Australian Geospatial Reference System Compendium

Intergovernmental Committee on Surveying and Mapping
Geodesy Working Group

16 August 2022

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Document history

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Foreword

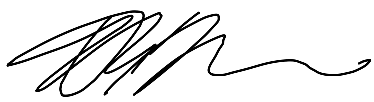
Welcome to the Australian Geospatial Reference System Compendium – your guide to the geodetic foundations for Australia.

In anticipation of the growing use and reliance on positioning technology, the Intergovernmental Committee on Surveying and Mapping Geodesy Working Group (ICSM GWG), has spent over 10 years upgrading elements of the Australian Geospatial Reference System (AGRS) to improve the accuracy with which spatial data can be aligned and combined with precise positioning data. The AGRS upgrade includes:

- Geocentric Datum of Australia 2020 (GDA2020): Australia's new static datum
- Australian Terrestrial Reference Frame 2014 (ATRF2014): Australia's first time-dependent coordinate reference frame, which moves with the Australian plate (~7 cm / yr).
- DynAdjust: World first software able to compute a continental scale least squares adjustment of all geodetic data (~2 million measurements) to define GDA2020 and ATRF2014.
- AUSGeoid2020: World first geoid model which provides location specific uncertainty; thus providing users with a rigorous method of deriving Australian Height Datum heights with uncertainty directly from GNSS.
- Commonwealth Law Changes: Worked with National Measurement Institute to update the Recognised Value Standard for Measurement of Position in Australia to legally recognise both static (GDA2020) and time-variable coordinate reference frames (ATRF2014).
- Australian Vertical Working Surface (AVWS): A new vertical datum enabling more accurate conversion of GNSS heights to mean sea level heights.
- GeodesyML: Development and release of the Geodesy Markup Language standard, which aims to make geodetic data more Findable, Accessible, Interoperable and Reusable (FAIR).

These upgrades to the AGRS are an outstanding example of how members of state, territory and Commonwealth governments have collaborated to resolve a challenging problem and deliver an authoritative foundation for improved decision making.

Craig Sandy
Chair of ICSM



Nicholas Brown
Chair of ICSM Geodesy Working Group

Acknowledgments

ICSM would like to acknowledge the following people, and organisations who played a significant role in the development, implementation and communication of the upgrade to the AGRS including:

- Members of the **Intergovernmental Committee on Surveying and Mapping Geodesy Working Group and Adjustment Working Group**. These groups are comprised of geodesy, positioning and survey measurement leaders, advisers and advocates from Australian and New Zealand governments (states, territories and Commonwealth) and universities. These teams of people led, project managed, tested, debated and implemented upgrades to the AGRS and over the past decade. I would like to especially thank:
    - **Mr Gary Johnston**, **Dr John Dawson** and **Mr Nicholas Brown** as Chairs of the Permanent Committee on Geodesy who were the visionaries of this work over the past decade.
    - **Dr Craig Harrison** for his role as Chair of the Adjustment Working Group.
- **Dr Roger Fraser** for his work on designing the method of computing a rigorous national adjustment from all available data and models, and for the development of the DynAdjust software which enables Australia to routinely undertake this adjustment in a completely automated way.
- **Dr Jack McCubbine, Prof Will Featherstone** and **Mr Nicholas Brown** for the creation of the Australian Gravimetric Quasigeoid model, AUSGeoid2020 model and development of the Australian Vertical Working Surface.
- Members of the **Intergovernmental Committee on Surveying and Mapping GDA2020 Modernisation Implementation Working Group** for their work consulting with users and building the tools and technical resources needed to assist with the transition from GDA94 to GDA2020. In particular:
    - **Mr Scott Strong** for his work on the development of mandate documents, project plans and business cases.
    - **Mr Joel Haasdyk**, **Mr Michael Giudici** and **Mr Nicholas Brown** for consulting with the standards communities and software development organisations.
- **Dr John Dawson, Dr Michael Moore and Dr Guorong Hu** for the creation of the Australian Plate Motion Model and updating the recognised value standard of measurement of position.
- Members of **ANZLIC – the Spatial Information Council** and **Intergovernmental Committee on Surveying and Mapping** who are representatives from all the Australian states, territories, the Commonwealth and New Zealand. These members are responsible for government surveying and mapping functions in their jurisdiction. They provided oversight and valuable advice throughout the upgrade process. Members of these committees also helped ensure the upgrades were coordinated and promoted across the owners of key national spatial data including geodetic, topographic, cadastral, street addressing, tides and sea level, and geographical names.
- **Mr Simon Fuller**, **Mr Alex Woods**, **Dr Irek Baran**, **Dr Phil Collier** and **Mr Nicholas Brown** for their work on the development of GDA94 to GDA2020 transformation grids.

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- **Dr Roger Fraser**, **Mr Nicholas Brown, Mr Steve Tarbit**, **Dr Nic Donnelly**, **Mr Joel Haasdyk** and **Mr Lazar Bodor** for their work on the development of GeodesyML.
- **Mr Alistair Deane, Dr Anna Riddell** and **Dr Phil Collier** for reviewing the document and providing thoughtful and useful feedback.

Contents

Terms and definitions

Symbol	Definition	Equation / Comment
a	Ellipsoid semi-major axis	
b	Ellipsoid semi-minor axis	$b = a(1 - f)$
f	Flattening of the reference ellipsoid.	$f = \frac{a - b}{a}$
$1/f$	Inverse flattening or reciprocal flattening.	$1/f$
n	Third flattening	$\frac{a - b}{a + b}$
ε	First eccentricity of the reference ellipsoid.	$\sqrt{\frac{a^2 - b^2}{a^2}}$
ε'	Second eccentricity of the reference ellipsoid.	$\sqrt{\frac{a^2 - b^2}{b^2}}$
ρ	The radius of curvature at a point on an ellipsoid with respect to the meridian through that point.	
ν	The radius of curvature at a point on an ellipsoid with respect to the prime vertical through that point.	
ϕ	Geodetic latitude; this is negative south of the equator. The angle that the *normal* to the ellipsoid at a point makes with the equatorial plane of the ellipsoid. A geodetic latitude differs from the corresponding astronomic latitude by the amount of the meridional component of the local deflection of the vertical.	
λ	Geodetic longitude; positive measured eastwards from the prime meridian. The angle between the plane of the local geodetic meridian and the prime meridian. A geodetic longitude differs from the corresponding astronomic longitude by the amount of the prime vertical component of the local deflection of the vertical.	
λ_0	Geodetic longitude of the central meridian of the UTM zone.	
ω	Geodetic longitude difference measured from the central meridian; positive measured eastwards.	$\lambda - \lambda_0$
α	Azimuth; the horizontal angle measured from the meridian measured clockwise from true north.	
s	Ellipsoidal distance; the distance on the ellipsoid. Spheroidal distance is the same as an ellipsoidal distance.	
E'	Easting; positive measured eastwards from a central meridian.	

E	Easting measured from the false origin.	E' + 500,000 metres for MGA2020
N'	Northing; negative measured southwards from the equator.	
N	Northing measured from the false origin.	N'+ 10,000,000 metres in the southern hemisphere for MGA2020
γ	Grid convergence; the angular quantity to be added algebraically to an azimuth to obtain a grid bearing. In the southern hemisphere, grid convergence is positive for points east of the central meridian (grid north is west of true north) and negative for points west of the central meridian (grid north is east of true north).	$\beta = \alpha + \gamma$
β	Grid bearing; the angle between grid north and the tangent to the arc at the point. It is measured from grid north clockwise through 360°.	
δ	Arc-to-chord correction; the angular quantity to be added algebraically to a grid bearing to obtain a plane bearing.	$\theta = \beta + \delta$ $= \alpha + \gamma + \delta$
θ	Plane bearing; the angle measured clockwise through 360°, between grid north and the straight line on the grid between the ends of the arc formed by the projection of the ellipsoidal distance.	
L	Plane distance is the straight-line distance on the grid between the ends of the arc of the projected ellipsoidal distance. The difference in length between the plane distance (L) and the grid distance (S) is nearly always negligible. Using plane bearings and plane distances, the formulae of plane trigonometry hold rigorously.	$L = Ks$ $\tan\theta = \frac{\Delta E}{\Delta N}$ $\Delta E = L\sin\theta$ $\Delta N = L\cos\theta$
k_0	Central scale factor; the scale factor on the central meridian.	0.9996 for MGA2020 and UTM
k	Point scale factor; the ratio of an infinitesimal distance at a point on the grid to the corresponding distance on the ellipsoid.	$k = \frac{dL}{dS} = \frac{dS}{ds}$
K	Line scale factor; the ratio of a plane distance L to the corresponding ellipsoidal distance s. The point scale factor will in general vary from point to point along a line on the grid.	$K = \frac{L}{s} \approx \frac{S}{s}$
h	Ellipsoidal height; the distance of a point measured along the normal from the ellipsoid. Spheroidal height is the same as an ellipsoidal height.	
H	Orthometric height; the height of a point above the geoid measured along the plumbline.	
H_{AHD}	Height of a point above AHD.	
N	Ellipsoid to quasigeoid separation.	
ζ_{AHD}	Ellipsoid to AHD separation.	
X, Y, Z	A three dimensional coordinate system (Cartesian) which has its origin at (or near) the centre of the Earth.	
$\Delta\alpha$	Meridian convergence at a point is the difference between grid north and true north along the meridian of the point. On an ellipsoid, it is the change in the azimuth of a geodesic between two points.	Reverse Azimuth = Forward Azimuth + Meridian Convergence ± 180°

$\Delta\beta$	Line curvature; the change in grid bearing between two points on the arc.	Reverse grid bearing = Forward grid bearing + Line curvature ± 180°
m	Meridian distance is the geodesic distance from the equator along the meridian, negative southwards.	
G	Mean length of an arc of one degree of the meridian.	
σ	Meridian distance expressed as units G.	$\sigma = m/G$
S	Grid distance; the length measured on the grid, along the arc of the projected ellipsoid distance.	
R	Geometric mean radius of curvature.	$\sqrt{\boldsymbol{\rho\nu}}$
R_α	Radius of curvature at a point in a given azimuth.	
r^2	Mean radius of curvature.	$R^2{k_0}^2 = \rho\nu{k_0}^2$
${r_m}^2$	r^2 at the mean latitude ϕ_m.	$\rho\nu{k_0}^2$ at ϕ_m
ψ	Ratio of the ellipsoidal radii of curvature.	ν/ρ
A	Rectifying radius	
ϕ_m	Mean latitude	$\frac{(\phi_1 + \phi_2)}{2}$
ϕ'	Foot point latitude; the latitude for which the meridian distance $m = N'/\,k_0$.	
u	Parametric latitude	
U	Reduced latitude	

Part A: Introduction

1. Australian Geospatial Reference System

Knowing where you are, where things are around you and being able to navigate between them has always been important. Explorers navigated the seas in search of far away lands and created detailed maps of the Earth using the sun and clocks to compute their position. Surveyors trekked through unchartered regions carrying heavy equipment to measure the highest peaks relative to sea level. Engineers met in the middle with incredible accuracy after tunnelling through mountains, underground or underwater.

In Australia, accurate and reliable positioning and navigation is enabled by the Australian Geospatial Reference System (AGRS; Figure 2). The AGRS is the collection of:

- *datums* (e.g. Geocentric Datum of Australia 2020), *reference frames* (e.g. Australian Terrestrial Reference Frame 2014) and *working surfaces* (e.g. Australian Vertical Working Surface);
- *models* (e.g AUSGeoid2020), tools and services; and
- *standards* (e.g. GeodesyML),

which are applied to:

- define latitude, longitude, height, orientation and gravity;
- model dynamic, geophysical processes that affect spatial measurements;
- transform and convert data; and
- ensure positioning information is Findable, Accessible, Interoperable and Reusable.

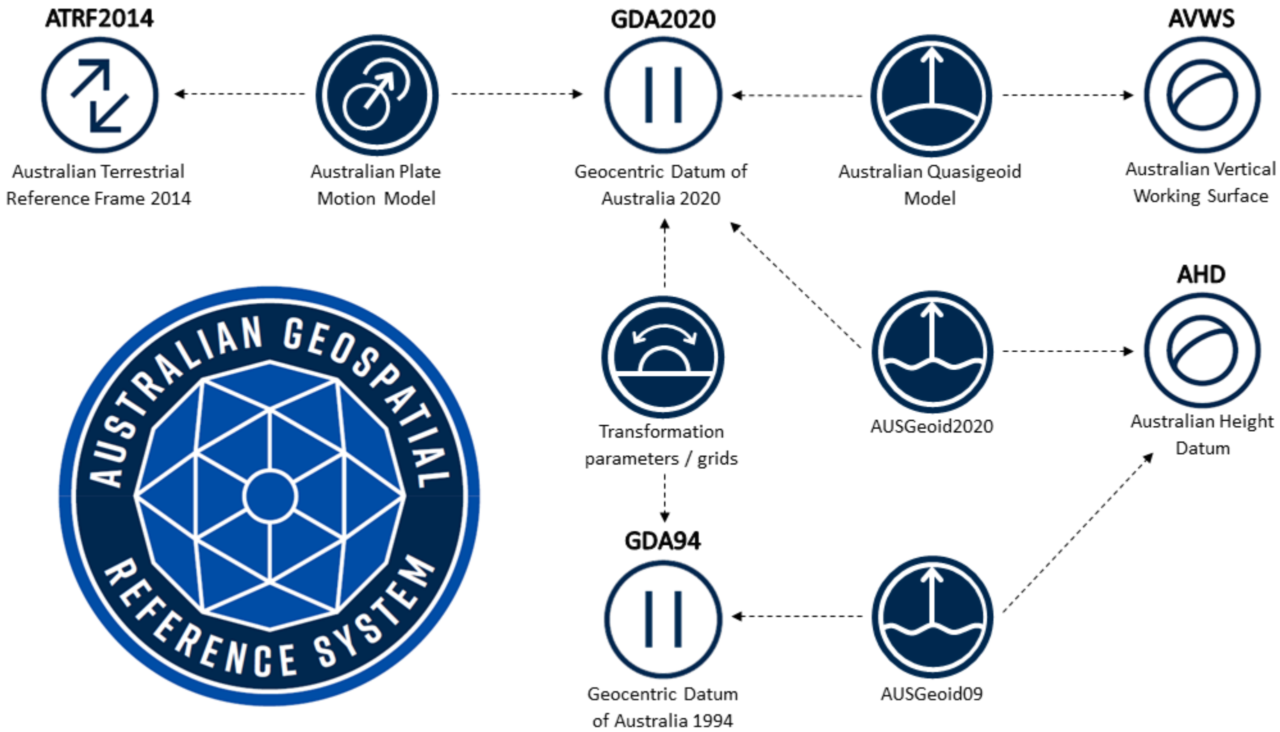

Figure 1: The datums, reference frame, models and tools of the Australian Geospatial Reference System required for accurate and reliable four dimensional positioning.

The recent draft of the United Nations Global Geospatial Information Management (UN-GGIM) Integrated Geospatial Information Framework (IGIF)[1], explores the need for expertise and excellence across three layers: *governance*, *technology* and *people* (Figure 3) in order to maximise the benefits of geospatial data.

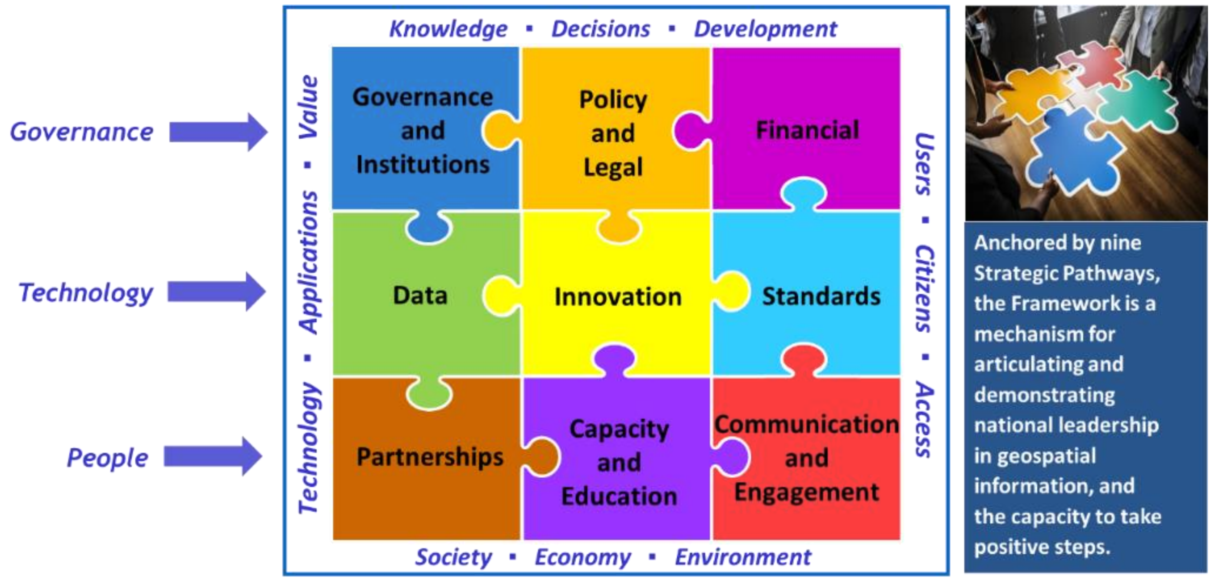

Figure 2: United Nations Integrated Geospatial Information Framework.

In recognition of this, it is important to note the following elements, which support AGRS and its users:

- *infrastructure*, including a national network of Global Navigation Satellite System Continuously Operating Reference Stations (GNSS CORS) and survey marks to provide an authoritative and accurate network in support of positioning applications;
- *standards* to ensure positioning information is Findable, Accessible, Interoperable and Reusable (e.g. ISO / OGC / GeodesyML);
- *analysis capability* provided by Geoscience Australia, state and territory land survey departments and through partners in Cooperative Research Centres; and
- *governance, consultation and communication* led by ANZLIC – the Spatial Information Council, Intergovernmental Committee on Surveying and Mapping (ICSM) and the ICSM Geodesy Working Group (GWG).
- *the people* within ANZLIC, ICSM, working groups, Geoscience Australia, state and territory land and survey departments, Cooperative Research Centres, universities and colleagues from international institutions.

