.20	0.21
Cape Lambert (Robe River Mining)	WA	62550	20° 35′ 16.7″	117° 11′ 09.7″		6.19	5.49	5.05	3.84	4.28	3.35	2.73	2.29	2.73	1.52	0	WADPI 1985 - 2009	1972-2009 (23.2 yrs of obs)	3.28	3.26	0.15	272.59	0.24	293.10	1.38	306.36	0.82	15.59	0.18
Port Hedland (Port Hedland	WA	62590	20° 19′ 03.3″	118° 34′ 27.9″		7.53	6.70	6.06	4.63	5.27	3.90	3.29	2.65	3.29	1.87	0	WADPI 1985 - 2009	1960-2009 (39.9 yrs of obs)	3.96	3.94	0.15	273.10	0.24	293.03	1.70	306.14	1.03	15.26	0.14

Port Authority)																													
Broome	WA	62650	18° 0'	122° 13'		10.49	9.29	8.22	6.33	7.40		4.52	3.45	4.52	2.62	0	WADPI 1986 - 2009	1966-2009 (35.4 yrs of obs)	5.42	5.40	0.16	272.63	0.26	292.26	2.39	297.86	1.48	6.03	0.11
Derby	WA	62780	17° 17′ 32.3″	123° 36′ 24.1″	16.22	12.03	10.89	9.79	7.82	8.92	6.30	4.78	3.69	4.78	2.82	0	WADPI			6.30	0.17	328.64	0.27	344.53	3.05	40.85	1.53	122.49	0.09
Wyndham	WA	63090	15° 27′ 11.8″	128° 06′ 03.7″	31.77	8.70	7.85	7.86	5.90	5.89	4.45	3.25	3.26	3.25	1.28	0	WADPI 1985 - 2009	1966-2009 (38.0 yrs of obs)	4.57	4.55	0.34	319.83	0.65	345.39	2.30	198.16	0.98	262.52	0.30
Cocos Island	WA	46280	12° 07'	96° 53′	-16.98	1.59	1.12	1.25	0.90	0.77		0.51	0.63	0.51	0.16	0	WADPI 1985 - 2009	See Source	0.70	0.68	0.09	235.99	0.15	252.39	0.31	139.71	0.11	183.01	0.56
Darwin	NT	63230	12° 28'	130° 51′	47.66	8.10	7.00	6.96	5.08	5.13	4.11	3.29	3.25	3.29	1.42	0	NT 1990 - 2009	1959-2009 (46.9 yrs of obs)	4.19	4.17	0.33	322.38	0.58	343.44	1.86	164.66	0.96	223.13	0.33
Groote Eylandt	NT	63511	13° 50'	136° 30'	54.74	2.38	1.28	1.83	1.20	1.71		1.16	0.65	1.16	0.53	0	NT 2008-2010	1980-2009 (22.1 yrs of obs)	1.18	1.16	0.26	292.08	0.33	13.61	0.06	330.14	0.04	32.05	6.12

Appendix D - Stage 1 LiDAR Analysis

The following figures (Figure 41 to Figure 44) show the Sunshine Coast and WA bathymetric LiDAR AHD and ellipsoid surfaces. The two Sunshine Coast surfaces exhibit the same degree of error (roughness), while the WA surfaces show the errors (spikes) were larger in the ellipsoidal data.

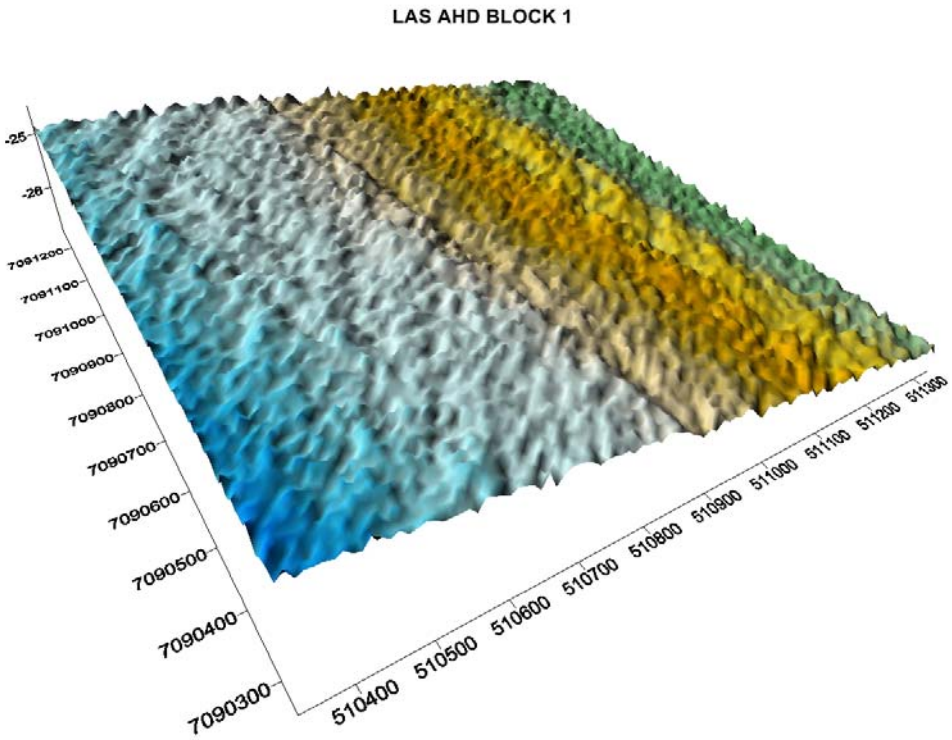


Figure 41. Stage 1 Sunshine Coast bathymetric LiDAR AHD surface.