1.1 Motivation for upgrading the AGRS

A country's geodesy capability and capacity underpins their ability to collect and manage nationally integrated geospatial information, and make evidence-based decisions and policies. In addition to the traditional survey, mapping and navigation fields, geodesy is relied upon for earth and climate science, economic development and sustainability, public safety and disaster management, land and water administration, and environmental management.

1 https://ggim.un.org/IGIF/

Recognising the importance of geodesy to an ever-increasing location-based society, the United Nations General Assembly adopted resolution 69/266[2] in February 2015, entitled 'A Global Geodetic Reference Frame for Sustainable Development'. Subsequently, the Committee of Experts on Global Geospatial Information Management (UN-GGIM) have established a process aimed at sustaining and enhancing the geodetic skills, geospatial reference systems and geospatial standards by delivering improvement in five focus areas[3]:

- Governance
- Geodetic Infrastructure
- Policies, Standards and Conventions
- Education, Training and Capacity Building
- Communication and Outreach.

In 2018, the Australian Commonwealth Government also demonstrated its awareness of the importance of geodesy, committing to the Positioning Australia program. The program will provide 10 cm (or better) accurate and reliable positioning to all Australians and accelerate the adoption and development of positioning technology and applications. This is a significant improvement from the 5–10 m accuracy that can currently be achieved using consumer positioning devices.

This funding commitment is an acknowledgement that geodesy is no longer an esoteric science. By 2023, location-based services (e.g. augmented reality and emergency services) and intelligent transport services (road, rail, maritime, and aviation) are expected to account for 93.5% of Global Navigation Satellite System (GNSS) chipset sales[4] (Figure 3). Furthermore, the Australian economy is estimated to grow by an additional AUD$73 billion by 2030, due to augmented positioning[5].

[2] https://ggim.un.org/documents/A_RES_69_266_E.pdf

[3] https://ggim.un.org/meetings/GGIM-committee/10th-Session/documents/DRAFT-Position-Paper-on-Sustaining-the-GGRF-20200806.pdf

[4] European GNSS Agency [Internet], GNSS market Report Issue 4, 2015, [cited 2020 July 1]. Available from: https://www.gsa.europa.eu/system/files/reports/GNSS-Market-Report-2015-issue4_0.pdf.

[5] Allen Consulting Group [Internet] Economic benefits of high resolution positioning services, 2008, [cited 2020 July 1]. Available from: https://www.crcsi.com.au/assets/Resources/ffa927a7-55d1-400a-b7d6-9234f4fe4ad2.pdf.

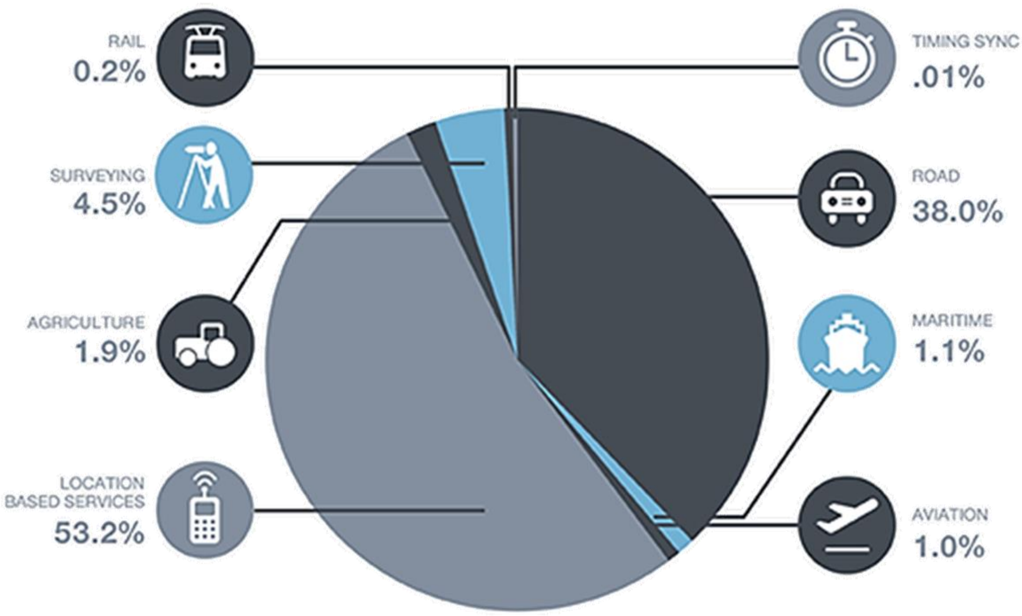

Figure 3: The expected GNSS chipset sales 2013-2023. Figure adapted from 2015 European GNSS Agency Market Report[6].

1.2 Positioning Australia

The Positioning Australia program is working to ensure that accurate positioning information is widely available to the Australian community. This is being delivered through two complementary projects: a national network of ground station infrastructure and GNSS analysis software (see below), and a system to deliver corrected positioning signals directly to Australians through a Satellite-Based Augmentation System (SBAS).

1.2.1 Satellite-Based Augmentation System

An SBAS overcomes current gaps in mobile and radio communications and, when combined with our national infrastructure network, ensures that accurate positioning information can be received. The SBAS augments and corrects GNSS signals to improve the accuracy of positioning data and makes it available across Australia and its maritime zones without the need for mobile phone or Internet coverage.

In February 2020, Australia and New Zealand entered into a partnership to jointly deliver the SBAS component of the program. This will be the first such system in the Southern Hemisphere, and will be called the Southern Positioning Augmentation Network (SouthPAN).

Current technology typically allows for positioning within 5–10 m accuracy; through this program, however, the accuracy will be improved to within 3 cm in areas with mobile phone coverage and to within 10 cm everywhere else. This will deliver accurate, reliable, and instantaneous positioning across Australia and its maritime zones (Figure 4). Together, these projects will provide more reliable positioning information, allowing for innovation and efficiency across a range of industries such as agriculture, transport, emergency management, mining, engineering, and logistics.

6 https://www.gsa.europa.eu/2015-gnss-market-report

Australian Government
Geoscience Australia

POSITIONING AUSTRALIA

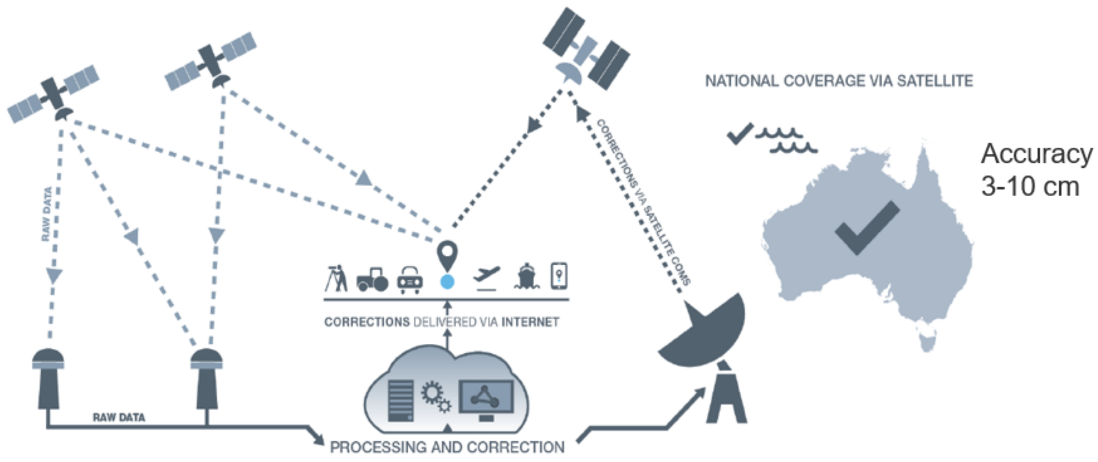

Figure 4: Users will be able to receive accurate and reliable positioning information from ground-based and satellite-based platforms.

1.2.2 Densification of GNSS infrastructure

To ensure that Geoscience Australia is able to provide high-quality positioning corrections across the continent, AUD$64 million (USD$46 million) is dedicated to upgrading and expanding Australia's ground network of GNSS infrastructure. A network of approximately 200 government-operated multi-GNSS ground stations will be densified with over 500 third-party ground stations to generate open-access, centimeter-accurate positioning corrections available over mobile Internet (when in a coverage area). Geoscience Australia will also establish a GNSS data center to monitor the GNSS network and to archive and distribute data and services to users from a variety of sectors, including system integrators and innovators. The network upgrade will be completed by June 2023.

1.2.3 Development of open-source real-time positioning software and products

To encourage the uptake and innovation of Positioning Australia's accurate and reliable positioning, navigation, and timing services, Geoscience Australia has developed multi-GNSS analysis software – known as Ginan[7] – that is capable of managing the acquisition, processing, and delivery of multi-GNSS data and related products.

This capability will comprise the following components:

- A network platform that accepts carrier, code, and ranging data to enable the computation of high-accuracy orbits, clocks, satellite phase biases, and atmospheric models, as well as station coordinates;
- A user platform that accepts high-accuracy orbits, clocks, satellite phase biases, and atmospheric models in addition to carrier and code data to enable single-receiver users to compute high-accuracy positions;

7 https://github.com/GeoscienceAustralia/ginan

- A combination platform that accepts parameter estimates and their variance-covariance information to enable the combination of geodetic solutions including combining station coordinates into multi-day solutions, combining station coordinates into multi-year solutions with the estimation of station velocities, and performing time series analysis.

1.2.4 Upgrade elements of the AGRS

In anticipation of the growing use and reliance on precise positioning technology, over the last decade, the ICSM GWG planned, developed and implemented a range of upgrades to AGRS including:

- Changing Australia's static datum from the Geocentric Datum of Australia 1994 to the Geocentric Datum of Australia 2020.
- Introducing the Australian Terrestrial Reference Frame 2014 – a nationally densified version of the International Terrestrial Reference Frame 2014.
- Changing the National Measurement (Recognized-Value Standard of Measurement of Position) Determination to recognise both GDA2020 and ATRF2014 as Australia's reference frames.
- Creating an Australian Plate Motion Model to propagate:
  - horizontal ATRF2014 coordinates back and forth through time.
  - GDA2020 coordinates from the epoch 1 January 2020, to another epoch where they are recognised as ATRF2014@epoch.
- Introducing the Australian Gravimetric Quasigeoid 2020 model which approximates mean sea level across the Australian region which can be used to measure precise surface elevations.
- Introducing the Australian Vertical Working Surface; a more accurate height datum than the Australian Height Datum which is preferred for heighting applications which extend over distances greater than 10 km. The Australian Height Datum has been retained and shown to be fit for purpose for applications over distances less than 10 km.
- Development of new EPSG codes and updates to the ISO Geodetic Register.
- Development of conversion / transformations software, online applications, API's, technical manuals and fact sheets to assist users with the transition from the older elements of the AGRS – to the new.

2. Strategic Direction and Governance

Upgrading the AGRS was a program of work in which a number of projects contained within the program had interdependencies. As such, it was important the program had effective leadership to ensure good governance and provide a clear strategic direction. Leadership for the program was provided at multiple levels; including high level strategic direction and governance from ANZLIC – the Spatial Information Council and the Intergovernmental Committee on Surveying and Mapping (ICSM). Technical leadership was provided by the ICSM Geodesy Working Group (ICSM GWG), the ICSM GWG Adjustment Working Group, the ICSM GWG eGeodesy Working Group and ICSM GDA Modernisation Implementation Working Group.

2.1 ANZLIC and ICSM Strategic Plan

ANZLIC – The Spatial Information Council is the peak intergovernmental group of senior officials from Australia and New Zealand who provide leadership on spatial service delivery and information. The Intergovernmental Committee on Survey and Mapping (ICSM) is the implementation arm of ANZLIC with its members from government surveying and mapping agencies. ANZLIC and ICSM's vision is to lead the development and implementation of spatial capabilities and place-based intelligence to drive social, economic and environmental benefits across Australia and New Zealand. This includes major initiatives such as:

1. **Modernise ANZLIC's Foundation Spatial Data Framework (FSDF)** – Modernise spatial information to increase its accuracy and reliability and adopt 3D and 4D formats (where applicable) to meet emerging user needs.
2. **Digital Twins and Smart Cities** – Support the development of standards based digital twins in accordance with the Principles for Spatially Enabled Digital Twins of the Built and Natural Environment in Australia.
3. **Improved spatial data delivery** – Explore improved, more efficient approaches to deliver spatial information and data across jurisdictions.
4. **Coordinated earth observation data acquisition** – Review existing earth observation acquisition approaches and identify opportunities to reduce costs, collaborate on procurement, achieve whole-of-economy licencing, and leverage new capabilities.
5. **Space and spatial integration** – Support downstream application of new space and satellite capabilities and data sources to maximise value to information supply chains, particularly for earth observation and positioning.

ANZLIC and ICSM recognise the success of these initiatives is based on having an accurate, reliable and accessible AGRS. For this reason, in 2015, ANZLIC endorsed the ICSM GWG plan to upgrade Australia's static datum (GDA2020) and introduce a time dependent reference frame (ATRF2014). Furthermore, since that time, they have resolved to support the implementation of the Australian Vertical Working Surface and eGeodesy work being done to improve how Findable, Accessible, Interoperable and Reusable geodetic data is.

2.2 ICSM Geodesy Working Group

The ICSM GWG is a group of geodesy, positioning and survey measurement leaders, advisers and advocates from Australian and New Zealand governments (states, territories and Commonwealth) and universities. The working group provides leadership through coordination and cooperation on the Geospatial Reference Systems of Australia and New Zealand.

The strategic objectives of the ICSM GWG are:

- Ensure geospatial reference frames meet the needs of current and emerging users
  - Lead the development, maintenance and continuous improvement of Australian and New Zealand geospatial reference frames.
  - Coordinate, develop and maintain world-class geodetic infrastructure.
- Make our products and services Findable, Accessible, Interoperable and Reusable (FAIR)
  - Coordinate the development of open source, freely available geodetic standards, software, products, and services aligned with international standards.
- Recognised as a provider of expert knowledge and advice on geodesy and positioning
  - Increase outreach and communications activities to demonstrate strong leadership in the field of geodesy.
  - Assist in efforts to monitor and measure climate change, crustal deformation and the land-sea interface by improving infrastructure, analysis and advice.

Members of this working group and sub groups within the GWG (e.g. Adjustment Working Group, eGeodesy Working Group) provided a great deal of the leadership to identify and articulate future user requirements, align the upgrades with international best practice and test those assumptions with stakeholders.

In particular, members of the ICSM GWG in collaboration with partners have:

- In 2010, undertook an assessment of the Geocentric Datum of Australia 1994 (GDA94) which concluded that eventually the datum would be unable to meet the requirements of all Australian spatial stakeholders because it was out of alignment with Global Navigation Satellite System (GNSS) derived International Terrestrial Reference Frame (ITRF) locations in real-time and ultimately this would require implementation of a national time dependent reference frame.

- In 2011, the GWG developed the first version of its Datum Roadmap which proposed a two stage process to implement a new national datum. The first stage involved the development of a national least squares adjustment of all geodetic data to develop a static datum with an epoch 2020. By 2020 it was anticipated that the necessary tools and resources would be available to enable the adoption of a time dependent Australian reference frame.

- Between 2012 and 2014, GWG and researchers in the Cooperative Research Centre for Spatial Information (CRCSI) worked on the technical components of the first version Datum Modernisation Roadmap. During this period both parties also promoted the key elements of the Roadmap in Australian jurisdictions in a variety of workshops and forums.

- In 2013, ICSM requested that at an appropriate time, the GWG, in conjunction with CRCSI participants, develop an implementation proposal for the next generation Australian Datum for formal endorsement by ICSM and ANZLIC.

- To inform the development of the proposal, CRCSI participants undertook an analysis of user requirements of the next Australian datum, engaging with spatial sector users before preparing two papers relating to user requirements (Haasdyk, et al., 2014; Donnelly, et al., 2014).
- PCG met in Canberra in February 2015 to consider the Roadmap, review current progress of the technical implementation tasks and discuss stakeholder requirements for modernising Australia's geocentric datum[8], agreed to a revised Roadmap proposal for ICSM and ANZLIC endorsement.
- In 2017, Geoscience Australia staff worked with the National Measurement Institute to changing the National Measurement (Recognized-Value Standard of Measurement of Position) Determination to recognise both GDA2020 and ATRF2014 as Australia's reference frames[9].
- Between 2010 and 2017, developed and implemented a beta version of GeodesyML[10]
- In 2018, completed the development, and released AUSGeoid2020 (Brown, et al., 2018a; Brown, et al., 2018b).
- In 2019:
    - released an Australian Plate Motion Model to propagate horizontal ATRF2014 coordinates back and forth through time (see Chapter 7.2);
    - developed and released the GDA2020 Technical Manual[11] and ATRF2014 Technical Implementation Plan[12] to provide background information explaining the need for new datums and assist users with the transition from GDA94;
    - released the Australian Gravimetric Quasigeoid model (Featherstone, et al., 2018) which approximates mean sea level across the Australian region which can be used to measure precise surface elevations;
    - introduced the Australian Vertical Working Surface; a more accurate height datum than the Australian Height Datum which is preferred for heighting applications which extend over distances greater than 10 km.
    - developed and released the AVWS Technical Implementation Plan[13] to provide background information explaining the need for new datums and assist users with the transition from GDA94;
    - developed and implemented a range of new EPSG codes and updates to the ISO Geodetic Register.
    - developed conversion / transformations software, online applications, API's, technical manuals and fact sheets to assist users with the transition from the older elements of the AGRS – to the new.
- In 2020, formally announced the release of ATRF2014 as Australia's first time-dependent reference frame.

8 https://www.icsm.gov.au/sites/default/files/2017-03/Stakeholder-Requirements-for-Modernising-Australias-Geocentric-Datum.pdf

9 https://www.legislation.gov.au/Details/F2017L01352

10 http://geodesyml.org/

11 https://www.icsm.gov.au/gda2020-and-gda94-technical-manuals

12 https://www.icsm.gov.au/publications/australian-terrestrial-reference-frame-technical-implementation-plan-v23

13 https://www.icsm.gov.au/sites/default/files/2020-08/AVWS%20Technical%20Implementation%20Plan_V1.2.pdf

2.3 ICSM GDA Modernisation Implementation Working Group

In September 2015, the ICSM formed a dedicated working group to oversee the implementation of Geocentric Datum of Australia 2020. The GDA Modernisation Implementation Working Group (GMIWG) included government representatives from the Commonwealth, states and territories who have a broad range of knowledge and experience in the surveying and spatial sciences industry. The group consulted with users and led the development of tools and technical resources needed to assist with the datum transition.

The GMIWG oversaw:

- The development of a new GDA2020 logo;
- The development of QGIS plugins[14] to assist users perform GDA94-GDA2020 transformations;
- Facilitated discussion in an online GDA2020 Forum[15];
- Presented at a number of conferences and workshops to assist users with the transition to GDA2020;
- Reviewed state and territory survey acts and regulations and assist land and survey departments make changes required.

14 https://www.icsm.gov.au/datum/gda-transformation-products-and-tools/software-and-plugins

15 http://gda2020.invisionzone.com/

3. Infrastructure

High quality geodetic infrastructure is necessary to: 1) develop global and national reference frames, and 2) enable access to reference frames. In Australia, Geoscience Australia contribute to the realisation of the International Terrestrial Reference Frame (ITRF) with infrastructure, data and analysis from Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and GNSS which are used to define of the shape, centre of mass, orientation and rotation rate of the Earth.

3.1 GNSS

3.1.1 Developing a reference frame

The construction and maintenance of a country's GNSS network underpins its ability to align national datums to the realisations of the International Terrestrial Reference Frame (ITRF). This is generally done by ensuring some of the GNSS Continuously Operating Reference Stations in a country are accepted by the International GNSS Service (IGS) and used in the determination of realisations of the ITRF. By using the same GNSS CORS in the development of a national datum, the national datum is aligned to the latest realisation of ITRF.

For the realisation of the Australia's first geocentric datum (Geocentric Datum of Australia 1994 (GDA94)), 10 GPS sites[16] across Australia defined the Australian Fiducial Network and therefore underpinned the derivation of GDA94 coordinates around Australia. Over time, Australia, through contributions from states, territories and the Commonwealth governments have improved the GNSS infrastructure to improve the connection to ITRF and access to precise positioning for users.

The AuScope GNSS project commenced in 2007. Funding from Commonwealth, state and territory governments was used to construct an approximately 100 station GNSS network, with stations located at distances of around 200 kilometres apart. Approximately 15 of the GNSS CORS were used in the realisation of ITRF2014. Given that GDA2020 and ATRF2014 are based on ITRF2014, there is close alignment between the three reference frames.

The AuScope GNSS network underpins Australia's positioning capability and has supported numerous advances in high precision positioning which have widespread industrial applications, including the agricultural sector where it supports control track farming practices. Another application of the data is an improved understanding of the deformation of the continent. We can now measure the crustal deformation of the Australian continent with unprecedented accuracy, to a level of approximately 0.3mm per year. This knowledge will directly improve assessments of earthquake hazard in Australia, and will ultimately support the development of improved risk mitigation procedures and updating of building codes.

16 https://www.legislation.gov.au/Details/F2009B00151

3.1.2 Access to accurate coordinates

Access to the reference frame is generally enabled through the use of GNSS. This could be in the form of metre level accurate positioning in mobile devices which receive signals directly from GNSS satellites, or centimetre accurate positioning provided with the help of GNSS corrections (e.g. atmosphere, orbit, clock) which are computed thanks to high precision data collected at GNSS CORS and transmitted to a user over the internet.

3.2 Satellite Laser Ranging

Satellite Laser Ranging (SLR) is used to measure the time of flight of a laser to reach a satellite and return to the Earth. The technique can be used to uniquely define the Earth's centre of mass and along with VLBI, the scale of the Earth. It is also used help compute the Earth Orientation Parameters (EOPs) of polar motion (pole coordinates) and the rapid variations in length-of-day (LoD). SLR is also the most accurate way to resolve the centre of satellites which helps to calibrate radar altimeters and separate long-term instrumentation drift from secular changes in ocean topography.

Geoscience Australia operates SLR infrastructure at the Yarragadee Geodetic Observatory (WA) and Mt Stromlo (ACT). The SLR infrastructure at Yarragadee (MOBLAS-5) is owned by NASA and operated by Geoscience Australia staff. The SLR infrastructure at Mt Stromlo is owned by Geoscience Australia and operated by a contractor.

3.3 Very Long Baseline Interferometry

Very Long Baseline Interferometry (VLBI) is a technique which detects radio transmissions from extragalactic radio sources. Using the difference in time at which the signals from the source arrive at different radio telescopes, it is possible to determine EOPs: Universal time (UT1), polar motion (pole coordinates), and precession and nutation. Along with SLR, VLBI is also used to measure the scale of the Earth.

Geoscience Australia has a collaborative agreement with the University of Tasmania to operate VLBI infrastructure at the Yarragadee Geodetic Observatory (WA) and Katherine (NT) and Hobart (Tas). The VLBI infrastructure was originally purchased by Geoscience Australia using funding provided by AuScope. AuScope also provided the operational funding up until 2018 when Geoscience Australia received the Positioning Australia funding which included funds operate the three VLBI telescopes.

3.4 Interferometric Synthetic Aperture Radar

Interferometric Synthetic Aperture Radar (InSAR) provides a way to observe ground surface deformation very precisely. Given that ground deformation (e.g. earthquakes, groundwater extraction) can be highly variable over a small area, and is often non-linear, it cannot be adequately monitored using sparse GNSS stations. Nonetheless, by combining GNSS with InSAR observations, surface deformation can be observed precisely and accurately.

Geoscience Australia is developing a surface movement monitoring capability using GNSS and InSAR. Ultimately, the aim is to have a national scale reconnaissance tool which can be used to detect changes in the Australian landscape and highlight where further investigation may be required.

3.5 Absolute Gravity

Absolute Gravity instruments use a laser interferometer to measure the time it takes for a mass to fall in a vacuum. The accuracy of absolute gravity instruments is about 1 microGal, equivalent to 1 ppb of the gravitational acceleration of the Earth and about 3 mm in height. Importantly, absolute gravity provides an independent measure of vertical motion to the geometric techniques of DORIS, VLBI, SLR and GNSS.

Geoscience Australia uses an absolute gravimeter to measure gravity at 15 sites throughout Australia. The results are uploaded to a database[17] managed by the German Federal Agency for Cartography and Geodesy (BKG) and are mirrored with a database[18] operated by the International Gravimetric Bureau (BGI) in Toulouse, France.

17 http://agrav.bkg.bund.de/agrav-meta/
18 https://www5.obs-mip.fr/

Part B: Geometric Geodesy

4. Preliminaries

4.1 The ellipsoid

The Earth's surface (the terrestrial surface) is highly irregular in shape and therefore often unsuitable for mathematical computations, especially over large distances. Instead a reference surface, known as an ellipsoid (Figure 5) is adopted and points on the Earth's terrestrial surface are projected onto the ellipsoid (Deakin, et al., 2012). The ellipsoid is a simplified mathematical representation of the Earth which approximates the global geoid (see Part C: Physical Geodesy). Given they are easily defined mathematically, this makes the ellipsoid a relatively simple surface to compute upon.

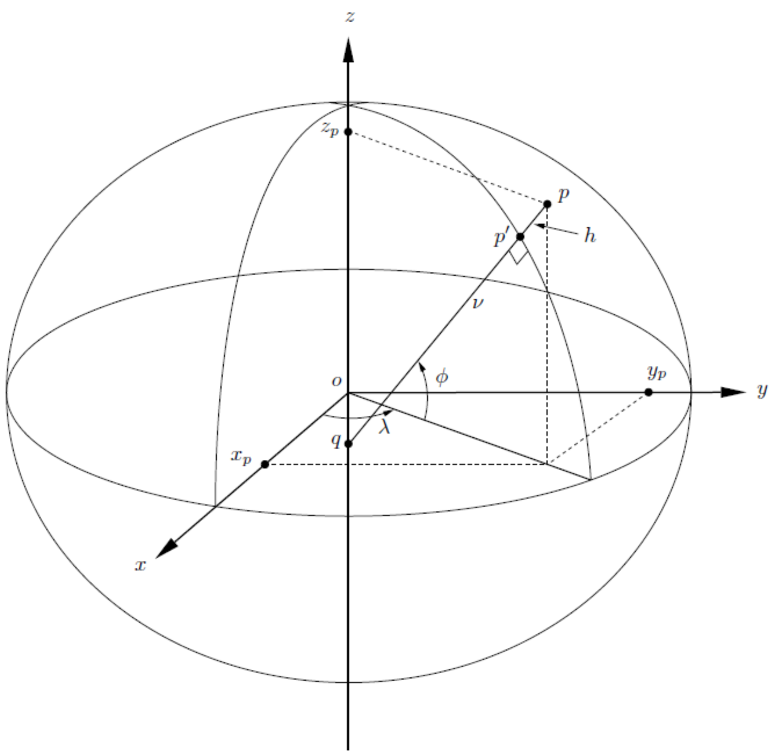

Figure 5: Relationship between ellipsoid based Cartesian and geographic coordinate systems.

4.2 Coordinate Systems

4.2.1 Cartesian

The Cartesian coordinate system is a three-dimensional system with positions p referenced to orthogonal axes $X\ Y\ Z$ with the origin at the centre of the reference ellipsoid (Figure 5). The Z-axis is in the direction of the rotational axis of the ellipsoid of revolution, the $X - Z$ plane is, by convention, the prime meridian plane (the origin of longitudes) and the $X - Y$ plane is the equatorial plane of the ellipsoid (the origin of latitudes) (Gerdan & Deakin, 1999).

4.2.2 Geographic

The geodetic coordinate system is a three-dimensional system with positions p referenced using geodetic latitude ϕ, geodetic longitude λ and ellipsoidal height h (Figure 5). Geodetic latitude and longitude are, by convention, angular quantities measured relative to the equator and prime meridian plane respectively.

Equations 1-3 can be iterated to convert from Cartesian coordinates to geodetic coordinates.

$$tan\,\lambda = \frac{Y}{X} \qquad (1)$$

$$tan\,\phi = \frac{(Z(1-f)+\varepsilon^2 a\, sin^3 u)}{((1-f)(p-\varepsilon^2 a\, cos^3 u))} \qquad (2)$$

$$h = p\, cos\,\phi + Z\, sin\,\phi - a\sqrt{(1-\varepsilon^2\, sin^2\,\phi)} \qquad (3)$$

where

$$p = \sqrt{(X^2 + Y^2)} \qquad (4)$$

$$tan\,u = \left(\frac{Z}{p}\right)\left[(1-f) + \left(\varepsilon^2 \frac{a}{r}\right)\right] \qquad (5)$$

$$r = \sqrt{(p^2 + Z^2)} \qquad (6)$$

$$\varepsilon^2 = 2f - f^2 \qquad (7)$$

Equations 8-10 can be used to convert from geodetic coordinates to Cartesian coordinates.

$$X = (\nu + h)\, cos\,\phi\, cos\,\lambda \qquad (8)$$

$$Y = (\nu + h)\, cos\,\phi\, sin\,\lambda \qquad (9)$$

$$Z = \{(1-\varepsilon^2)\nu + h\}\, sin\,\phi \qquad (10)$$

where

$$\nu = \frac{a}{\left\{\sqrt{(1-\varepsilon^2\, sin^2\,\phi)}\right\}} \qquad (11)$$

$$\varepsilon^2 = 2f - f^2 \qquad (12)$$

$$h = N + H \qquad (13)$$

Further reading on geographic to Cartesian conversion techniques, including some well suited for efficient use in software can be found in Gerdan & Deakin (1999).

4.2.3 Local

The local coordinate system is a three-dimensional system with positions referenced using orthogonal axes $e\ n\ up$ with the origin on or above a point on the ellipsoid, and orientation with respect to a local geodetic meridian (Fraser, et. al., 2017) (Figure 6).

Vectors in the Cartesian reference frame can be represented in the local reference frame as x_l

$$x_l = \begin{bmatrix} \Delta e \\ \Delta n \\ \Delta up \end{bmatrix} \tag{14}$$

A vector x_l in the local reference frame is related to the Cartesian reference frame by

$$x_c = \boldsymbol{R}_l x_l \tag{15}$$

where $\boldsymbol{R}_l$ is the rotation matrix with origin at latitude ϕ and longitude λ

$$\begin{bmatrix} -\sin\lambda & -\sin\phi\cos\lambda & \cos\phi\cos\lambda \\ \cos\lambda & -\sin\phi\sin\lambda & \cos\phi\sin\lambda \\ 0 & \cos\phi & \sin\phi \end{bmatrix} \tag{16}$$

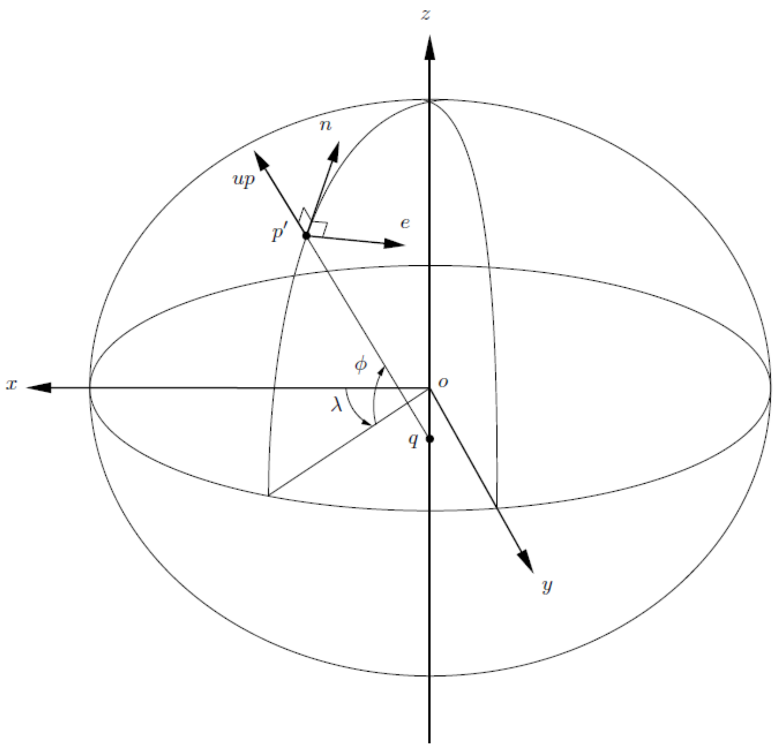

Figure 6: The local coordinate reference system.

5. History of Australian geometric reference frames

5.1 Early history

Between 1858 and 1966, geodetic surveys in Australia were computed on either a jurisdiction (state or territory) or regional basis using more than four different spheroids and as many as twenty coordinate origins.

The National Mapping Council (NMC), at its 23rd meeting in April 1965, adopted the Geodetic Reference System 1967 (GRS 1967) ellipsoid, then recommended for general use by the International Union of Geodesy and Geophysics, with the flattening term taken to two decimal places. The NMC decided to call this ellipsoid the Australian National Spheroid (ANS) (National Mapping Council, 1966).

5.2 Australian Geodetic Datum 1966

Re-computation and adjustment of all geodetic surveys in Australia on ANS were commenced by the Division of National Mapping in June 1965. By 8 March 1966, all geodetic surveys in Australia were re-computed and adjusted to form the Australian Geodetic Datum (AGD). This datum was subsequently adopted by the NMC on 21 April 1966, during its 24th meeting in Melbourne, and was proclaimed in the Commonwealth Gazette No. 84 of 6 October 1966.

In 1966, the minor axis of the spheroid was defined as being parallel to the Earth's mean axis of rotation at the start of 1962. In 1970 the NMC decided to adopt the Conventional International Origin (CIO), previously known as the mean pole 1900.0-1906.0, for the direction of the minor axis. The NMC decided that no change in the 1966 coordinates was necessary. The AGD66 reference meridian plane of zero longitude was defined as being parallel to the Bureau International de l'Heure (BIH) mean meridian plane near Greenwich. This gave a value of 149° 00' 18.885” East for the plane contained by the vertical through the Mount Stromlo photo zenith tube and the CIO. The position of the centre of the ANS was defined by the following coordinates of Johnston Geodetic Station:

Table 1: Johnston Geodetic Station coordinates.

Geodetic Latitude	25° 56' 54.5515” South
Geodetic Longitude	133° 12' 30.0771” East
Spheroidal Height	571.2 metres

The size, shape, position and orientation of ANS were thus completely defined, and together with the coordinates of the Johnston Geodetic Station, defined AGD66. The coordinates for Johnston Geodetic Station were derived from astronomical observations at 275 stations on the geodetic survey distributed all over Australia. The spheroidal height was adopted to be 571.2 metres, which was equal to the height of the station above the geoid as computed by trigonometrical levelling in 1965.

Due to the almost complete lack of geoidal profiles at the time of the 1966 national adjustment, it was then assumed that the geoid-spheroid separation was zero not only at Johnston Geodetic Station but also at all other geodetic stations listed in this adjustment. This assumption implied that every distance used in the 1966 adjustment was a geoidal or sea level distance (assumed spheroidal distance).

A Universal Transverse Mercator (UTM) projection was associated with AGD66 and was referred to as the Australian Map Grid (AMG66). The AGD66 and UTM projection, AMG66, were adopted by all the States and Territories in Australia, particularly in support of the national mapping program.

5.3 Australian Geodetic Datum 1984

Since 1966, there were several readjustments of the national geodetic survey. Each readjustment was referred to as a Geodetic Model of Australia (GMA) and was identified by the year in which the data set used in the readjustment was compiled. The adjustment, GMA82, included satellite Transit Doppler, Satellite Laser Ranging (SLR), Electronic Distance Measurement (EDM) tellurometer and Very Long Baseline Interferometry (VLBI) observations.