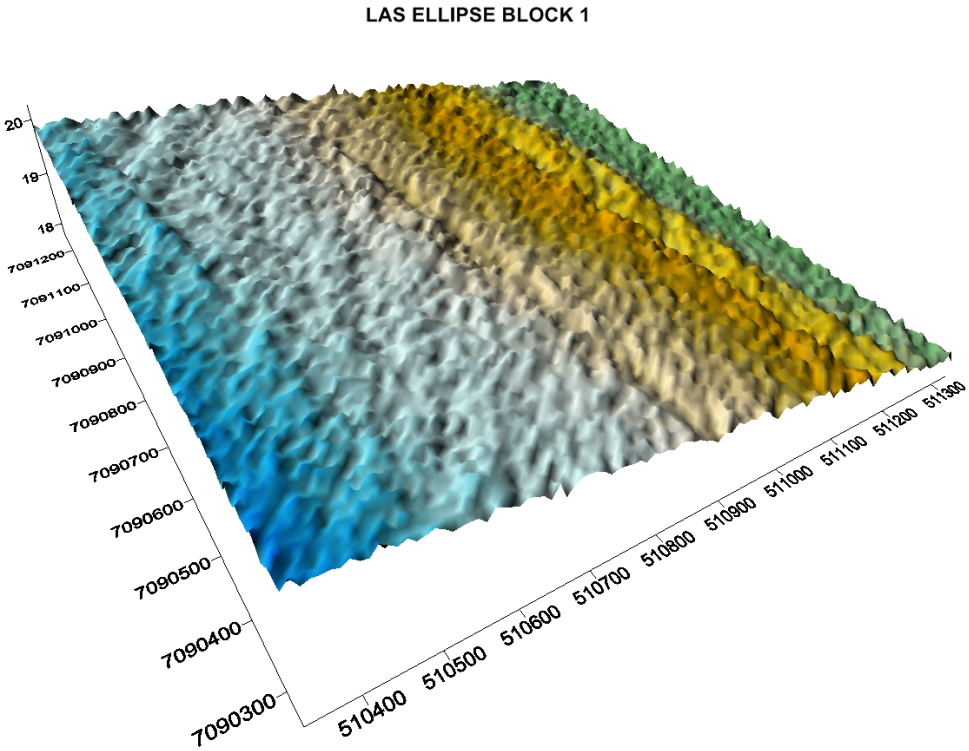


Figure 42. Stage 1 Sunshine Coast bathymetric LiDAR ellipsoid surface.

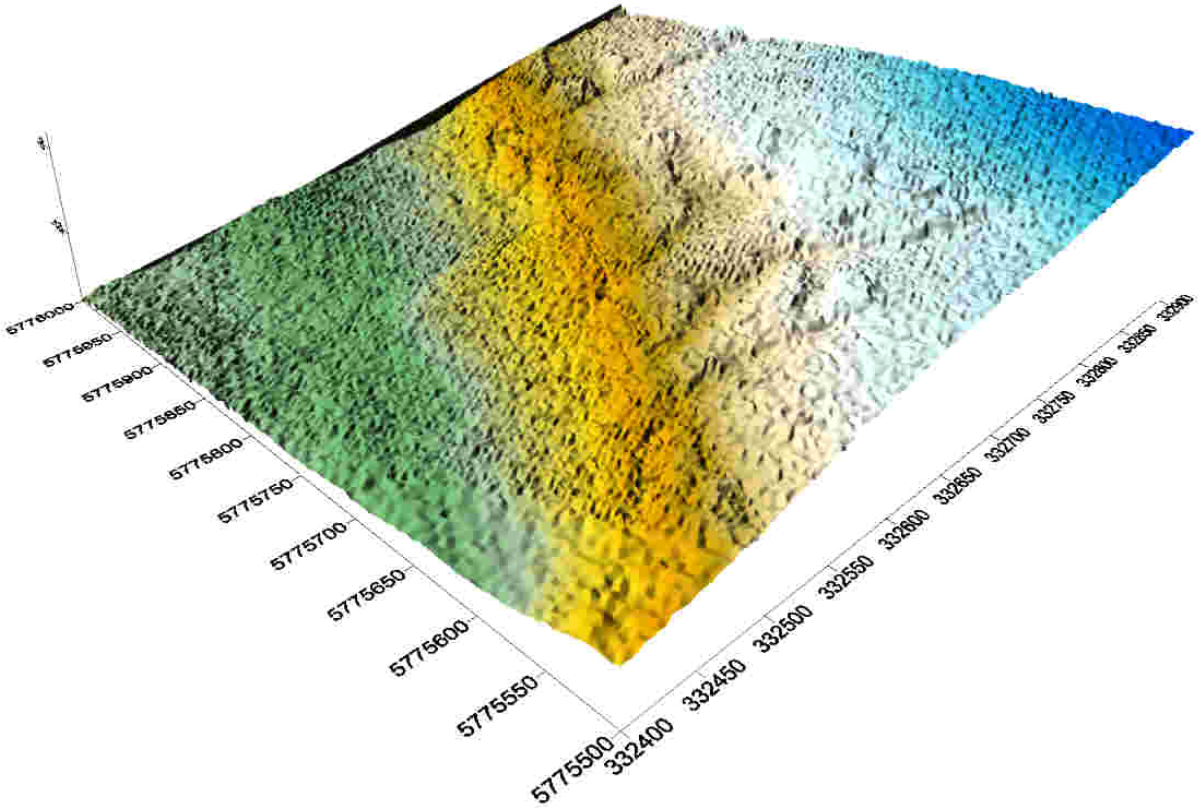


Figure 43. WA research bathymetric LiDAR AHD surface.