Recognising the need for Australia to eventually convert to a geocentric geodetic datum, the NMC, at its 42nd meeting in October 1984, resolved that the GMA82 adjustment would be adopted as the first step in the conversion process. However, the Council also resolved that members could use their discretion in the timing of the conversion process.

The GMA82 adjustment maintained AGD as originally defined by the combination of the 1966 coordinate set for Johnston Geodetic Station and the defining parameters for the ANS. This led to the development of the Australian Geodetic Datum 1984 (AGD84) coordinate set and associated UTM projection, known as the Australian Map Grid 1984 (AMG84).

In order to prevent any confusion arising with regard to the terminology to be used in conjunction with the 1966 and GMA82 adjustments, the NMC adopted the following definitions for general usage:

Table 2: Terminology used to differentiate between AGD66 and AGD84.

Datum	Australian Geodetic Datum
Spheroid	Australian National Spheroid
1966 Coordinate Set	Australian Geodetic Datum 1966
	Australian Map Grid 1966
1982 Adjustment	GMA82
1984 Adopted Coordinate Set	Australian Geodetic Datum 1984
	Australian Map Grid 1984

Unlike the 1966 adjustment, the GMA82 adjustment is a truly spheroidal adjustment. Therefore, any observations used in conjunction with the AGD84 coordinate set should first be reduced to the ANS using the appropriate geoid-spheroid separation values in terms of N = +4.9 metres at Johnston Geodetic Station.

NOTE: Not all jurisdictions adopted AGD84. Northern Territory, New South Wales, Australian Capital Territory, Victoria and Tasmania chose to stay on AGD66.

5.4 Geocentric Datum of Australia 1994

To align the Australian datum to a global reference frame, Australia adopted the Geocentric Datum of Australia 1994 (GDA94) and UTM projection the Map Grid of Australia 1994 (MGA94). At this time the recommended reference ellipsoid was also changed from ANS to the Geodetic Reference System 1980 (GRS80) ellipsoid after it was adopted at the XVII General Assembly of the International Union of Geodesy and Geophysics (IUGG) in Canberra, Australia, 1979 as the recommended best-fit ellipsoid for the Earth (Moritz, 2000). GRS80 has its geometric centre coincident with the centre of the mass of the Earth whereas the centre of the ANS lay about 200 m from the centre. Hence, the GDA94 coordinates of a point differ by about 200 metres (north-east) compared to AGD coordinates.

In 1992, as part of an International GPS Service (now known as the International Global Navigation Satellite System Service (IGS)) campaign, continuous GPS observations were undertaken on eight geologically stable marks at sites across Australia, which formed the Australian Fiducial Network (AFN). During this campaign, GPS observations were also carried out at a number of existing geodetic survey stations across Australia. These were supplemented by further observations in 1993 and 1994, producing a network of about 70 well-determined Global Navigation Satellite System (GNSS) sites, with nominal 500 km spacing across Australia. These sites are collectively known as the Australian National Network (ANN).

The GPS observations at both the AFN and ANN sites were combined in a single regional GPS solution in terms of the International Terrestrial Reference Frame 1992 (ITRF92) and the resulting coordinates were mapped to a common epoch of 1994.0.

The positions for the AFN sites were estimated to have an absolute accuracy of about 2 cm at 95% confidence level in the horizontal component (Morgan & Bock, 1996), while the ANN positions are estimated to have an absolute accuracy of about 5 cm in the horizontal component. The positions of the AFN sites were used to determine GDA94 and were published in the Commonwealth of Australia Government Gazette on 6 September 1995.

On 4 April 2012, the AFN was updated to include 21 sites. The purpose of the update was to improve its consistency with the most recent realisation of the International Terrestrial Reference System (ITRS) at the time (ITRF2008). The updated AFN coordinates were adopted from ITRF2008 and subsequently transformed to GDA94 (i.e. ITRF1992 at epoch 1994.0) using Australian transformation parameters (Dawson & Woods, 2010). For those stations with multiple coordinate estimates in ITRF2008 the most recent coordinate estimate was adopted.

6. Upgrading the geometric reference frame

6.1 Introduction to GDA2020 and ATRF2014

In anticipation of the growing use and reliance on positioning technology, Australia updated its static datum from the GDA94 to GDA2020 in 2017. One of the prime reasons for the upgrade was because Australia's previous static datum, the Geocentric Datum of Australia 1994 (GDA94), assumes the Australian continent is fixed in its location as of 1994.0. The Australian tectonic plate – the Earth's fastest moving continental plate – has moved up to 1.8 m north-northeast (~7 cm/yr) between 1994 and 2020. Given that Australians will soon have the capability to position themselves using GNSS with centimetre level accuracy in mobile devices, GDA94 was no longer fit for purpose for many of the users of precise positioning. In addition to the implementation of a new static datum – GDA2020 – the Intergovernmental Committee on Surveying and Mapping (ICSM) and the Spatial Information Council (ANZLIC) also endorsed the introduction of a time dependent reference frame – the Australian Terrestrial Reference Frame 2014 (ATRF2014). ATRF2014 provides a reference frame to support a rapidly growing user community that need real-time, centimetre accurate positioning solutions aligned to the reference frame of GNSS.

6.2 Issues with the Geocentric Datum of Australia 1994

The world of geospatial has changed significantly since 1994. The breadth of users and applications has expanded from spatial professionals to consumers. As a result, on average, the user has very little knowledge / expertise (and sometimes interest) in the field of positioning and geospatial technology. Furthermore, the cost of precise positioning technology has significantly reduced and will continue to do so.

Importantly, the vast majority of these new and emerging users are accessing precise positioning information from GNSS. These users / applications simply want to know where they are, and where things are around them. Given that GNSS positions are natively observed in a time dependent reference frame, like International Terrestrial Reference Frame 2014 (ITRF2014), and the Australian tectonic plate is moving at approximately 7 cm/yr north northeast, a national datum based on the location of the Australian continent in 1994 was not practical for some users.

GDA2020 is based on a realisation of the ITRF2014 (ITRF2014; Altamimi et al., 2016) at epoch 2020.0. GDA94 was based on the realisation of ITRF1992 at epoch 1994.0. Since then:

- Due to plate tectonic motion, GDA94 coordinates have continued to diverge from ITRF92 coordinates. By 2020, the difference was up to 1.8 m (Figure 7).

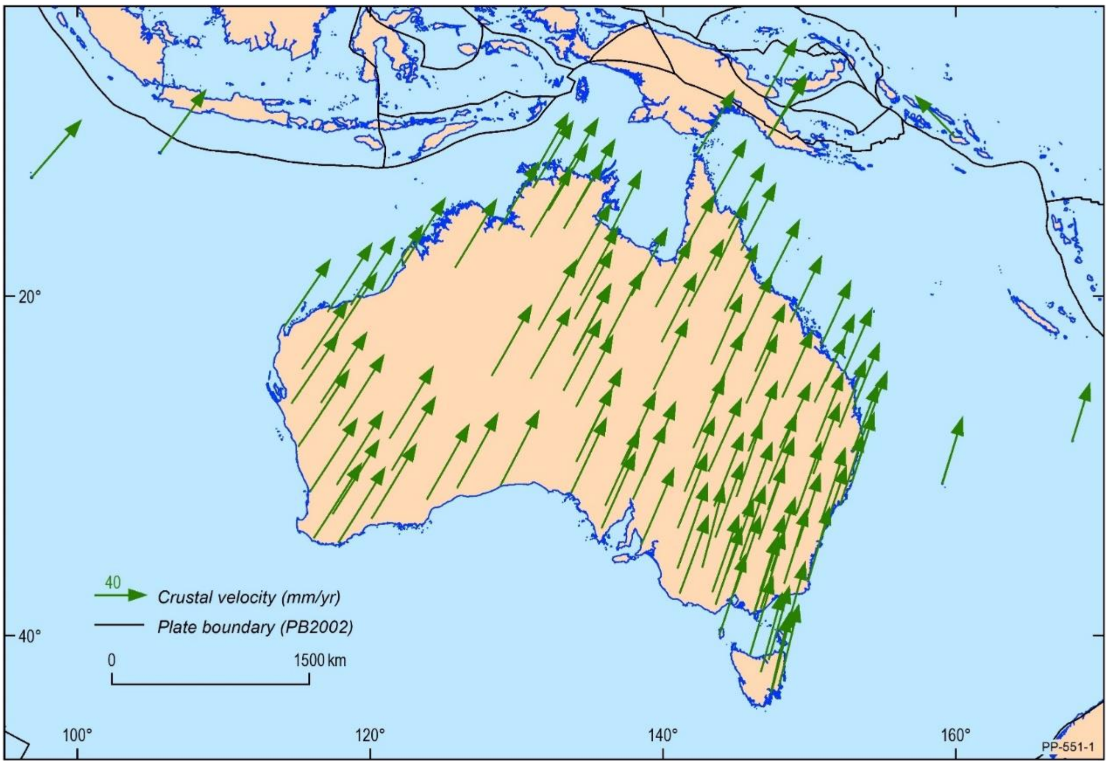

Figure 7: The Australian tectonic plate is moving approximately 7 cm/yr north northeast.

- There have been many improvements and realisations of the International Terrestrial Reference System (ITRS) which better define the shape of the Earth. For example, differences between ITRF1992 and ITRF2014 (on which GDA2020 is based) causes a ~9 cm change in ellipsoidal heights in Australia (GDA2020 heights are ~9 cm less than GDA94 ellipsoidal heights).
- Parts of the Australian crust have deformed (e.g. subsidence).
- A lack of rigor in the determination of GDA94 has become apparent. Studies comparing GDA94 coordinates as derived in the original GDA94 adjustment (Morgan & Bock, 1996) to ITRF2008 coordinates transformed to GDA94 show significant distortions of up to 0.5 m (Haasdyk et al., 2014). This is predominantly due to the lack of rigour in uncertainty propagation caused by performing a hierarchical adjustment. For example, to compute Australian National Network (ANN) coordinates at approximately 70 sites across Australia, the AFN sites were held fixed (zero positional uncertainty) in the adjustment (see Figure 8). The ANN sites were then held fixed in the combined state/territory adjustments and so on. As a result, state and territory survey control marks lower in the hierarchy have an unrealistic uncertainty value.

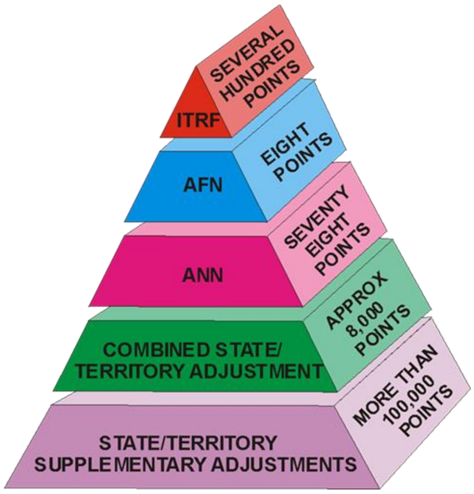

Figure 8: Constraint was not rigorously applied to the least-squares adjustment of coordinates for GDA94.

- There has been significant investment in positioning infrastructure since the production of GDA94 in 1997. This includes the construction of the AuScope Continuously Operating Reference Station (CORS) network, state and territory government CORS networks, privately operated CORS networks, and improvements in GNSS hardware and analysis including absolute antenna modelling. These infrastructure and technological developments have led to higher quality geodetic measurements.

6.3 The demand for a time dependent reference frame

Australia has traditionally used a static reference frame for its national geodetic datums (e.g. Clarke, AGD66, AGD84, GDA94) to which all spatial information can be consistently georeferenced and aligned. With a static datum, the positions of features appear to remain fixed despite the ongoing changes in the Earth's surface including plate tectonic motion (e.g. Australian plate moves ~7 cm/yr).

Australian and International research shows there is a rapidly growing user community including Location Based Services and Intelligent Transport Systems employing applications that require real-time, high-precision positioning solutions aligned to a global, time-dependent reference frame, such as the frames in which Global Navigation Satellite Systems (GNSS) operate. When such applications are aligned to a global, time-dependent frame, positioning and navigation is not only compatible with GNSS, but also more closely reflects the ongoing changes in the Earth's surface over time.

In recognition of the two use cases for geo-referencing, the Intergovernmental Committee on Surveying and Mapping (ICSM) and the Spatial Information Council (ANZLIC) endorsed a "two-frame" approach to support users who prefer to use a static datum, while also meeting the needs of those who require a reference frame that accommodates ongoing changes in the Earth. In 2020, Australia adopted the two-frame approach, enabling users to work with a static datum, the Geocentric Datum of Australia 2020 (GDA2020), or with a time-dependent reference frame known as the Australian Terrestrial Reference Frame 2014 (ATRF2014). GDA2020 and ATRF2014 were equivalent at the date of 1 January 2020. Given the diverse range of user requirements in Australia, the choice of which reference frame to use (GDA2020 or ATRF2014) will remain with the user for the foreseeable future.

Users are able to propagate coordinates between GDA2020 and ATRF2014 using the Australian Plate Motion Model (Figure 9).

Figure 9: A user can choose to use either GDA2020 or ATRF2014 depending on their requirements.

7. GDA2020 and ATRF2014

7.1 Legally defining GDA2020 and ATRF2014

Enabling the legal definition of both Australia's new static datum (GDA2020) and time-dependent reference frame (ATRF2014) required a change to the National Measurement (Recognized-Value Standard of Measurement of Position) Determination for legal traceability. The previous Determination (April 2012[19]) defined GDA94 as Australia's reference frame realised by the coordinates of 21 Australian Fiducial Network (AFN) sites throughout Australia.

The 2017 Determination[20] defines GDA2020 coordinates at 109 AFN sites and introduced coordinate uncertainties, velocities, velocity uncertainties and an equation which allows GDA2020 coordinates to be propagated to another epoch and described as ATRF2014 coordinates.

The 109 AFN sites described in the 2017 Determination were chosen as follows:

- Reduce the cumulative Asia-Pacific Reference Frame (APREF) solution to stations on Australian Tectonic Plate.
- Further reduce solution by removing New Zealand sites.
- Further reduce solution to contain just Tier 2 GNSS sites (high quality and high stability survey monuments such as AuScope GNSS CORS).
- Estimate an Australian Plate Motion Model (PMM) (see Section 7.2) and iteratively remove outliers (values greater than 1 mm/yr in the X, Y or Z component were considered outliers)
  - The outliers were Macquarie Islands (MAC1), Borroloola (BRLA), Mitchell (MCHL), Georgetown (GGTN), Marengo (MNGO), Cocos Island (COCO), Port Stanvac (PTSV), Stonehenge (STHG), Blinman (BMAN), Mareeba (MRBA), Mt Isa (MTIS), Yulara (YULA), Yanakie (YNKI), Kununurra (KUNU)

The length of time-series was not used to eliminate/include stations; however, all but six of the 109 stations have time-series longer than two years. The use of Tier 3 GNSS stations (survey quality GNSS CORS) was considered in the analysis but a decision was made to exclude them on the basis that their residuals were an order of magnitude greater than those of the Tier 2 stations. The cause of the difference was interpreted as being monument stability differences. Additionally, the geographic distribution of the Tier 3 stations in Australia, essentially limited to Victoria and NSW, did not improve the geometry of the plate estimator and consequently the uncertainties of the model were not improved to warrant their use. It was determined that the Australian tectonic plate is stable (i.e. moving in a uniform fashion with no internal distortion) at the 0.3 mm/yr level at the 109 AFN stations.

The coordinates defining GDA2020 in the 2017 Determination are ITRF2014 coordinates from the 109 AFN sites propagated to 2020.0 using the Australian Plate Motion Model (PMM). The velocities of the AFN sites in the 2017 Determination which allow the propagation (and legal traceability) between GDA2020 and ATRF2014 are also computed from the Australian PMM.

19 https://www.legislation.gov.au/Details/F2012L00800
20 https://www.legislation.gov.au/Details/F2017L01352

7.2 Australian Plate Motion Model

A key requirement to ensure the successful implementation of ATRF2014 is that software is able to transform / propagate data from the epoch it is captured or stored in (e.g. GDA2020), to a user-defined epoch. This is achieved through application of an Australian Plate Motion Model (PMM). For example, it can be applied in software to align road map data which may be stored in GDA2020 with real-time vehicle positions in ITRF2014/ATRF2014.

Computed from the GNSS time series from the 109 AFN sites, the Australian PMM accounts for the horizontal tectonic motion of the Australian plate of up to ~7 cm / year to the NNE (Figure 10).

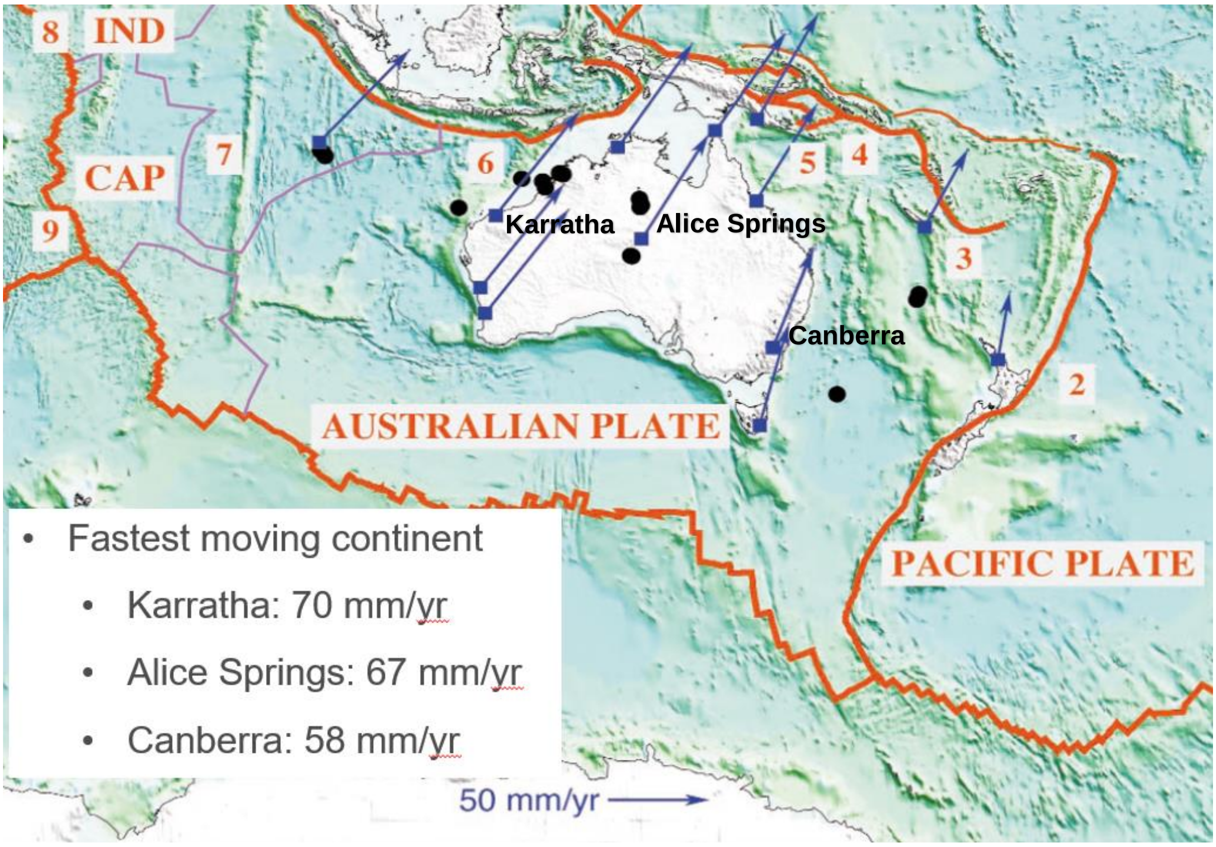

Figure 10: The rate of motion of the Australian Plate varies between 5 cm/yr and 7 cm/yr depending on the distance from the Euler pole south of New Zealand. The rate of motion experienced in Karratha is therefore greater than Canberra given the further distance away from the Euler pole.

Australia is in the middle of the Australian tectonic plate and experiences relatively little intraplate deformation. A three parameter model is able to adequately represent the horizontal (latitude and longitude) motion of the Australian plate over time. This 3-parameter model can be expressed in the form of a 14-parameter similarity transformation with the only non-zero values being the rate of change of the rotation components (Computationally, this transformation is performed using a similarity transformation (see Chapter 10; Equation 17) on the Cartesian coordinates (Earth Centred $X\ Y\ Z$), not on the geographic coordinates (latitude, longitude and ellipsoidal height).

Table 3).

Computationally, this transformation is performed using a similarity transformation (see Chapter 10; Equation 17) on the Cartesian coordinates (Earth Centred $X\ Y\ Z$), not on the geographic coordinates (latitude, longitude and ellipsoidal height).

Table 3: Parameters to propagate coordinates from ATRF2014 / ITRF2014 to GDA2020 along with their one sigma uncertainties (1σ). Units are in metres (m) and m/yr for the translations and their rates, respectively, parts-per-million (ppm) and ppm/yr for scale and its rate, respectively, and arcseconds and arcseconds/yr for rotations and their rates, respectively. The reference epoch t_0 is 2020.0.

	$t_x, \dot{t}_x$	$t_y, \dot{t}_y$	$t_z, \dot{t}_z$	$s_c, \dot{s}_c$	$r_x, \dot{r}_x$	$r_y, \dot{r}_y$	$r_z, \dot{r}_z$
parameters	0.00	0.00	0.00	0.00	0.00	0.00	0.00
uncertainty	0.00	0.00	0.00	0.00	0.00	0.00	0.00
rates	0.00	0.00	0.00	0.00	0.00150379	0.00118346	0.00120716
uncertainty	0.00	0.00	0.00	0.00	0.00000417	0.00000401	0.00000370

The rotation rate ($\dot{r}$) quantities are Euler pole vector components multiplied by the rotation angle rate. These values need multiplying by $\pi/648000$ to convert to radians before they can be subbed into the Equation 17 in Section 10.

i.e. $\dot{r}_x = 0.00150379 \frac{\pi}{648000}$

7.2.1 Australian Euler Pole

The Australian PMM parameters are rates of change of the rotations components around the Cartesian X, Y, Z axis, rather than rotations around a geographic Euler pole.

In order to visualise plate motion, it can be useful to define the Australian Euler pole in terms geographic coordinates about which the Australian Plate rotates. Results from a range of studies suggest the pole is somewhere south of New Zealand. See Beavan et al. (2002) for more information.

7.3 Deformation model

Surface deformation caused by natural events (e.g. earthquakes) or anthropogenic activities (e.g. groundwater extraction, mining activities) can be significant over small areas and is often non-linear. This complex deformation cannot be adequately represented by static datums or monitored using the tools traditionally used in the geodetic surveying community. For example, even though GNSS data has high temporal resolution, it has low spatial resolution. In an attempt to overcome these problems, Geoscience Australia is planning to include Interferometric Synthetic Aperture Radar (InSAR) data in the development of a 4D national scale surface deformation model to describe surface deformation over time.

InSAR is a geodetic remote sensing technique that can identify relative movements of the Earth's surface over large areas with millimetre precision, spatial resolution at the metre level and multiple observations per month. Complementary GNSS and InSAR observations can be combined in a least squares adjustment to create displacement estimates in a 3D velocity field with high spatial resolution and accuracy (Fuhrmann, 2016). When combined with the Australian PMM to describe the secular motion of the continent, the deformation model will enable the alignment of GDA2020 and ATRF2014 coordinates for high-accuracy positioning applications. While the Australian PMM would cover the entire continent, a deformation model would only need to cover the area impacted by the deformation.

7.4 GDA2020 and ATRF2014 extent

The extent of the GDA2020 and ATRF2014 includes all the areas contained within Australia's marine jurisdiction (within 200 nautical miles of Australia) and its external territories, and the areas of

Australia's continental shelf beyond 200 nautical miles as confirmed by the United Nations Commission on the Limits of the Continental Shelf. The areas include Cocos (Keeling) Islands, Christmas Island, Norfolk Island and Macquarie Island but exclude Heard-McDonald Islands and the Australian Antarctic Territory (AAT) as shown in Figure 11. The extent of GDA2020 and ATRF2014 is the same as the extent of GDA94.

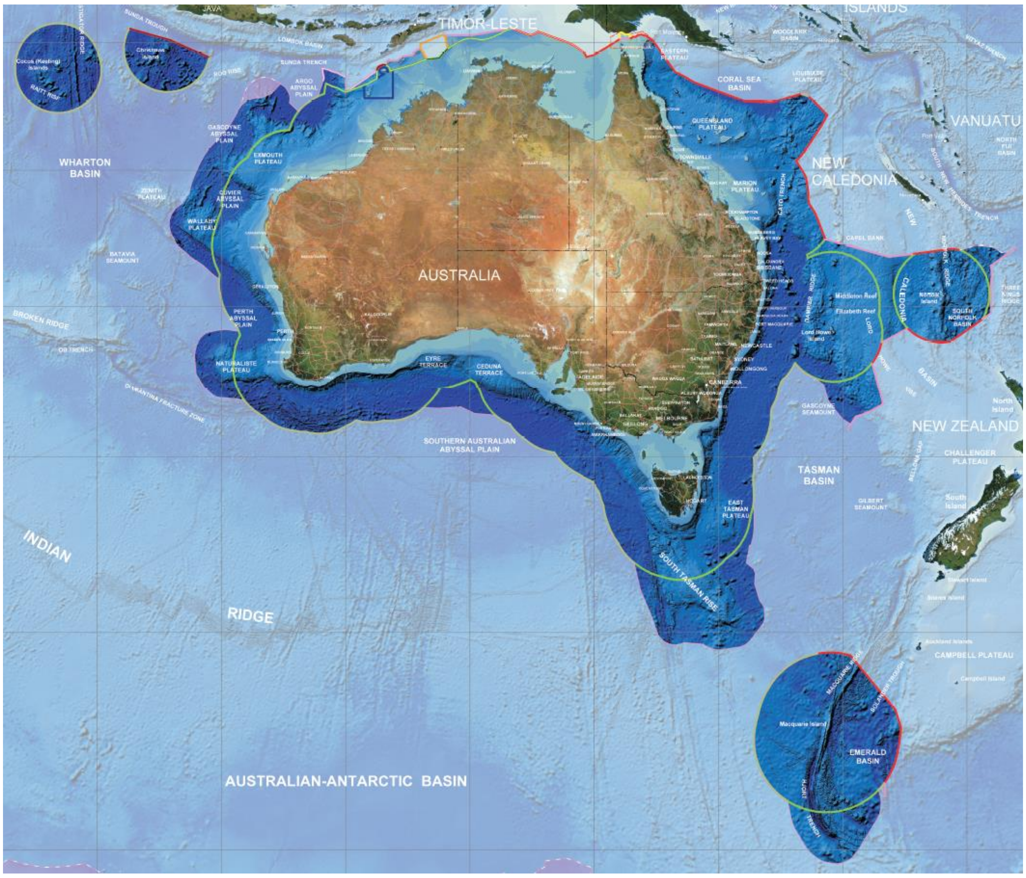

Figure 11: The area shown in dark blue is the GDA2020 extent[21]. The colours of the lines represent different types of jurisdictional boundaries or proposed jurisdictional boundaries.

21 http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_70362A

8. Differences between GDA2020, ITRF2014, ATRF2014 and WGS84

8.1 Summary of Australian geometric datums

A summary of the datums commonly used in Australia is provided in Table 4.

Table 4: Summary of the parameters of geometric datums used in Australia.

Datum	Static / Time-variable	Grid Coordinates	Reference Frame	Ellipsoid / Spheroid	Semi-major axis (m)	Inverse Flattening
GDA2020	Static	MGA2020	ITRF2014	GRS80	6378137.0	298.2572221009
ATRF2014	Time variable	---	ITRF2014	GRS80	6378137.0	298.2572221009
ITRF2014	Time variable	---	ITRF2014	GRS80	6378137.0	298.2572221009
WGS84 (1762) (EPSG::1156)	Time variable	---	WGS84 (EPSG::7664)	WGS84 (EPSG::7030)	6378137.0	298.257223563
GDA94	Static	MGA94	ITRF1992	GRS80	6378137.0	298.2572221009

8.1.1 GDA2020 and ATRF2014

- As described in detail in Chapter 9, GDA2020 coordinates are computed via a national least squares adjustment computed every month using all available terrestrial and GNSS data throughout Australia. This is a datum maintenance exercise run by Geoscience Australia using data supplied from state and territory governments. It is the choice of the state and territory governments as to, if and when, they update the GDA2020 coordinates used within their jurisdiction.
- GDA2020 (static datum) coordinates can be propagated to ATRF2014 (time dependent reference frame) using the Australia Plate Motion Model (PMM) which accounts for the horizontal motion (latitude and longitude) of the Australian tectonic plate (~7 cm/yr).

8.1.2 ATRF2014 and ITRF2014

- ATRF2014 coordinates are computed by propagating GDA2020 coordinates to the epoch of interest using the Australian PMM.
- This is a legally traceable method of deriving time dependent coordinates in an Australian reference frame based on an Australian PMM derived from the 2017 Determination sites.
- ATRF2014 and ITRF2014 are aligned at the centimetre level.
- ITRF2014 is the most recent realisation of a global network of accurate coordinates (and their velocities) maintained by the International Earth Rotation and Reference Systems Service (IERS) and derived from geodetic observations (VLBI, SLR, GPS and DORIS) (Seeber, 1993).
- The minor differences between ATRF2014 (regional time dependent reference frame) and ITRF2014 (global time dependent reference frame) are due to:
  - the inclusion of extra data used in the computation of GDA2020, and;

- the use of a more precise Australian PMM (as opposed to the ITRF2014 plate motion mode) to compute ATRF2014 coordinates. See Chapter 9 for more information.

8.1.3 World Geodetic System 1984 and ATRF2014/ITRF2014

- The World Geodetic System, of which the latest revision is WGS84 (G1762), is the datum used by the GPS operated by the U.S. Department of Defense.
- The datum is defined and maintained by the United States National Geospatial-Intelligence Agency (NGA).
- WGS84 has had six realisations since its inception.
- The current realisation of WGS84 (1762) is aligned at the centimetre level to ITRF2014 (NGA, 2014a).
- The WGS84 coordinates of tracking stations used to compute the GPS broadcast orbit are adjusted annually for plate tectonic motion to an epoch at the half year mark, e.g. WGS84 as used in the GPS broadcast orbit during calendar year 2014 was ITRF2008 at 2014.5. Consequently, differences between the ATRF2014/ITRF2014 and WGS84 are negligible for most users.
- For information on the reference systems of GLObal NAvigation Satellite System (GLONASS), Galileo, BeiDou, Indian Regional Navigation Satellite System (IRNSS) and Quasi Zenith Satellite System (QZSS), please refer to UNOOSA, 2016.

9. Computing GDA2020 coordinates

GDA2020 coordinates and uncertainties are computed monthly via a national least squares adjustment undertaken by Geoscience Australia with input from geodetic specialists from all jurisdictional survey organisations. The adjustment is a national scale, fully rigorous, 3D Cartesian network adjustment of all available GNSS and terrestrial data from Commonwealth, state and territory jurisdictional archives.

9.1 National least squares adjustment software

Historically, the size of the geodetic network that could be adjusted was limited by the amount of the computing memory and hardware available. This limitation was removed with the use of DynAdjust (Fraser et al., 2017). DynAdjust is a rigorous, high performance least squares adjustment open source application. It has been designed to estimate 3D station coordinates and uncertainties for both small and extremely large geodetic networks, and can be used for the adjustment of a large array of Global Navigation Satellite System (GNSS) and conventional terrestrial survey measurement types. On account of the phased adjustment approach used by DynAdjust, the maximum network size which can be adjusted is effectively unlimited, other than by the limitations imposed by a computer's processor, physical memory and operating system memory model.

To perform the national least squares adjustment of ~2 million measurements and ~250,000 stations, DynAdjust automatically segments the network up a number of smaller blocks. Variance-covariance information from each block is passed to next block in the chain, ensuring rigorous parameter estimates and variance information can be obtained for all stations. The efficiency gain from a phased adjustment is achieved by finding the optimum balance between block size and computing resource availability.

For more information on DynAdjust, refer to the DynAdjust User Guide (Fraser et al., 2017) and access the open source least adjustment software from the GitHub repository[22].

9.2 Asia-Pacific Reference Frame constraint

To ensure the GDA2020 coordinates output from the monthly national least squares adjustment are aligned to the latest realisation of ITRF (currently ITRF2014) Geoscience Australia use the cumulative Asia-Pacific Reference Frame (APREF) solution as constraint (Figure 12; see Section 9.2.1).

22 https://github.com/icsm-au/DynAdjust

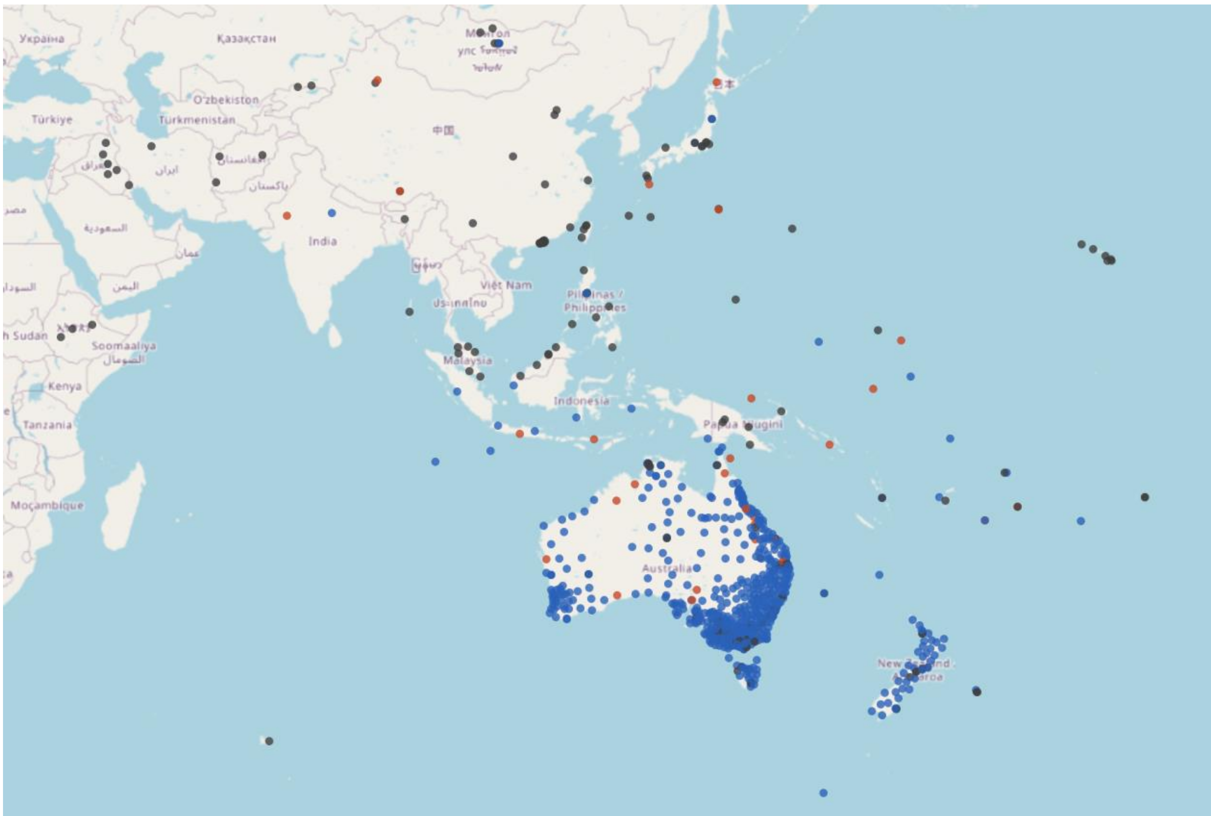

Figure 12: The Asia-Pacific Reference Frame Network (as of June 2022).