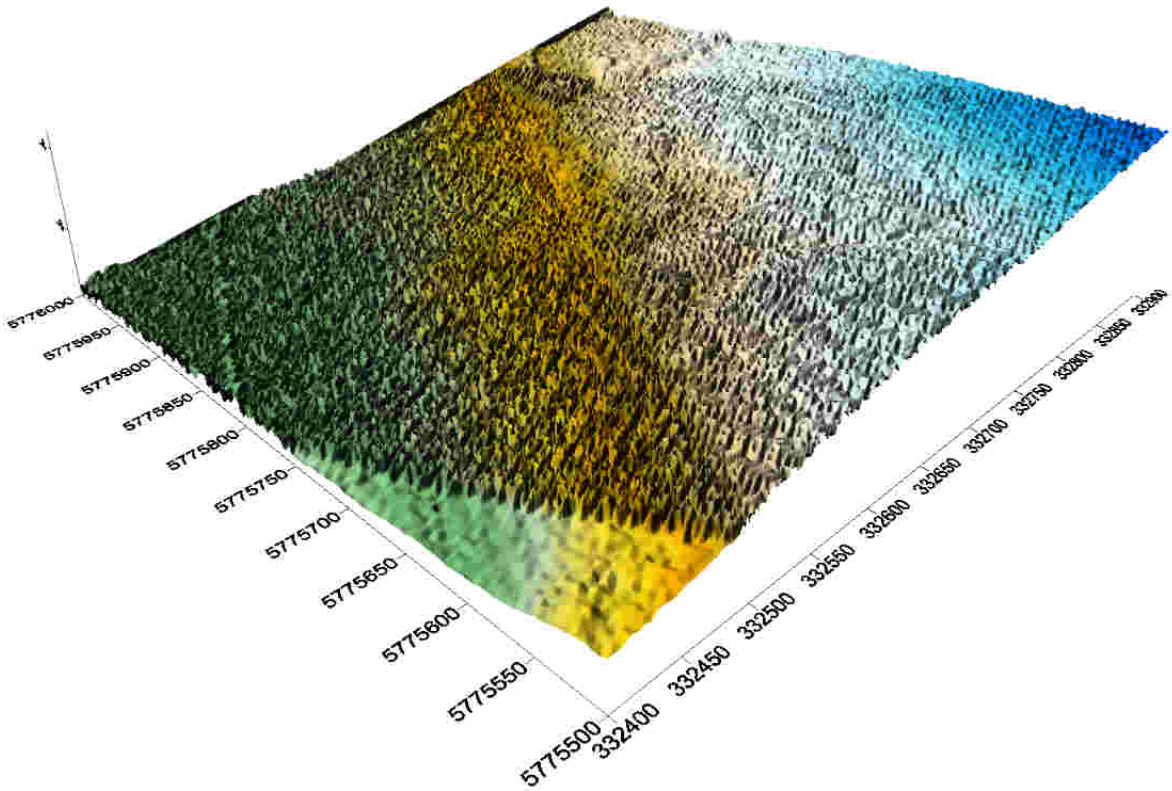


Figure 44. WA research bathymetric LiDAR ellipsoid surface.

Appendix E – Ellipsoid to Australian Height Datum

Table 20. Summary statistics for the AUSGeoid09 degradation profiles.

Profile	Magnitude of Degradtaion (slope of trend line) cm/km	R2
1	1.48	0.206
2	1.34	0.155
3	0.48	0.023
4	2.22	0.146
5	1.56	0.186
6	1.71	0.168
7	0.81	0.029
8	2.30	0.254
9	2.02	0.205
Mean	1.55	0.152

Appendix F – Tide Gauge Derived Mean Sea Surface

Table 21. Australian East coast tide gauge latitude versus ellipsoidal MSL value; study area gauges highlighted in blue.

Australian East Coast Tide Gauges	State	Latitude	Ellipsoidal MSL
Ince Point	QLD	-12.409	71.9408
Port Douglas	QLD	-16.48	63.6582
Cairns Storm Tide	QLD	-16.926	62.2967
Lucinda Storm Tide	QLD	-18.528	59.4075
Cape Ferguson	QLD	-19.277	58.6358
Bowen Storm Tide	QLD	-20.023	57.3395
Shute Harbour Storm Tide	QLD	-20.293	57.3299
Mackay Outer Harbour	QLD	-21.107	55.7876
Half Tide Tug Harbour (HAY PT)	QLD	-21.274	55.3142
Rosslyn Bay	QLD	-23.164	51.3187
Port Alma	QLD	-23.584	50.6314
Bundaberg (Burnett Heads)	QLD	-24.758	47.8284
Urangan Storm Tide	QLD	-25.294	46.5011
Marine Operations Base Southport	QLD	-27.938	40.3877
Tweed Heads Regional	NSW	-28.169	39.684
Brunswick Heads	NSW	-28.538	38.6467
Ballina	NSW	-28.875	37.4277
Yamba	NSW	-29.43	35.8253
Coffs Harbour	NSW	-30.305	33.661
Port Macquarie	NSW	-31.429	31.6332
Crowdy Head	NSW	-31.841	29.2917
Forster	NSW	-32.176	28.195
Port Stephens	NSW	-32.716	26.3447
Newcastle Pilot Station	NSW	-32.924	25.6897
Middle Head Cobblers Bay	NSW	-33.827	22.831
Fort Denison	NSW	-33.855	22.7078
Botany Bay	NSW	-33.983	22.2745
Port Hacking	NSW	-34.077	21.962
Port Kembla	NSW	-34.483	20.6889
Crookhaven Heads	NSW	-34.907	19.225
HMAS Creswell Jervis Bay	NSW	-35.123	18.2255
Bermagui	NSW	-36.425	14.21
Eden Boat Harbour	NSW	-37.074	11.9972

Table 22. Comparison of interpolation methods for study area gauges with ellipsoidal MSL values. Ballina and New Castle Pilot Station gauges are missing as fall outside the interpolation mask.

Station	Tide Gauge (TG) MSL	IDW	Kriging	Spline	IDW – TG Difference	Kriging – TG Difference	Spline – TG Difference
Urangan Storm Tide	46.5011	46.5011	46.5011	46.5018	0.0000	0.0000	0.0007
Marine Operations Base Southport	40.3877	40.3869	40.3743	40.3790	-0.0008	-0.0134	-0.0087
Tweed Heads Regional	39.6840	39.6837	39.6844	39.6545	-0.0003	0.0004	-0.0295
Brunswick Heads	38.6467	38.6468	38.6208	38.6199	0.0001	-0.0259	-0.0268
Yamba	35.8253	35.8255	35.8344	35.8397	0.0002	0.0091	0.0144
Coffs Harbour	33.6610	33.6612	33.6625	33.6595	0.0002	0.0015	-0.0015
Port Macquarie	31.6332	31.6330	31.6257	31.6440	-0.0002	-0.0075	0.0108
Crowdy Head	29.2917	29.2919	29.2844	29.2723	0.0002	-0.0073	-0.0194
Forster	28.1950	28.1950	28.1953	28.1909	0.0000	0.0003	-0.0041
Port Stephens	26.3447	26.3451	26.3339	26.3769	0.0004	-0.0108	0.0322
Middle Head Cobblers Bay	22.8310	22.8310	22.8310	22.8310	0.0000	0.0000	0.0000
				Mean	0.0000	-0.0049	-0.0029
				Std Dev	0.0003	0.0095	0.0182

Table 23. Removal test results for the comparison of study area tide gauge interpolation methods. Urangan Storm Tide and Middle Head Cobblers Bay are not included as are at the northern and southern extents of the data so when removed from the interpolation they

Stations Removed	Tide Gauge (TG) MSL	IDW	Kriging	Spline	IDW – TG Difference	Kriging – TG Difference	Spline – TG Difference
Marine Operations Base Southport	40.3877	39.3139	39.6572	40.5202	-1.0738	-0.7305	-0.0608
Tweed Heads Regional	39.6840	39.4544	39.6436	39.7993	-0.2296	-0.0404	0.1153
Brunswick Heads	38.6467	38.5193	38.4880	38.4142	-0.1274	-0.1587	-0.2325
Yamba	35.8253	37.1288	35.9315	35.5991	1.3035	0.1062	-0.2262
Coffs Harbour	33.6610	34.0404	33.9820	34.7557	0.3794	0.3210	1.0947
Port Macquarie	31.6332	29.3503	29.2818	30.5698	-2.2829	-2.3514	-1.0634
Crowdy Head	29.2917	29.3844	29.8612	29.9533	0.0927	0.5695	0.6616
Forster	28.1950	28.5831	28.1215	27.6058	0.3881	-0.0735	-0.5892
Port Stephens	26.3447	26.6531	26.7412	26.3314	0.3084	0.3965	-0.0133
				Mean	-0.0209	-0.1539	-0.0316
				Std Dev	1.0264	0.9233	0.6787

Appendix G – Satellite Altimetry Derived Mean Sea Surface

Table 24. Differences between tide gauge MSL and satellite altimetry derived MSS referenced to tide-free GRS80 in metres. Values highlighted pink are outliers, and blue are study area gauges.

Station	State	Tide Gauge MSL relative to tide-free GRS80 ellipsoid	DTU10 MSL relative to tide-free GRS80 ellipsoid	CLS11 MSL relative to tide-free GRS80 ellipsoid	Difference b/n TG and DTU10	Difference b/n TG and CLS11
Ballina	NSW	37.4277	37.4394	37.6383	-0.0117	-0.2106
Bermagui	NSW	14.2100	14.3374	14.4905	-0.1274	-0.2805
Botany Bay	NSW	22.2745	22.2666	22.4135	0.0079	-0.1390
Brunswick Heads	NSW	38.6467	38.5666	38.8935	0.0801	-0.2468
Coffs Harbour	NSW	33.6610	33.4023	33.4752	0.2587	0.1858
Crookhaven Heads	NSW	19.2250	19.2392	19.3451	-0.0142	-0.1201
Crowdy Head	NSW	29.2917	29.2990	29.3869	-0.0073	-0.0952
Eden Boat Harbour	NSW	11.9972	12.2245	12.0874	-0.2273	-0.0902
Forster	NSW	28.1950	28.1760	28.9289	0.0190	-0.7339
Fort Denison	NSW	22.7078	22.6768	22.8849	0.0310	-0.1771
HMAS Creswell Jervis Bay	NSW	18.2255	18.3844	18.3375	-0.1589	-0.1120
Middle Head Cobblers Bay	NSW	22.8310	22.7546	22.9667	0.0764	-0.1357
Newcastle Pilot Station	NSW	25.6897	25.7373	25.7444	-0.0476	-0.0547
Port Hacking	NSW	21.9620	22.0182	22.1021	-0.0562	-0.1401
Port Kembla	NSW	20.6889	20.8106	20.7545	-0.1217	-0.0656
Port Macquarie	NSW	31.6332	30.3697	30.3406	1.2635	1.2926
Port Stephens	NSW	26.3447	26.4111	26.6620	-0.0664	-0.3173
Tweed Heads Regional	NSW	39.6840	39.6546	39.7635	0.0294	-0.0795
Yamba	NSW	35.8253	35.9165	35.8544	-0.0912	-0.0291
Darwin	NT	51.8257	51.5137	51.7216	0.3120	0.1041
Groote Eylandt	NT	55.9062	55.7365	56.0115	0.1697	-0.1053
Booby Island	QLD	70.5763	70.4500	70.4309	0.1263	0.1454
Bowen Storm Tide	QLD	57.3395	57.3956	57.2006	-0.0561	0.1389
Bundaberg (Burnett Heads)	QLD	47.8284	47.6600	47.8370	0.1684	-0.0086
Cairns Storm Tide	QLD	62.2967	62.8256	62.8207	-0.5289	-0.5240
Cape Ferguson	QLD	58.6358	58.7406	58.7075	-0.1048	-0.0717
Goods Island	QLD	71.3196	71.2359	71.1439	0.0837	0.1757
Half Tide Tug Harbour (HAY PT)	QLD	55.3142	55.4539	55.6409	-0.1397	-0.3267
Ince Point	QLD	71.9408	69.2555	69.2714	2.6853	2.6694
Karumba Bar	QLD	51.7975	51.4797	51.2237	0.3178	0.5738
Lucinda Storm Tide	QLD	59.4075	59.5017	59.5406	-0.0942	-0.1331
Mackay Outer Harbour	QLD	55.7876	55.7922	55.8131	-0.0046	-0.0255
Marine Operations Base Southport	QLD	40.3877	40.5543	40.6262	-0.1666	-0.2385
Nardana Patches	QLD	71.9701	71.6337	71.7377	0.3364	0.2324
Port Alma	QLD	50.6314	50.3633	50.9934	0.2681	-0.3620
Port Douglas	QLD	63.6582	63.3401	63.4010	0.3181	0.2572
Rosslyn Bay	QLD	51.3187	51.1565	51.1574	0.1622	0.1613
Shute Harbour Storm Tide	QLD	57.3299	56.9957	57.3957	0.3342	-0.0658
Turtle Head	QLD	71.4491	66.4676	66.3547	4.9815	5.0944
Urangan Storm Tide	QLD	46.5011	46.9796	46.3237	-0.4785	0.1774
Weipa Storm Tide	QLD	65.3699	64.8372	64.7552	0.5327	0.6147
Burnie	TAS	-1.5214	-1.5154	-1.3743	-0.0060	-0.1471
Devonport	TAS	-1.3777	-1.3885	-1.3576	0.0108	-0.0201
Hobart	TAS	-3.6749	-3.7355	-3.7807	0.0606	0.1058
Low Head	TAS	-0.9985	-0.9701	-0.7183	-0.0284	-0.2802
Spring Bay	TAS	-3.4556	-2.9317	-3.0586	-0.5239	-0.3970
Corner Inlet, Port Franklin	VIC	3.8547	3.3328	3.3117	0.5219	0.5430
Corner Inlet, Port Welshpool	VIC	2.5404	3.4516	3.6155	-0.9112	-1.0751
Lorne Jetty	VIC	1.2376	0.5187	0.9786	0.7189	0.2590
Portland	VIC	-3.4921	-3.4235	-3.4176	-0.0686	-0.0745