The cumulative APREF solution is preferred to a cumulative ITRF solution because APREF is a regional reference frame which provides a dense, accurate and continually refined reference frame for the Asia-Pacific region. The APREF Permanent Network has contributions from 28 countries and includes 718 CORS sites that have been operational since at least August 2016. Of the 718 CORS sites, 488 are on the Australian tectonic plate. In contrast, only 15 Australian sites were incorporated into ITRF2014; purely because it is not feasible to incorporate all possible sites in computations for the global reference frame. The increased number of reference sites within APREF provides a denser and more accessible reference frame and velocity field, leading to a more robust positioning capability, and ultimately improved interoperability of spatial data in Australia.

9.2.1 Cumulative APREF position and velocity solutions

The cumulative APREF solution is computed by:

- Computing a daily solution for all APREF stations
- Combining daily solutions into a weekly solution (Hu et al., 2019) aligned to the latest GNSS reference frame adopted by the International GNSS Service (IGS) (currently IGSb14).
    - The weekly combined solutions are generated with Bernese software on the ‘daily normal equations level’. That is, daily station solutions appearing to be inconsistent with a weekly trend are removed from the weekly combined solutions based on a comparison of the residuals of seven-parameter Helmert transformations generated from daily and weekly solutions. The threshold of the residuals is 10 mm horizontally and 20 mm vertically.

- Rigorously stacking all historical weekly combined solutions (from 1994 onwards) using the CATREF software to obtain cumulative station coordinates and velocities as well as the station position time series.

These cumulative APREF solutions are the most accurate and up-to-date coordinates for APREF stations, and as such, are the constraint (with a variance-covariance matrix) in the national least squares adjustment. The combined weekly APREF solutions are published on the APREF website (http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame) and are available as Earth centred XYZ coordinates dated at an epoch of the middle of the week (UTC time).

9.2.2 Constraint for the national least squares adjustment

The constraint used for the monthly national adjustment is the cumulative APREF solution from ~3 months prior. For example, the national least squares adjustment for April 2020 was based on the cumulative APREF solution from January 2020. This allows enough time for any discontinuities in the APREF solution to be identified and resolved.

Before the cumulative APREF solution (from 3 months prior) is used as constraint in the national least squares adjustment, the following actions are performed:

- Stations outside the extent of GDA2020 (see Chapter 7.4) are removed.
- The coordinates from the remaining stations are propagated from ITRF2014@2010.0 to GDA2020 using the Australian Plate-Motion Model (see Chapter 7.2).
- Type B uncertainties, to account for instability of the GNSS antenna mounting and modelling of the antenna phase centre variations, are introduced by applying the the values listed below to the diagonal terms of the Variance Covariance (VCV) matrix:
    - The 109 AFN sites have apriori Type B uncertainties of 3 mm, 3 mm, and 6 mm (east, north, and up) included.
    - For all other APREF stations, apriori Type B uncertainties of 6 mm, 6 mm, and 12 mm (east, north, and up) are included.

9.3 National GNSS Campaign Archive

The National GNSS Campaign Archive (NGCA) is a collection of high-quality GNSS data, often collected on passive survey control marks, supplied by each of the Australian jurisdictions. To be included in the NGCA, observations must be submitted in Receiver INdependent EXchange format (RINEX), the observations must be made after 1 June, 1994, and they must contain between 6 and 48 hours of observations sampled at 30 second epochs. Only observations inside the extent of GDA2020 are accepted. Data from before 1 June, 1994 cannot be processed because there are no International GNSS Service (IGS) products available before that date. Observations of lower quality (e.g., those with large uncertainties) can still be included in the national adjustment via a Jurisdictional Data Adjustment (JDA).

9.3.1 Processing RINEX files

Geoscience Australia maintains the NGCA data supplied by the jurisdictions and undertakes monthly processing of all NGCA data to ensure all measurements are processed in a consistent way. The processing of the NGCA RINEX files is carried out using the AUSPOS GNSS Processing Service (currently using Bernese GNSS Software v5.2) hosted by Geoscience Australia. This service uses products from the IGS to compute precise coordinates in ITRF2014. It requires dual frequency GPS phase data collected with a known antenna type and antenna height. The reference stations used during the NGCA processing are the nearest seven IGS GNSS stations (to provide a reliable alignment to ITRF2014) and the nearest eight non-IGS APREF GNSS stations.

Given that large number of RINEX files in the NGCA, the files are broken up into a number of 'clusters', where a cluster contains up to 20 RINEX files which are processed together to maintain covariance information between stations in the output SINEX file. Clusters are created by grouping RINEX files that have overlap in the time data was observed. Every file in the cluster must have at least two hours of overlap with every other file in the cluster. This is achieved using the following procedure:

- All RINEX files in an NGCA are ordered by start time.
- If the first and the second file have at least two hours overlap then they are both included in the cluster.
- If the third file has at least two hours overlap with the first two, then it is added to the cluster.
- This process continues until a file is found that does not have two hours overlap with all the files already assigned to the cluster.
- That file is then the first file in the next cluster and the process repeats.
- This continues until all files have been assigned to a cluster.
- No consideration is given to the length of the baselines formed in a cluster as this was shown not to affect the quality of the solution.

Even after clustering the RINEX files contained in an archive, it is possible for the number of files being processed concurrently will exceed the limits imposed by the processing software. For example, the Bernese software used by Geoscience Australia needs to estimate troposphere parameters for each of the RINEX files that are being processed, and there is a limit to the number of the parameter estimates that Bernese can store. This limit is set when the program is compiled. Practically, this means clusters cannot be larger than a certain size, but the exact number depends on the amount of time spanned by all the RINEX files in the cluster. To prevent this from causing the processing to fail, clusters are limited to 20 RINEX files.

For each cluster of NGCA data processed, a SINEX file is output from AUSPOS containing the GNSS station coordinates (in ITRF2014) and station covariances. Each SINEX file is then converted to a GNSS baseline cluster.

9.3.2 GNSS baseline clusters

To ensure that the APREF SINEX solution provides the primary constraint on the national least squares adjustment all other measurements in the adjustment are input as relative measurements. Therefore, the SINEX files output from the NGCA processing are converted to GNSS baseline cluster files. These files contain only the independent (non-trivial) baselines between the stations in the SINEX file. The baseline uncertainties are rigorously propagated from the VCV in the SINEX file.

The clusters of GNSS baselines are relative measurements within a reference frame. The frame in which jurisdictions supply the relative measurements can vary. The NGCA baselines are currently processed in the IGb14 frame. Ultimately, these are then aligned to the GDA2020 reference frame.

9.3.3 Scaling measurement uncertainties

The combined uncertainty of a measurement is a combination of the statistical uncertainty (Type A) and that from the uncertainty evaluated using available knowledge (Type B). In the case of GNSS measurements, the estimated annual movement of the monument due to various geophysical forces would be an example of an uncertainty that would be captured in the Type B component.

Type A uncertainties are output by the Bernese GNSS analysis software. Type B uncertainties are estimated from a minimally-constrained adjustment as described in the Guideline for the Adjustment and Evaluation of Survey Control V2.2 (ICSM, 2020). For each GNSS baseline cluster, a minimally-constrained adjustment is performed and the resulting sigma zero value σ_0 is used to scale the baseline uncertainties so that the cluster fits well with the APREF network. A fully-constrained adjustment is then performed with the APREF solution as the constraint. The purpose of the fully-constrained adjustment is to check that the clusters, collectively, fit well with the APREF solution.

9.4 Jurisdictional Data Archive

The Jurisdictional Data Archive (JDA) is a collection of survey observations data jurisdictions wish to include in the national adjustment which is not from a GNSS CORS station and is not a GNSS RINEX file with more than six hours of observations. Data commonly added to JDAs are terrestrial data and GNSS baselines with less than six hours of observations.

9.4.1 Jurisdictional adjustment process

Prior to submitting their data for inclusion in the national least-squares adjustment, jurisdictions run a jurisdictional adjustment to ensure that the latest version of their NGCA and their JDA fit with the APREF constraint being used for the national adjustment. The process, which is carried out by each jurisdiction separately, contains the following steps:

- Rename any APREF stations in the JDA that have a discontinuity. The different sections of the time series for an APREF station with one or more discontinuities are treated as separate stations in the National Adjustment (NADJ). It is important to make sure any measurements that include one of these stations is connecting to the right section of the time series.
- Check that stations referenced by two or more jurisdictions (e.g., close to a jurisdiction border) are named the same. Stations that potentially may need to be renamed are identified using DynAdjust’s near-station search feature to identify any nearby stations (the default is 30 cm apart).
- The jurisdiction's data (JDA and NGCA) are then imported into DynAdjust. Note, these data can be in any reference frame. Before the adjustment is done, a combined measurement file consisting of jurisdiction's JDA and NGCA is exported. The measurements are exported at this stage because they are now correctly named and the APREF solution is yet to be imported. If the measurement file exported later in the process was used, then it would result in the APREF solution being introduced into the NADJ multiple times. It is this combined measurement file that will be submitted by the jurisdiction for inclusion in the national adjustment. All measurements are in the reference frame and at the epoch they were captured in.

- The jurisdiction’s measurements (JDA and NGCA) are then transformed to GDA2020 and the APREF solution is imported to be used as the constraint for the adjustment. Both the APREF SINEX file and the APREF GNSS baseline clusters files are used.
- A geoid correction is made to all measurements to convert all orthometric heights to ellipsoidal heights and to correct for deflections from the vertical.
- The jurisdiction’s network is then segmented and adjusted, and the adjusted coordinates are exported in GDA2020. It is this station file that will be submitted for inclusion in the national adjustment.

If there are problems with the jurisdictional adjustment, e.g., large station shifts or failing the statistical tests carried out by DynAdjust, these must be addressed before submitting the jurisdictional adjustment to the national adjustment. As the APREF solution and NGCA are provided correctly scaled, only measurements in the JDA can be rescaled by the jurisdictions to address issues. Additionally, the APREF solution is used by all jurisdictions and so cannot be modified to suit the needs of any one jurisdiction.

Type B uncertainties are also added after the adjustment (a posteriori) to increase the uncertainty of station positions. This is based on professional judgement of GA and jurisdictional representatives to provide coordinates with realistic uncertainties to users.

9.5 National adjustment output data

The output from the national least squares adjustment are GDA2020 coordinates and positional uncertainties of each station. Geoscience Australia maintains a national database of this data. The decision as to whether jurisdictions choose to update the coordinates and velocities for their products and services is left to the individual jurisdictions.

For each station the Cartesian VCV matrix is provided along with the semi-major axis, the semi-minor axis, and the orientation of the error ellipse defined by the VCV. This error ellipse is converted into a circularised horizontal positional uncertainty and vertical positional uncertainty.

9.6 Converting to ATRF2014 coordinates

GDA2020 (static datum) coordinates can be propagated to ATRF2014 (time dependent reference frame) using the Australia PMM which accounts for the horizontal motion (latitude and longitude) of the Australian tectonic plate (~7 cm/yr) (Figure 13).

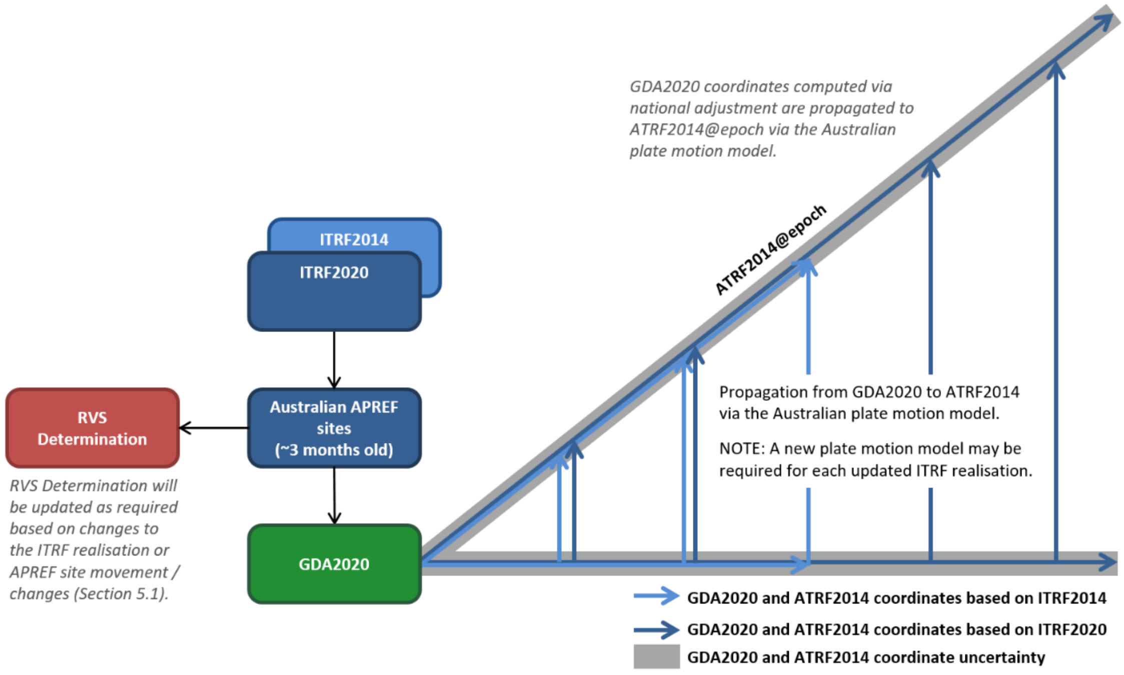

Figure 13: Summary of the workflow to compute GDA2020 and ATRF2014 coordinates.

10. Coordinate Transformations

Coordinate *transformation* is the process of changing the coordinates from one reference frame to another.

A similarity transformation (also known as a conformal transformation) can be used to transform coordinates (or vectors) from one geodetic reference frame (A) to another (B). At the computational level, this transformation is performed on the Cartesian $X\ Y\ Z$ coordinates. The 14-parameter similarity transformation (Equation 17) is the 7-parameter transformation (3 translations $t_x\ t_y\ t_z$, 3 rotations $r_x\ r_y\ r_z$ and scale s_c) with an additional 7 parameters used to describe the rates of change of the translations $\dot{t}_x\ \dot{t}_y\ \dot{t}_z$, rotations $\dot{r}_x\ \dot{r}_y\ \dot{r}_z$ and scale $\dot{s}_c$ in time (Altamimi et al., 2002). This allows for transformation between datums with data sets at any given epoch t where t_0 is the reference epoch. The translations and their rates are expressed in m and m/yr, respectively. The rotation and their rates are expressed in radians and radians/yr, respectively. The scale is unit-less and the scale rate is expressed in yr^{-1}. Parameters $X'\ Y'\ Z'$ are the transformed $X\ Y\ Z$ coordinates.

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = \begin{pmatrix} t_x + \dot{t}_x(t-t_0) \\ t_y + \dot{t}_y(t-t_0) \\ t_z + \dot{t}_z(t-t_0) \end{pmatrix} + \left(1 + s_c + \dot{s}_c(t-t_0)\right) \begin{pmatrix} 1 & r_z + \dot{r}_z(t-t_0) & -r_y - \dot{r}_y(t-t_0) \\ -r_z - \dot{r}_z(t-t_0) & 1 & r_x + \dot{r}_x(t-t_0) \\ r_y + \dot{r}_y(t-t_0) & -r_x - \dot{r}_x(t-t_0) & 1 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (17)$$

10.1 Rotation matrix sign convention

There are two different ways of applying the sign conventions for the rotations. In both cases a positive rotation is an anti-clockwise rotation, when viewed along the positive axis towards the origin but:

1. The IERS assumes the rotations to be of the points around the Cartesian axes, while;

2. The method historically used in Australia assumes the rotations to be of the Cartesian axes around the points.

Although these two conventions exist, to enforce the property that all rotations describe anticlockwise rotation as positive when viewed along the axis towards the origin (from the positive direction), the rotation of the coordinate axes around the points should be a skew-symmetric matrix with the opposite sign to the rotation of the point/s around the coordinate axis.

The transformation parameters in this compendium and Australian geodesy technical manuals adhere to the Australian convention. Due to the potential for confusion, it is advisable to ensure that the conventions used in software are well understood and tested against the sample data supplied in this Chapter.

10.2 GDA94 - GDA2020 transformation options

Options to transform coordinates between GDA94 - GDA2020 are:

- a 7-parameter similarity transformation,
- a conformal transformation grid, and;
- a conformal plus distortion transformation grid.

10.2.1 Similarity transformation

The 7-parameter similarity transformation (Equation 18), also known as a conformal transformation, accounts for the difference in scale, rotation, and translation between two reference frames. The official GDA94 to GDA2020 conformal transformation parameters and their uncertainties are shown in Table 5. These parameters were computed using 18 GNSS CORS common to both the GDA94 RVS and the GDA2020 RVS. The GDA94 RVS (from 2012[23]) had 21 AFN stations. GNSS CORS located at Cocos Island (COCO), Christmas Island (XMIS) and Macquarie Island (MAC1) were excluded from the computation due to deformation from earthquake.

$$\begin{pmatrix} X_{GDA2020} \\ Y_{GDA2020} \\ Z_{GDA2020} \end{pmatrix} = \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix} + (1 + s_c) \begin{pmatrix} 1 & r_z & -r_y \\ -r_z & 1 & r_x \\ r_y & -r_x & 1 \end{pmatrix} \begin{pmatrix} X_{GDA94} \\ Y_{GDA94} \\ Z_{GDA94} \end{pmatrix} \quad (18)$$

Table 5: Transformation parameters for GDA94 to GDA2020 along with the one-sigma uncertainties (1σ). Units are in metres for the translation, parts-per-million for scale, and arcseconds for rotations.

	t_x	t_y	t_z	s_c	r_x	r_y	r_z
parameter	0.06155	-0.01087	-0.04019	-0.009994	-0.0394924	-0.0327221	-0.0328979
uncertainty	0.0007	0.0006	0.0007	0.00010	0.000011	0.000010	0.000011

The parameters to transform GDA2020 coordinates to GDA94 coordinates are obtained by multiplying the values in Table 5 by -1.