Pt Lonsdale Jetty	VIC	2.2602	2.1540	2.3172	0.1062	-0.0570
Queenscliff Pilots Jetty	VIC	2.4250	2.2420	2.6589	0.1830	-0.2339
Stony Point	VIC	3.5804	3.6787	3.4336	-0.0983	0.1468
Western Port, Flinders Jetty	VIC	2.9372	2.8493	3.0132	0.0879	-0.0760
Williamstown, Breakwater Pier	VIC	4.6515	4.1325	4.3304	0.5190	0.3211
Bremer Bay	WA	-21.4500	-30.8608	-30.8227	9.4108	9.3727
Busselton	WA	-28.3150	-32.7996	-32.6895	4.4846	4.3745
Dampier, King Bay (Hammersley Iron, Woodside)	WA	-7.0990	-6.9759	-7.1819	-0.1231	0.0829
Derby	WA	22.5225	22.5219	22.7310	0.0006	-0.2085
Exmouth	WA	-14.2633	-14.0571	-13.8391	-0.2062	-0.4242
Fremantle	WA	-32.7898	-33.1136	-32.8957	0.3238	0.1059
Jurien	WA	-29.3300	-29.3279	-29.1918	-0.0021	-0.1382
Lancelin	WA	-31.6680	-31.6847	-31.8748	0.0167	0.2068
Onslow - Beadon Creek	WA	-10.6382	-10.6815	-10.5514	0.0433	-0.0868
Peel Inlet Dawesville	WA	-32.6336	-32.4087	-32.5196	-0.2249	-0.1140
Two Rocks Marina	WA	-32.4060	-33.2149	-32.8280	0.8089	0.4220
Wyndham	WA	36.3218	35.9956	35.7026	0.3262	0.6192
				Mean	0.3804	0.3009
				Std Dev	1.4438	1.4622
				Study Area Mean	0.0660	-0.0373
				Study Area Std Dev	0.3971	0.4617

Appendix H – Integrated Mean Sea Surface

Table 25. The difference between the study area tide gauge ellipsoidal MSL values and the corresponding integrated MSS values (in metres).

Station	State	Tide Gauge MSL relative to tide-free GRS80 ellipsoid	DTU10 MSL relative to tide-free GRS80 ellipsoid	Integrated MSS	Difference b/n TG and DTU10	Difference b/n TG and Integrated MSS
Ballina	NSW	37.4277	37.4394	37.4233	-0.0117	0.0044
Brunswick Heads	NSW	38.6467	38.5666	38.6446	0.0801	0.0021
Coffs Harbour	NSW	33.6610	33.4023	33.6675	0.2587	-0.0065
Crowdy Head	NSW	29.2917	29.2990	29.3127	-0.0073	-0.0210
Forster	NSW	28.1950	28.1760	28.2098	0.0190	-0.0148
Marine Operations Base Southport	QLD	40.3877	40.5543	40.3903	-0.1666	-0.0026
Middle Head Cobblers Bay	NSW	22.8310	22.7546	22.8506	0.0764	-0.0196
Newcastle Pilot Station	NSW	25.6897	25.7373	25.6878	-0.0476	0.0019
Port Macquarie	NSW	31.6332	30.3697	31.6745	1.2635	-0.0413
Port Stephens	NSW	26.3447	26.4111	26.3355	-0.0664	0.0092
Tweed Heads Regional	NSW	39.6840	39.6546	39.6798	0.0294	0.0042
Urangan Storm Tide	QLD	46.5011	46.9796	46.5047	-0.4785	-0.0036
Yamba	NSW	35.8253	35.9165	35.7741	-0.0912	0.0512
				Mean	0.0660	-0.0028
				Std Dev	0.3971	0.0213

Appendix I – GEMS

Table 26. Differences between tide gauge tidal datums relative to MSL and GEMS results in metres. Values highlighted pink are outliers, blue are study area gauges, and yellow are missing values.

		Tide gauge tidal datum values relative to MSL subtract those computed by GEMS		
Station	**State**	**HAT**	**LAT**	**MHWS**
Ballina	NSW	0.11	-0.20	-0.11
Bermagui	NSW	0.34	-0.19	0.06
Botany Bay	NSW	0.11	-0.01	-0.18
Brunswick Heads	NSW	0.86	-0.56	0.43
Coffs Harbour	NSW	-0.01	0.07	-0.14
Crookhaven Heads	NSW		-0.12	-0.22
Crowdy Head	NSW	0.09	-0.01	-0.13
Eden Boat Harbour	NSW	0.11	0.03	-0.10
Forster	NSW	-0.06	-0.10	0.01
Fort Denison	NSW	0.13	0.04	-0.05
HMAS Creswell Jervis Bay	NSW	0.26	-0.35	0.00
Lord Howe Island	NSW	0.17	-0.10	-0.11
Middle Head Cobblers Bay	NSW		0.08	-0.07
Newcastle Pilot Station	NSW	0.12	0.00	-0.15
Norfolk Island	NSW	0.13	-0.03	0.00
Port Hacking	NSW	0.10	0.00	-0.17
Port Kembla	NSW	0.22	-0.11	-0.07
Port Macquarie	NSW	0.57	-0.35	0.23
Port Stephens	NSW	0.16	-0.05	-0.16
Tweed Heads Regional	NSW	-0.05	0.14	-0.22
Yamba	NSW	0.07	-0.15	-0.08
Darwin	NT	0.03	0.03	-0.46
Groote Eylandt	NT	0.12	-0.16	-0.69
Auckland Point, Gladstone	QLD	0.39	-0.52	-0.06
Booby Island	QLD	0.31	0.09	-0.23
Bowen Storm Tide	QLD	0.25	-0.25	-0.21
Brisbane Bar	QLD	-0.04	-0.06	-0.18
Bundaberg (Burnett Heads)	QLD	0.52	-0.50	-0.01
Cairns Storm Tide	QLD	0.31	-0.18	-0.26
Caloundra Headland	QLD	-0.03	0.05	-0.21
Cape Ferguson	QLD	0.46	-0.08	-0.10
Cardwell	QLD	-2.01	2.26	-2.02
Cooktown	QLD	0.19	0.07	-0.18
Goods Island	QLD	0.53	-0.23	-0.16
Half Tide Tug Harbour (HAY PT)	QLD	2.53	-2.15	1.45
Ince Point	QLD	0.84	-0.59	-0.10
Karumba Bar	QLD	0.47	0.00	-1.46
Lucinda Storm Tide	QLD	-0.03	0.02	-0.59
Mackay Outer Harbour	QLD	-0.06	0.00	-0.40
Marine Operations Base Southport	QLD	0.55	-0.37	0.16
Mooloolaba	QLD	0.83	-0.55	0.42
Mornington Island	QLD	1.04	-0.90	-0.52
Mourilyan Storm Tide	QLD	-0.52	0.68	-0.87
Nardana Patches	QLD	0.24	-0.05	-0.67
Port Alma	QLD	0.31	-0.59	-0.05
Port Douglas	QLD	0.27	-0.18	-0.19
Port Office Brisbane River	QLD	0.97	-0.91	0.49
Rosslyn Bay	QLD	2.00	-1.72	1.32
Shute Harbour Storm Tide	QLD	0.01	0.10	-0.30
Townsville Storm Tide	QLD	0.06	-0.13	-0.51
Turtle Head	QLD	1.00	-0.83	-0.06
Urangan Storm Tide	QLD	0.09	-0.27	-0.17
Weipa Storm Tide	QLD	0.33	-0.74	-0.31
Ardrossan	SA	0.04	-0.07	-0.14
Cape Jervis	SA	0.37	-0.29	0.00