23 https://www.legislation.gov.au/Details/F2012L00800

10.2.2 Example: GDA94 - GDA2020 (7–parameter transformation)

GDA94 coordinates of Alice Springs (ALIC)

Latitude (DMS)	Longitude (DMS)	Ellipsoidal Height (m)
-23° 40’ 12.446019”	133° 53’ 07.847844”	603.3466

Latitude (DD)	Longitude (DD)	Ellipsoidal Height (m)
-23.6701239	133.8855133	603.3466

X	Y	Z
-4052051.7643	4212836.2017	-2545106.0245

GDA2020 coordinates of Alice Springs (ALIC)

X	Y	Z
-4052052.7379	4212835.9897	-2545104.5898

Latitude (DMS)	Longitude (DMS)	Ellipsoidal Height (m)
-23° 40’ 12.39650”	133° 53’ 07.87779”	603.2489

Latitude (DD)	Longitude (DD)	Ellipsoidal Height (m)
-23.6701101	133.8855216	603.2489

Difference (GDA2020 – GDA94)

	Latitude	Longitude	Height (m)
Alice Springs (ALIC)	0.04952"	0.02995"	-0.0977

	N (m)	E (m)	U (m)
Alice Springs (ALIC)	1.5236	0.8487	-0.0977

10.2.3 Transformation grids

Transformation grids provide users of spatial data with a simple and nationally consistent method to transform data between datums. The transformation grids used in the Australian Geospatial Reference System are National Transformation version 2 (NTv2) files of binary grid shift (.gsb) format and they are the preferred method for transforming between Australian datums. The transformation grids are available from the ICSM GitHub repository[24].

The NTv2 format is not truly a 3D format and does not store ellipsoidal height information. NTv2 files therefore cannot be used to transform the heights of data from one datum to another. To transform heights, it is recommended that the data be converted from latitude, longitude, and height (LLH) to Earth-centred Cartesian coordinates (XYZ), apply the 7-parameter transformation from GDA94 to GDA2020 Table 5 and then convert back to LLH.

10.2.3.1 Types of transformation grids

Two types of GDA94-GDA2020 transformation grids have been developed:

- conformal: predominantly plate tectonic motion (~1.8 m NNE)
- conformal + distortion: includes regional distortion

The difference between the coordinates of a position in GDA94 and that same position in GDA2020 is composed of a conformal transformation component, due to plate tectonic motion (see Figure 14), and an irregular (non-conformal) distortion component. The distortion component is attributable to several second-order effects, such as: an improved realisation of the global reference frame over time; irregular ground movement since GDA94 was established; and a lack of rigour in the computation of GDA94. These effects vary in magnitude and direction around the country and can be as large as ~0.5 m.

The combined conformal and distortion grids model both the conformal transformation (i.e., translation, rotation, and scale) and distortion components of the datum differences. The GDA94-GDA2020 conformal only transformation grid delivers the same result as the 7-parameter similarity transformation (see Section 10.2). It has been developed at the request of some software providers who are moving towards the use of grids as the preferred method of geodetic transformation in selected software platforms. A particular example of its application would be for users who may be using GDA94 coordinates which were observed in ITRF2008/2014 and transformed back to GDA94 (e.g., CORS network operators) using a 7-parameter similarity transformation. These coordinates are not impacted by distortion in the realisation of the GDA94 datum and the use of the conformal and distortion transformation grid would actually introduce distortion, not remove it.

The appropriate NTv2 transformation grid to use differs between jurisdictions and the positional uncertainty (or accuracy) of the dataset being transformed.

24 https://github.com/icsm-au/transformation_grids

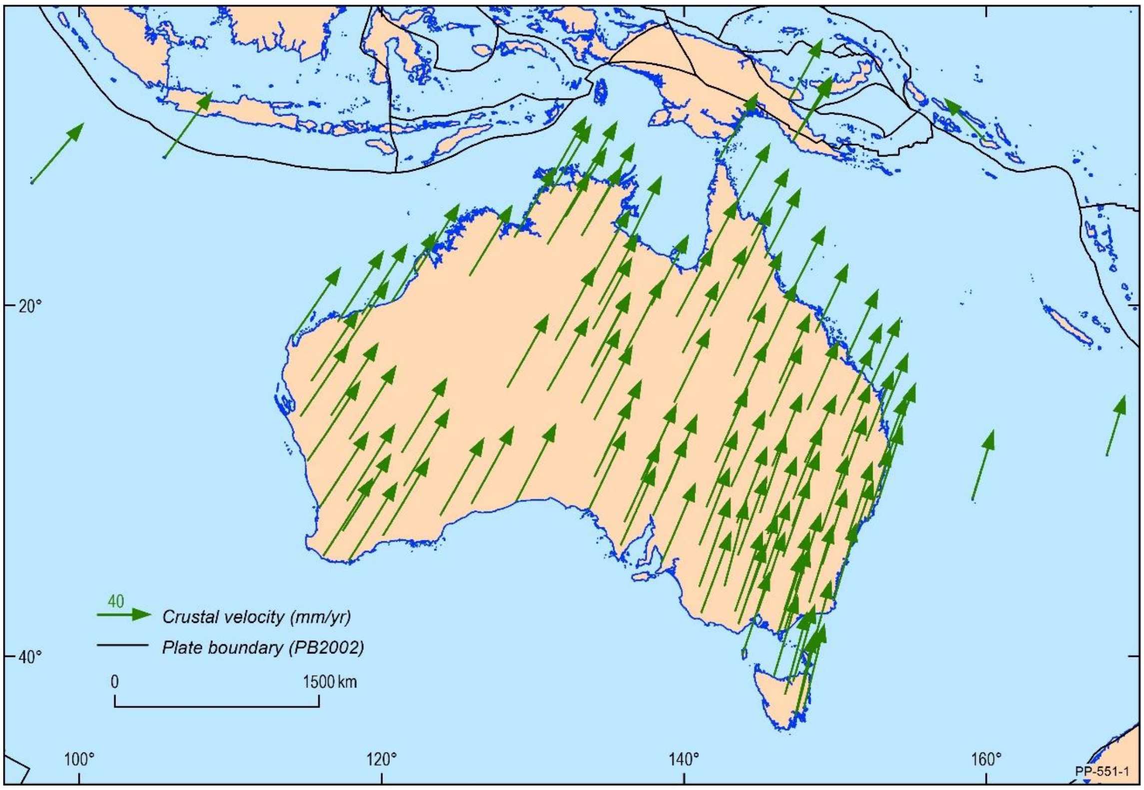

Figure 14: The difference between GDA94 and GDA2020 coordinates is primarily due to plate tectonic motion.

If GDA94 coordinates were observed using Global Navigation Satellite System (GNSS) technology, with corrections coming from a network of reference stations (e.g. GPSnet, CORSnet-NSW), it is likely that the coordinates are unaffected by localised distortions and the conformal only grid would be most suitable. However, if survey ground marks were used for referencing / control, localised distortions will likely need to be accounted for and the combined 'conformal and distortion' grid should be used. Some recommendations are shown in Table 6, but if in doubt, contact your state / territory land survey authority.

Table 6: Advice on the use of NTv2 transformation grid files across jurisdictions.

Jurisdiction	NTv2 transformation grid	Comments
ACT	GDA94_GDA2020_conformal	Recommended for users transforming from GDA94 coordinates derived from CORS
ACT	GDA94_GDA2020_conformal_and_distortion	Recommended for users transforming from GDA94 coordinates derived from survey control marks within ACTmapi
NSW	GDA94_GDA2020_conformal	Appropriate for users transforming GDA94 coordinates derived from unlocalised CORS or AUSPOS control.
NSW	GDA94_GDA2020_conformal_and_distortion	Appropriate for users transforming GDA94 coordinates derived from SCIMS (Survey Control Information Management System) or SCIMS-localised CORS control.
NT	GDA94_GDA2020_conformal	Appropriate for users transforming from GDA94 coordinates determined from CORS.

NT	GDA94_GDA2020_conformal_and_distortion	Recommended for users transforming from GDA94 coordinates determined from the survey ground control network.
Qld	GDA94_GDA2020_conformal	Recommended for transforming all GDA94 data sets in Queensland.
Qld	GDA94_GDA2020_conformal_and_distortion	Not recommended for use on Queensland data sets due to distortions at the state borders.
SA	GDA94_GDA2020_conformal	Appropriate for users transforming from GDA94 coordinates determined from CORS.
SA	GDA94_GDA2020_conformal_and_distortion	Recommended for users transforming from GDA94 coordinates determined from the survey ground control network.
Tas	GDA94_GDA2020_conformal	Appropriate for users transforming from GDA94 coordinates determined solely from unlocalised CORS or AUSPOS observations and recommended where the origin of survey control is unknown or mixed (e.g. aggregated datasets available from LISTdata).
Tas	GDA94_GDA2020_conformal_and_distortion	Recommended for users transforming from GDA94 coordinates determined solely from the survey ground control network.
Vic	GDA94_GDA2020_conformal	Recommended for users transforming from GDA94 coordinates derived directly from GNSS CORS.
Vic	GDA94_GDA2020_conformal_and_distortion	Recommended for users transforming from GDA94 coordinates derived from survey control marks within the Survey Marks Enquiry Service (SMES).
WA	GDA94_GDA2020_conformal	Appropriate for users transforming from GDA94 coordinates determined from CORS.
WA	GDA94_GDA2020_conformal_and_distortion	Recommended for users transforming from GDA94 coordinates determined from the local geodetic network (GOLA).
WA – Christmas and Cocos Island	GDA94_GDA2020_conformal	Recommended for Christmas and Cocos Island.

The transformation grids cover the regions shown in Figure 15. Separate conformal transformation grids have also been developed for Christmas Island (EPSG::8444) and Cocos Island (EPSG::8445). In regions not covered by the grids, but within the GDA2020 extent (Chapter 7.4), the 7-parameter similarity transformation is recommended to transform between GDA94 and GDA2020.

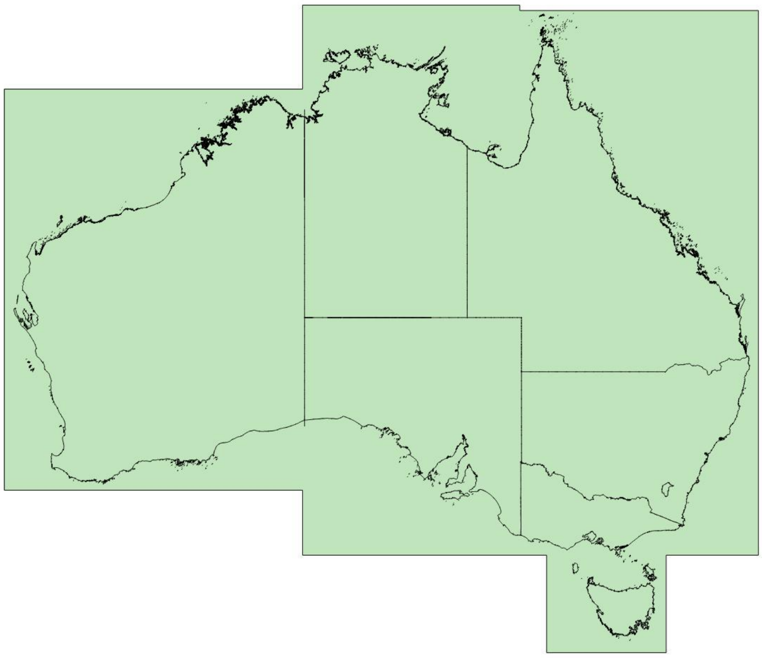

Figure 15: Extent of the GDA94-GDA2020 conformal, and conformal and distortion grids.

10.2.4 Development of transformation grids

The GDA94-GDA2020 transformation grids were developed using over 170,000 points at which both GDA94 and GDA2020 coordinates were available. The difference that remain after the conformal component is removed, is the distortion component. In some regions the distortion component is regular with a similar magnitude and direction (see Figure 16a), while in other cases it is irregular with a different magnitude and/or direction (see Figure 16b). In regions with an irregular distortion component, the transformation grid will be less reliable.

After removing the conformal component, a least squares prediction was used to compute the distortion in latitude $(\Delta\varphi)$ and longitude $(\Delta\lambda)$ on a regular 1' grid (see Figure 16c). The conformal component is then added back to each grid point to complete the conformal + distortion grid.

For a comprehensive review of the development of the transformation grids, refer to Appendix B.

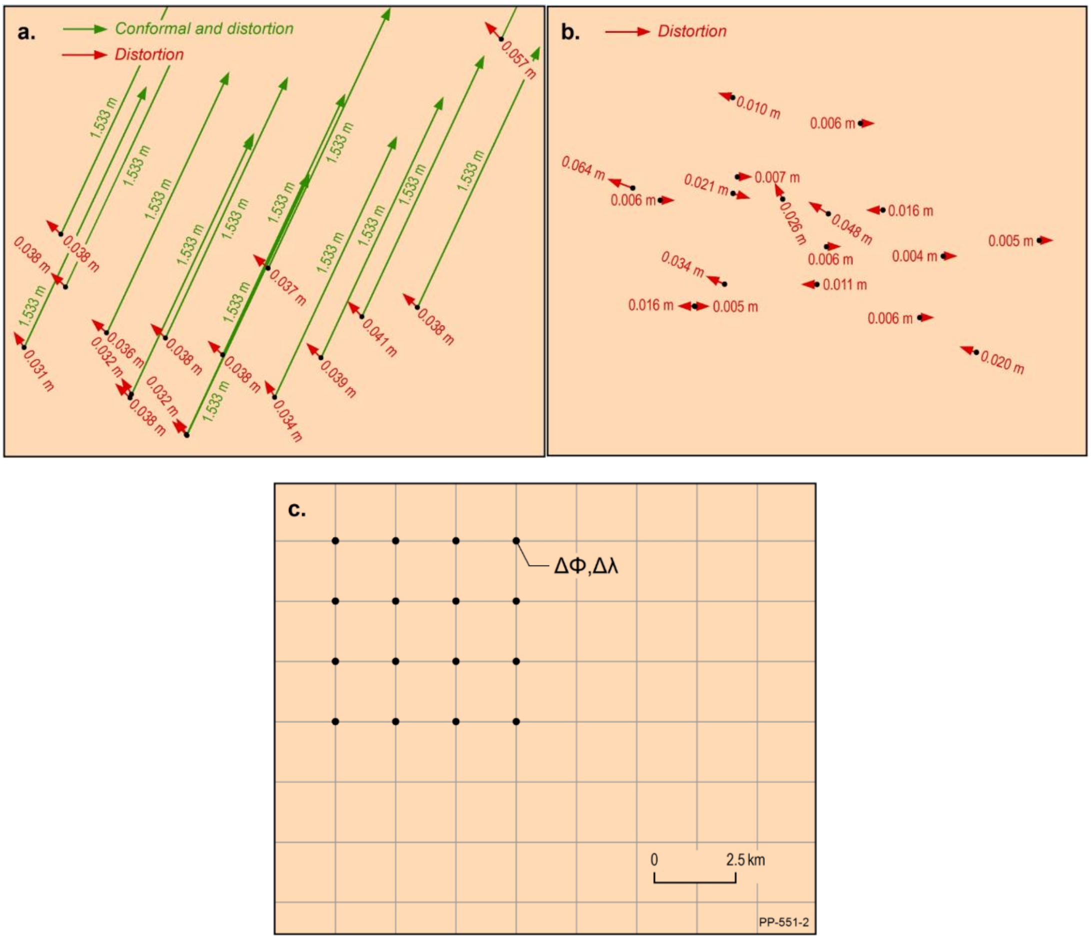

Figure 16 a) conformal (green) and distortion (red; high reliability) components of the transformation grids; b) low reliability; c) the grid has a latitude component and longitude component.

10.3 AGD66/84 - GDA2020 transformation options

ICSM has not defined a set of parameters that directly transform between historical Australian geodetic datums (AGD66 and AGD84) and GDA2020. It is recommended to first transform to GDA94 and then to GDA2020.

For transforming AGD66 or AGD84 coordinates to GDA94, Geoscience Australia recommends the use of the AGD66/84 – GDA94 transformation grids[25].

10.4 ITRF2008 (and older) - GDA2020 transformation parameters

Transformations between ITRF2008 (and older) and GDA2020 have been compiled by ICSM and are shown in Table 7. These transformations are a concatenation of existing ITRFxxxx to GDA94 transformations (Dawson and Woods (2010)) with the GDA94 to GDA2020 similarity transformation. Propagation of coordinates between ITRF2014 and GDA2020 can be performed using the Australian PMM (see Chapter 7.2).

25 https://github.com/icsm-au/transformation_grids

Table 7: ITRF (historic) - GDA2020 transformation parameters. Units are in metres for the translation, parts-per-million for scale, and arcseconds for rotations.

ITRF2008-GDA2020	$t_x, \dot{t}_x$	$t_y, \dot{t}_y$	$t_z, \dot{t}_z$	$s_c, \dot{s}_c$	$r_x, \dot{r}_x$	$r_y, \dot{r}_y$	$r_z, \dot{r}_z$
parameters	0.01379000	0.00455000	0.01522000	0.00255000	0.00028080	0.00026770	-0.00046380
rates	0.00142000	0.00134000	0.00090000	0.00010900	0.00154610	0.00118200	0.00115510

ITRF2005-GDA2020	$t_x, \dot{t}_x$	$t_y, \dot{t}_y$	$t_z, \dot{t}_z$	$s_c, \dot{s}_c$	$r_x, \dot{r}_x$	$r_y, \dot{r}_y$	$r_z, \dot{r}_z$
parameters	0.04032000	-0.03385000	-0.01672000	0.00428600	-0.00128930	-0.00084920	-0.00033420
rates	0.00225000	-0.00062000	-0.00056000	0.00029400	0.00147070	0.00114430	0.00117010

ITRF2000-GDA2020	$t_x, \dot{t}_x$	$t_y, \dot{t}_y$	$t_z, \dot{t}_z$	$s_c, \dot{s}_c$	$r_x, \dot{r}_x$	$r_y, \dot{r}_y$	$r_z, \dot{r}_z$
parameters	-0.10552000	0.05158000	0.23168000	0.00355000	0.00421750	0.00639410	0.00086170
rates	-0.00466000	0.00355000	0.01124000	0.00024900	0.00174540	0.00148680	0.00122400

ITRF1997-GDA2020	$t_x, \dot{t}_x$	$t_y, \dot{t}_y$	$t_z, \dot{t}_z$	$s_c, \dot{s}_c$	$r_x, \dot{r}_x$	$r_y, \dot{r}_y$	$r_z, \dot{r}_z$
parameters	-0.17668000	-0.02913000	0.22699000	-0.00311700	0.00134270	0.00618800	0.00398090
rates	-0.00860000	0.00036000	0.01125000	0.00000700	0.00163940	0.00151980	0.00138010

ITRF1996-GDA2020	$t_x, \dot{t}_x$	$t_y, \dot{t}_y$	$t_z, \dot{t}_z$	$s_c, \dot{s}_c$	$r_x, \dot{r}_x$	$r_y, \dot{r}_y$	$r_z, \dot{r}_z$
parameters	-0.48071000	0.07516000	0.57471000	0.00699500	0.01029950	0.02174580	0.00982920
rates	-0.02180000	0.00471000	0.02627000	0.00038800	0.00202030	0.00217350	0.00162900

The parameters to transform GDA2020 coordinates to ITRFxxxx coordinates are obtained by multiplying the values in Table 7 by -1.