Middle Bank South	SA	0.13	-0.29	-0.48
Port Adelaide Outer Harbour	SA	0.12	-0.03	0.04
Port Bonython	SA	0.87	-0.60	0.34
Port Giles	SA	-0.04	-0.01	-0.12
Port Lincoln	SA	0.00	0.00	-0.28
Port Pirie	SA	0.10	-0.09	-0.16
Port Stanvac	SA	0.05	-0.15	-0.04
Thevenard	SA	0.10	0.08	-0.21
Victor Harbour	SA	0.28	-0.08	-0.10
Wallaroo	SA	0.09	-0.15	-0.45
Whyalla	SA	-0.02	-0.28	-0.28
Burnie	TAS	-0.02	-0.05	-0.08
Devonport	TAS	0.00	0.06	0.04
Hobart	TAS	0.12	-0.08	-0.22
Low Head	TAS	0.23	-0.23	0.09
Spring Bay	TAS	0.13	0.06	-0.15
Corio Bay No 1. Pt Richards Channel	VIC		0.94	-0.79
Corner Inlet, Port Franklin	VIC		-0.48	0.06
Corner Inlet, Port Welshpool	VIC	0.05	-0.17	-0.14
Geelong Shell Refinery (GL)	VIC	-0.04	-0.03	-0.04
Lorne Jetty	VIC	0.26	-0.60	0.11
Portland	VIC	0.21	-0.13	-0.11
Pt Lonsdale Jetty	VIC	0.01	0.07	-0.01
Queenscliff Pilots Jetty	VIC		0.37	-0.26
Sth Channel, Hovell Pile	VIC		0.89	-0.83
Stony Point	VIC	0.01	-0.13	-0.17
West Channel Pile	VIC		0.99	-0.83
Western Port, Flinders Jetty	VIC		-0.05	-0.10
Williamstown, Breakwater Pier	VIC	-0.13	-0.07	-0.19
Albany (Albany Port Authority)	WA	0.23	-0.17	-0.20
Bremer Bay	WA	0.22	-0.05	-0.19
Broome	WA	0.09	-0.30	-0.01
Bunbury	WA	0.04	-0.10	-0.27
Busselton	WA	0.12	-0.21	-0.29
Cape Lambert (Robe River Mining)	WA	0.13	-0.46	0.02
Carnarvon	WA	0.19	-0.13	-0.12
Cocos Island	WA	0.31	-0.28	0.04
Dampier, King Bay (Hammersley Iron, Woodside)	WA	0.07	-0.22	-0.11
Derby	WA	0.43	-0.20	0.28
Esperance	WA	0.16	-0.12	-0.24
Exmouth	WA	0.22	-0.16	-0.11
Fremantle	WA	-0.78	0.65	-0.08
Geraldton (Geraldton Port Authority)	WA	0.06	-0.07	-0.26
Hillarys	WA	0.09	-0.27	-0.18
Jurien	WA	0.13	-0.13	-0.20
Lancelin	WA	0.21	-0.08	-0.20
Mandurah	WA	0.05	0.07	-0.25
Onslow – Beadon Creek	WA	0.31	-0.36	-0.06
Peel Inlet Dawesville	WA	0.00	0.15	-0.28
Port Hedland (Port Hedland Port Authority)	WA	0.09	-0.14	0.06
Two Rocks Marina	WA	-0.01	-0.33	0.27
Wyndham	WA	0.45	-0.15	0.20
	Mean	0.21	-0.13	-0.15
	Std Dev	0.46	0.46	0.39
	Study Area Mean	0.22	-0.15	-0.02
	Study Area Std Dev	0.32	0.22	0.21

Appendix J – Process to Develop the Demonstration Tool and Extend it to Additional Areas

OBTAIN THE REQUIRED DATA

1. Tide gauge data including horizontal coordinates, (GRS80) ellipsoidal and MSL heights with the datum they are relative to (most likely LAT), and metadata if available. This data may be obtained through the AHS collation project and/or individual gauge operators.
2. A satellite altimetry derived MSS and error surface e.g. DTU10MSS & DTU10ERR from DTU DNSC (http://www.space.dtu.dk/English/Research/Scientific_data_and_models/Global_Mean_sea_surface.aspx) or as part of the GUT apriori data package (part of step 10)
3. AUSGeoid09 from GA (http://www.ga.gov.au/geodesy/ausgeoid/nvalcomp.jsp)
4. Australian coastline data GEODATA COAST 1000K 2004 from GA (https://www.ga.gov.au/products/servlet/controller?event=FILE_SELECTION&catno=61395)
5. The Australian Bathymetry and Topography Grid 2009 AU$99 from GA (http://www.ga.gov.au/oracle/agsocat/geocat_brief.php?catno=67703)
6. Optional - EGM2008 WGS84 version GIS Data from NG-IA (http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/)

OBTAIN THE REQUIRED TOOLS

7. A copy of the "Vertical Datum Transformation Demonstration Tool" python script and "Vertical Datum Tools" toolbox
8. ArcGIS with 3D Analyst and Spatial Analyst extensions, Multidimension Tools, and Python.
9. The LAStools; LASmerge, LASboundary, and LASclip from Martin Isenburg (http://www.cs.unc.edu/~isenburg/lastools/)
10. The GOCE User Toolbox (GUT) from ESA (https://earth.esa.int/web/guest/software-tools/gut/about-gut/overview)
11. A copy of the GEMS tide model or a tide model relevant to the area of interest

CREATE BOUNDARIES

12. Study area
    a. Add the coastline and Bathymetry and Topography Grid data to ArcGIS
    b. Offset the coastline 20km inland to define the inland extent
    c. Select the 2000m bathymetric contour as the offshore extent
    d. Create a study area polygon from these extents and the limits of the tide gauge data in the appropriate GDA94 MGA Zone
13. Tide gauge mask
    a. Offset the coastline 5km (to ensure the actual 4km area is populated) seaward to define the offshore extent
    b. Create a tide gauge mask polygon using the coastline, the 5km offshore extent, and the limits of the tide gauge data in the appropriate GDA94 MGA Zone
14. MSS zone
    a. Offset the coastline 22km seaward to define the coastal extent

b. Create a MSS polygon from the 22km coastal extent, the 2000m bathymetric contour, and the limits of the tide gauge data in the appropriate GDA94 MGA Zone

15. Interpolation zone
    a. Offset the coastline 4km seaward to define the coastal extent
    b. Create an interpolation polygon from the 4km coastal extent, the 22km seaward extent (step 14.a), and the limits of the tide gauge data in the appropriate GDA94 MGA Zone

CREATE THE ESRI GRID TIDE GAUGE ENHANCED SATELLITE ALTIMETRY DERIVED ELLIPSOIDAL MSS

PREPARE THE TIDE GAUGE DATA

16. Import the tide gauge data into ArcGIS and create points.
17. Establish a common horizontal datum - project the points to the appropriate GDA94 MGA Zone.
18. Establish a common vertical datum - convert MSL heights so they are relative to the GRS80 ellipsoid e.g. $MSL_{Ellipsoid} = MSL_{LAT} + LAT_{Ellipsoid}$
19. Establish a common epoch - use the current NTDE for Australia which is 1992-2011 and which tide gauge data should be relative to.
20. Establish a common permanent tide system – use the tide-free system, assume the data is tide-free if ellipsoid heights were collected with GNSS

PREPARE THE SATELLITE ALTIMETRY DERIVED MSS

21. Establish a common vertical datum - convert the MSS so it is relative to the GRS80 ellipsoid using one of three methods;
    a. Basic - Determine the average vertical difference between the two ellipsoids by averaging the difference between the two equatorial radii and two polar radii, and then simply add/subtract the average value as a constant from the MSS.
    b. Close Approximation - The change in elevation between ellipsoids for a particular latitude can be approximated using an empirically-derived formula
    e.g. *delta_h = h2 - h1 = - ((a2 - a1) * cos(phi)^2 + (b2 - b1) * sin(phi)*
    where; *phi* is latitude
    h1 and *h2* are elevations for ellipsoids 1 and 2, respectively
    a1 and a2 are equatorial radii of ellipsoids 1 and 2, respectively
    b1 and b2 are polar radii of ellipsoids 1 and 2, respectively.
    c. Accurate – Use a software program such as GUT e.g. to convert from the Topex/Poseidon ellipsoid to GRS80 use the command line function
    "gut changeellipse_gf -InFile MSS_DTU_10_2M.nc -Ellipse GRS80 -OutFile MSSDTU10_GRS80.nc"
22. Establish a common epoch – if the epoch is the same or similar to the epoch of the tide gauge data (e.g. 1993-2009), consider them equal. Otherwise convert the epoch of the MSS to match that of the tide gauge data (no instructions available).
23. Establish a common permanent tide system – MSS are usually provided relative to the mean-tide system so convert to the tide-free system use the GUT software e.g. command line function
    "gut changetide_gf -InFile MSSDTU10_GRS80.nc -OutFile MSSDTU10_GRS80_TF.nc -T tide-free"
24. Import the converted netCDF MSS and the MSS error data into ArcGIS using the Multidimensional Tools and save as ESRI GRID files.
25. Establish a common horizontal datum - project the MSS and MSS error rasters to the appropriate GDA94 MGA Zone

THE TIDE GAUGE DERIVED MSS

26. Use (thin plate) Spline (or IDW) interpolation to interpolate the ellipsoidal MSL values of the tide gauge data into a surface extending from the coastline to 4km offshore
    a. Regularized Spline with the default weighting and 2 as the number of points (depending on the configuration of your tide gauge data)
    b. Use the (5km) tide gauge mask to define the area of interpolation
    c. Use the same cell size as the satellite altimetry derived MSS
27. Convert the resulting surface to points

THE SATELLITE ALTIMETRY DERIVED MSS

28. Clip the ESRI GRID MSS to the MSS zone polygon and convert to points
29. Clip the ESRI GRID MSS to the Interpolation zone polygon and convert to points
30. Extract the ESRI GRID MSS error raster values into a field in the Interpolation zone MSS points (created in step 29)
31. Delete all points with an error value greater than 0.03m from the Interpolation zone MSS points (created in step 30)
32. You should have two shapefiles of MSS points
    a. One from 4km-22km offshore which only contains points with an error <=0.03m
    b. One from 22km offshore to the 2000m bathymetric contour with a point for every cell within this zone of the original raster

THE FINAL TIDE GAUGE ENHANCED SATELLITE ALTIMETRY DERIVED ELLIPSOIDAL MSS

33. Combine the interpolated tide gauge points and the two shapefiles of MSS points into a single point shapefile
34. Use Kriging (ordinary least squares collocation) interpolation (or another method) to interpolate/extrapolate the combined ellipsoidal MSL point shapefile (created in step 33) into an ESRI GRID surface covering the extent of the study area
    a. Ordinary Kriging with 6 as the number of points
    b. Use the study area polygon to define the area of interpolation/extrapolation
    c. Use the same cell size as the satellite altimetry derived MSS (or a smaller cell size e.g. 1minute)

<u>CREATE THE 3 ESRI GRID ELLIPSOIDAL TIDAL DATUM SURFACES</u>

35. Create a point grid in ArcGIS for the study area with 1 kilometre (or <1km) point spacing
36. Export the table and format in the required input format for GEMS (or other tide model)
37. Run the point grid file through GEMS (or other tide model) to find the MSL to LAT, MHWS and HAT offsets for every point in the grid file
38. Using (thin plate) Spline (or another) interpolation technique, interpolate 3 tidal surfaces from the tide model point results; MSL-LAT, MSL-MHWS, & MSL-HAT.
39. Individually add each of the three MSL-tidal surface to the enhanced ellipsoidal MSS (finalised in step 34), to produce three ESRI GRID ellipsoidal tidal datum separation surfaces; ellipsoid-LAT, ellipsoid-MHWS, and ellipsoid-HAT.

PREPARE AUSGEOID09

40. Add the AUSGeoid09 text file to ArcGIS and create points
41. Clip the points to the study area
42. Interpolate it into a 1minute ESRI GRID surface

OPTIONAL – MEAN DYNAMIC TOPOGRAPHY

43. Clip EGM2008 to the study area
44. Subtract EGM2008 from the enhanced ellipsoidal MSS (finalised in step 34)
45. Filter the resulting MDT to remove noise e.g. using a simple Gaussian or Hamming filter or a more complex filter (no instructions available)
46. Alternatively use/compare to the freely available DTU10 MDT

SETTING UP THE TOOL

47. Save the following together in the same directory folder location, named exactly as described, for access by the script. This is the 'Demonstration Tool Data Package Directory'.
    a. The four ESRI GRID separation surfaces created i.e. enhanced ellipsoidal MSS named "integmss", ellipsoid-LAT named "ell_lat", ellipsoid-MWHS named "ell_mhws", and ellipsoid-HAT named "ell_hat"
    b. The clipped AUSGeoid09 surface named "ausgeoid09"
    c. The polygon shapefile extent of your transformation surfaces named "StudyArea_bound.shp"
    d. The three LAStools (LASboundary, LASclip, and LASmerge)
48. Save the "Vertical Datum Transformation Demonstration Tool" python script and "Vertical Datum Tools" toolbox on a local drive. Ensure they are placed in a location with a simple directory name – if it is too long or contains too many spaces, the tool will fail. This is a limitation of ArcGIS. It is best GIS practise to keep directory names short and use underscores instead of spaces.
49. Load ArcMap and add the toolbox to ArcToolbox
50. Ensure the script file is correctly identified as part of the toolbox
51. The tool is now ready to be used for the study area developed.

USING THE TOOL

52. If input data is not already in the appropriate GDA94 MGA Zone, pre-transform data
53. Input data can be either LAS or Raster format
54. The tool can be run for one file at a time or in batch mode for multiple LAS files
55. The user must provide the tool with the following information
    a. The existing MGA Zone of the input file
    b. The existing vertical datum of the input file
    c. The desired output vertical datum
    d. The desired output directory location
    e. The directory of the Demonstration Tool Data Package (DTDP) (set in step 47)

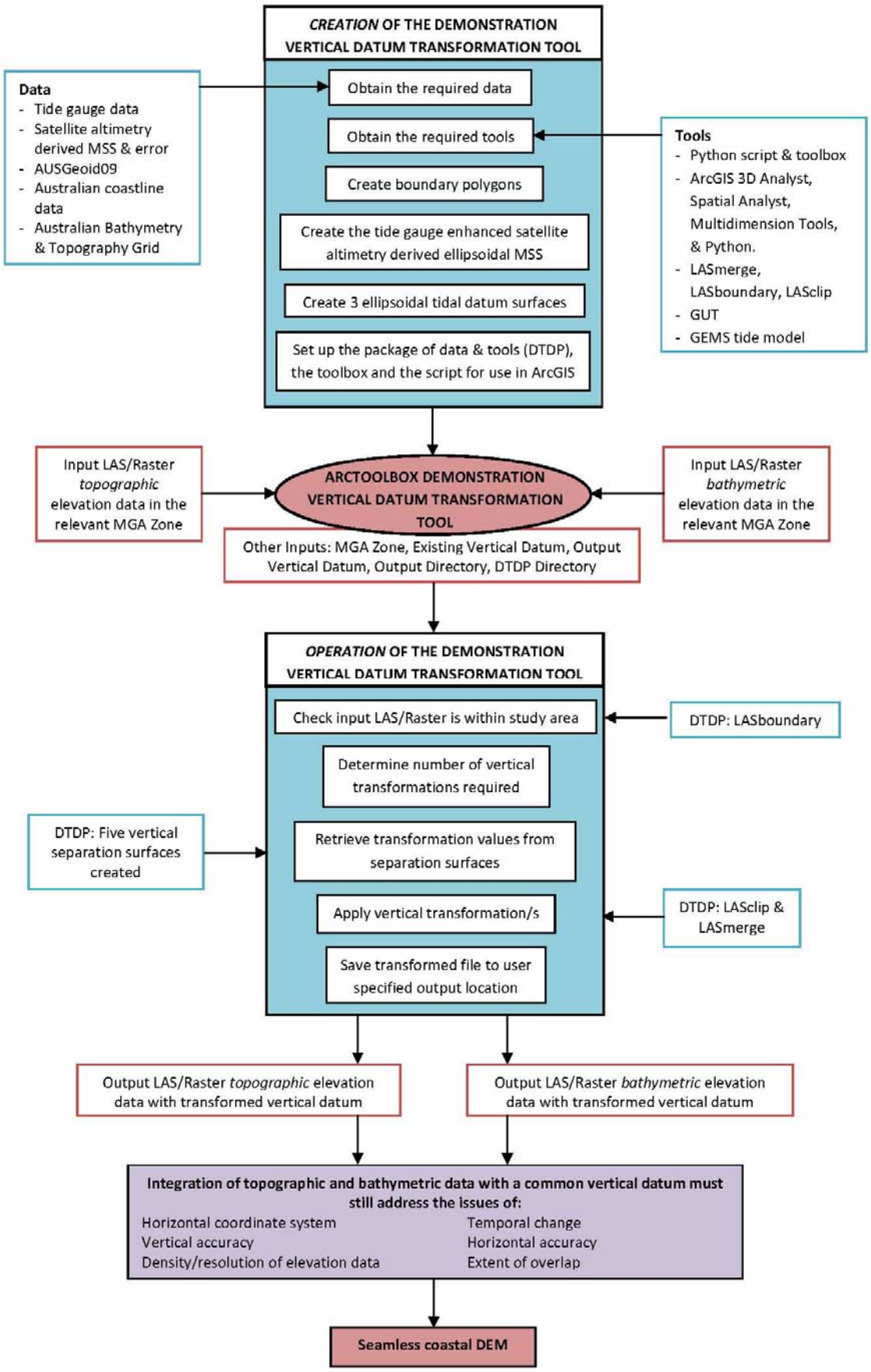


Figure 45. The demonstration vertical datum transformation process; from creation of the tool to the seamless integration of elevation data.