10.5 Transformation of Map Grid coordinates

To transform map grid coordinates from one reference frame to another (e.g. from MGA94 to MGA2020), the suggested approach is:

- Grid to Geographic conversion (MGA94 to GDA94)
- Datum transformation (GDA94 to GDA2020)
- Geographic to Grid conversion (GDA2020 to MGA2020)

- Tools are available to perform these coordinate conversions and transformations from https://www.ga.gov.au/scientific-topics/positioning-navigation/australian-geospatial-reference-system/agrstoolsandmodels or https://github.com/GeoscienceAustralia/GeodePy.

11. Coordinate Conversions

Coordinate conversion is a conversion of coordinates from one coordinate system to a different coordinate system referenced to the same datum (e.g. Cartesian coordinates to geographic coordinates).

11.1 Geographic from / to grid

Two methods are presented to convert geographic to / from grid coordinates; Krueger n-series equations and Krueger λ-series equations (Krueger, 1912). The Krueger λ-series equations are also known as Redfearn's formulae (Redfearn, 1948) and were used in the GDA94 Technical Manual. These equations are accurate to better than 1 mm within any zone of the Map Grid of Australia 1994, Map Grid of Australia 2020 and can still be used for many purposes. However, for applications where users are working across multiple UTM/MGA zones, Krueger n-series equations are recommended and are explained in this Technical Manual. The Krueger n-series equations are particularly beneficial in software to avoid error build up when conversions are done back and forth between geographic and grid coordinates.

11.1.1 Krueger n-series equations

Krueger's n-series equations (Karney, 2011) with coefficients that are functions of n (a geometric constant of the reference ellipsoid known as the third flattening), give micrometre accuracy anywhere within 30° of a central meridian (Deakin et al., 2012).

The National Geospatial-Intelligence Agency have adopted the Krueger n-series equations (to the 6th power of n) for improved efficiency and expanded coverage of the ellipsoid. Software that uses these formula are usually shorter and simpler to write, and, by implication, less likely to have bugs than other methods (NGA, 2014b).

A spreadsheet is available on the ICSM GitHub repository **(**https://github.com/icsm-au/DatumSpreadsheets**)** to perform geographic to grid conversions (and vice-versa) with Krueger n-series equations (Karney, 2011; Deakin, 2014).

The development of the Krueger n-series equations for the transverse Mercator projection involves three steps (Figure 17):

1. Mapping of the ellipsoid to a conformal sphere (a sphere of radius A).
2. Mapping of the conformal sphere to the plane using spherical transverse Mercator projection equations with spherical latitude replaced by conformal latitude; yielding Gauss-Schreiber coordinates with a scale factor on the central meridian, which is not constant.
3. Mapping of Gauss-Schreiber coordinates (plane) to transverse Mercator coordinates (plane) with a scale factor on the central meridian that is constant.

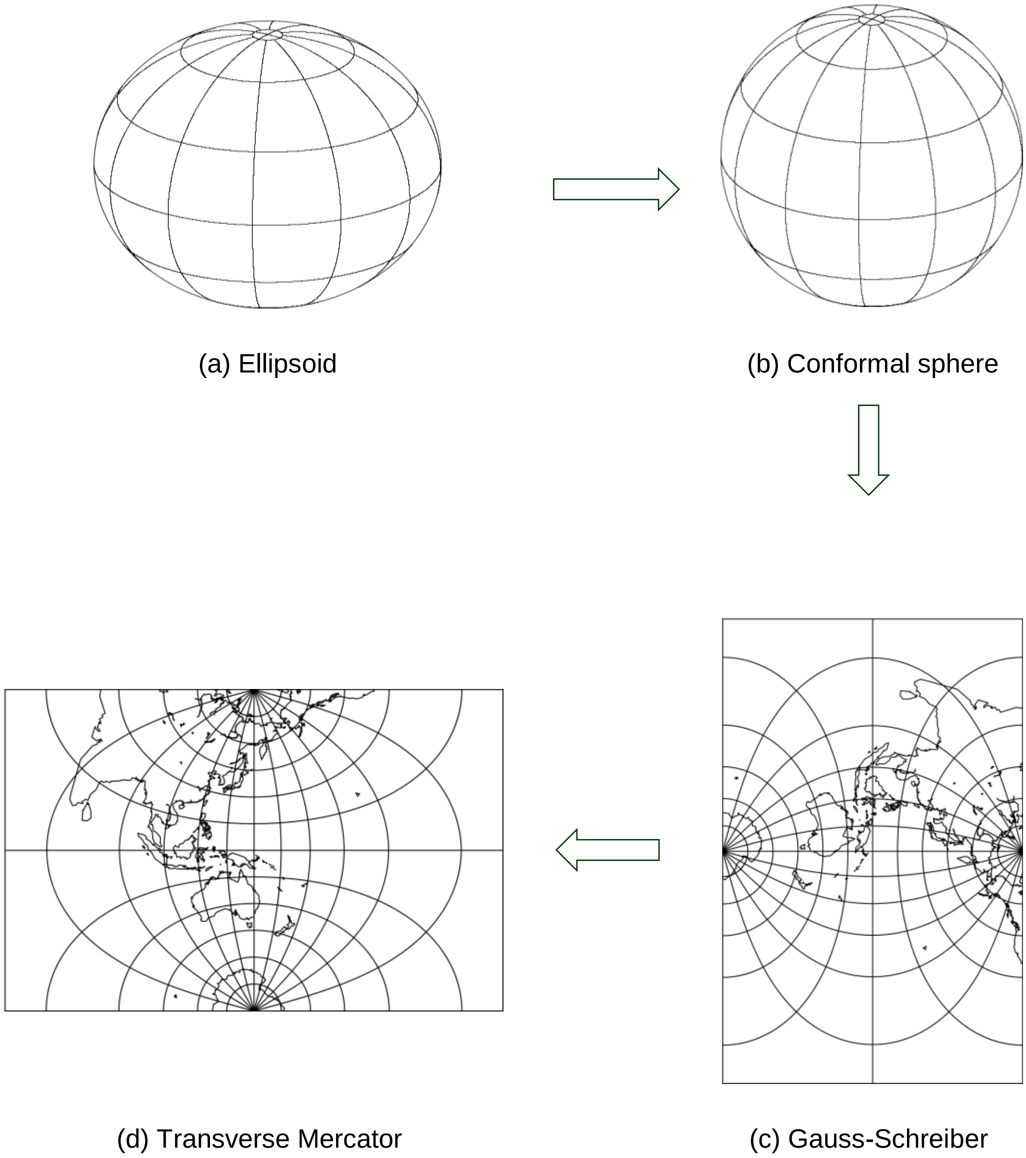

Figure 17: Sequence of conformal mapping used for geographic to grid conversion using Krueger n-series (adapted from Deakin, 2014).

11.1.2 Forward conversion (geographic to grid)

The forward conversion (geographic to grid) converts the latitude and longitude to eastings and northings using the ellipsoidal parameters a, f, the longitude of the central meridian λ_0, the central scale factor k_0 and the offsets of the false origin.

The following are the steps required to perform the conversion. For more information on the derivation of the equations or more efficient numerical evaluations, refer to Deakin et al. (2012).

1. Compute ellipsoidal constants (ε^2, n)

$$\varepsilon^2 = \frac{a^2 - b^2}{a^2} = f(2 - f) \tag{18}$$

$$n = \frac{a-b}{a+b} = \frac{f}{2-f} \tag{19}$$

2. Compute the rectifying radius A

$$A = \frac{a}{1+n}\left\{1 + \frac{1}{4}n^2 + \frac{1}{64}n^4 + \frac{1}{256}n^6 + \frac{25}{16384}n^8 + \cdots\right\} \tag{20}$$

3. Compute the coefficients $\{\alpha_{2r}\}$ for $r = 1, 2, \ldots, 8$

$$\begin{aligned}
\alpha_2 &= \frac{1}{2}n - \frac{2}{3}n^2 + \frac{5}{16}n^3 + \frac{41}{180}n^4 - \frac{127}{288}n^5 + \frac{7891}{37800}n^6 + \frac{72161}{387072}n^7 - \frac{18975107}{50803200}n^8 \\
\alpha_4 &= \frac{13}{48}n^2 - \frac{3}{5}n^3 + \frac{557}{1440}n^4 + \frac{281}{630}n^5 - \frac{1983433}{1935360}n^6 + \frac{13769}{28800}n^7 + \frac{148003883}{174182400}n^8 \\
\alpha_6 &= \frac{61}{240}n^3 - \frac{103}{140}n^4 + \frac{15061}{26880}n^5 + \frac{167603}{181440}n^6 - \frac{67102379}{29030400}n^7 + \frac{79682431}{79833600}n^8 \\
\alpha_8 &= \frac{49561}{161280}n^4 - \frac{179}{168}n^5 + \frac{6601661}{7257600}n^6 + \frac{97445}{49896}n^7 - \frac{40176129013}{7664025600}n^8 \\
\alpha_{10} &= \frac{34729}{80640}n^5 - \frac{3418889}{1995840}n^6 + \frac{14644087}{9123840}n^7 + \frac{2605413599}{622702080}n^8 \\
\alpha_{12} &= \frac{212378941}{319334400}n^6 - \frac{30705481}{10378368}n^7 + \frac{175214326799}{58118860800}n^8 \\
\alpha_{14} &= \frac{1522256789}{1383782400}n^7 - \frac{16759934899}{3113510400}n^8 \\
\alpha_{16} &= \frac{1424729850961}{743921418240}n^8
\end{aligned} \tag{11}$$

4. Compute conformal latitude ϕ'

$$\tan\phi' = \tan\phi\sqrt{1+\sigma^2} - \sigma\sqrt{1+\tan^2\phi} \tag{22}$$

where

$$\sigma = \sinh\left\{\varepsilon \tanh^{-1}\left(\frac{\varepsilon\tan\phi}{\sqrt{1+\tan^2\phi}}\right)\right\} \tag{23}$$

5. Compute longitude difference

$$\omega = \lambda - \lambda_0 \tag{24}$$

6. Compute the Gauss-Schreiber ratios from the $\xi' = \frac{u}{a}$ and $\eta' = \frac{v}{a}$ from the Gauss-Schreiber coordinates u, v

$$\xi' = \tan^{-1}\left(\frac{\tan\phi'}{\cos\omega}\right) \tag{25}$$

$$\eta' = \sinh^{-1}\left(\frac{\sin\omega}{\sqrt{\tan^2\phi' + \cos^2\omega}}\right) \tag{26}$$

7. Compute the transverse Mercator ratios $\eta = \frac{X}{A}$ and $\xi = \frac{Y}{A}$

$$\eta = \eta' + \sum_{r=1}^{N} \alpha_{2r} \cos 2r\,\xi' \sinh 2r\,\eta' \tag{27}$$

$$\xi = \xi' + \sum_{r=1}^{N} \alpha_{2r} \sin 2r\,\xi' \cosh 2r\,\eta' \tag{28}$$

8. Compute the traverse Mercator coordinates X, Y

$$X = A\eta \tag{29}$$

$$Y = A\xi \tag{30}$$

9. Compute the MGA2020 coordinates E, N

$$E = k_0 X + E_0 \tag{31}$$

$$N = k_0 Y + N_0 \tag{32}$$

where E_0 N_0 are the false easting and northing respectively.

10. Compute q and p (to order n^8 and $N = 8$)

$$q = -\sum_{r=1}^{N} 2r\alpha_{2r} \sin 2r\,\xi' \sinh 2r\,\eta' \tag{33}$$

$$p = 1 + \sum_{r=1}^{N} 2r\alpha_{2r} \cos 2r\,\xi' \cosh 2r\,\eta' \tag{34}$$

11. Compute the point scale factor k

$$k = k_0 \left(\frac{A}{a}\right) \sqrt{q^2 + p^2} \left\{ \frac{\sqrt{1 + \tan^2\phi}\sqrt{1 - \varepsilon^2 \sin^2\phi}}{\sqrt{\tan^2\phi' + \cos^2\omega}} \right\} \tag{35}$$

12. Compute the grid convergence γ

$$\gamma = tan^{-1}\left\{\left|\frac{q}{p}\right|\right\} + tan^{-1}\left\{\frac{|tan\,\phi'\,tan\,\omega|}{\sqrt{1 + tan^2\,\phi'}}\right\} \tag{36}$$

11.1.3 Inverse conversion (grid to geographic)

The inverse conversion (grid to geographic) converts eastings and northings to latitude and longitude.

1. Compute ellipsoidal constants (ε^2, n). See Equations (18, 19)
2. Compute the rectifying radius A. See Equation (20)
3. Compute the coefficients $\{\alpha_{2r}\}$ for $\mathrm{r} = 1, 2, \ldots, 8$. See Equation (21)
4. Compute the coefficients $\{\beta_{2r}\}$ for $\mathrm{r} = 1, 2, \ldots, 8$.

$$\begin{aligned}
\beta_2 &= -\frac{1}{2}n + \frac{2}{3}n^2 - \frac{37}{96}n^3 + \frac{1}{360}n^4 + \frac{81}{512}n^5 - \frac{96199}{604800}n^6 + \frac{5406467}{38707200}n^7 - \frac{7944359}{67737600}n^8 \\
\beta_4 &= -\frac{1}{48}n^2 - \frac{1}{15}n^3 + \frac{437}{1440}n^4 - \frac{46}{105}n^5 + \frac{1118711}{3870720}n^6 - \frac{51841}{1209600}n^7 - \frac{24749483}{348364800}n^8 \\
\beta_6 &= -\frac{17}{480}n^3 + \frac{37}{840}n^4 + \frac{209}{4480}n^5 - \frac{5569}{90720}n^6 - \frac{9261899}{58060800}n^7 + \frac{6457463}{17740800}n^8 \\
\beta_8 &= -\frac{4397}{161280}n^4 + \frac{11}{504}n^5 + \frac{830251}{7257600}n^6 - \frac{466511}{2494800}n^7 - \frac{324154477}{7664025600}n^8 \\
\beta_{10} &= -\frac{4583}{161280}n^5 + \frac{108847}{3991680}n^6 + \frac{8005831}{63866880}n^7 - \frac{22894433}{124540416}n^8 \\
\beta_{12} &= -\frac{20648693}{638668800}n^6 + \frac{16363163}{518918400}n^7 + \frac{2204645983}{12915302400}n^8 \\
\beta_{14} &= -\frac{219941297}{5535129600}n^7 + \frac{497323811}{12454041600}n^8 \\
\beta_{16} &= -\frac{191773887257}{3719607091200}n^8
\end{aligned} \tag{37}$$

5. Compute the transverse Mercator coordinates X, Y

$$X = \frac{E - E_0}{k_0} \tag{38}$$

$$Y = \frac{N - N_0}{k_0} \tag{39}$$

6. Compute the transverse Mercator ratios η and ξ

$$\eta = \frac{X}{A} \tag{40}$$

$$\xi = \frac{Y}{A} \tag{41}$$

7. Compute the Gauss-Schreiber ratios $\xi' = \frac{u}{a}$ and $\eta' = \frac{v}{a}$

$$\eta' = \eta + \sum_{r=1}^{N} \beta_{2r} \cos 2r\,\xi \sinh 2r\,\eta \tag{42}$$

$$\xi' = \xi + \sum_{r=1}^{N} \beta_{2r} \sin 2r\,\xi \cosh 2r\,\eta \tag{43}$$

8. Compute $t' = \tan\phi'$

$$t' = \tan\phi' = \frac{\sin\xi'}{\sqrt{\sinh^2\eta' + \cos^2\xi'}} \tag{44}$$

9. Solve for $t = \tan\phi$ by Newton-Raphson iteration and then determine latitude ϕ

The equations linking $t = \tan\phi$ and $t' = \tan\phi'$ are (22) and (23) given here in modified form

$$t' = t\sqrt{1+\sigma^2} - \sigma\sqrt{1+t^2} \tag{45}$$

where

$$\sigma = sinh\left\{\varepsilon\, tanh^{-1}\left(\frac{\varepsilon t}{\sqrt{1+t^2}}\right)\right\} \tag{46}$$

t can be evaluated using the Newton-Raphson method for the real roots of the equation $f(t) = 0$ given in the form of an iterative equation

$$t_{n+1} = t_n - \frac{f(t_n)}{f'(t_n)} \tag{47}$$

where t_n denotes the nth iterate and $f(t)$ is given by

$$f(t) = t\sqrt{1+\sigma^2} - \sigma\sqrt{1+t^2} - t' \tag{48}$$

and $t' = \tan\phi'$ is a fixed value. The derivative is given by

$$f'(t) = \left(\sqrt{1+\sigma^2}\sqrt{1+t^2} - \sigma t\right)\frac{(1-\varepsilon^2)\sqrt{1+t^2}}{1+(1-\varepsilon^2)t^2} \qquad (49)$$

An initial value for t_1 can be taken as $t_1 = t' = \tan\phi'$ and the functions $f(t_1)$ and $f'(t_1)$ evaluated from equations (46), (48) and (49). t_2 is computed from equation (47) and this process repeated to obtain $t_3, t_4, \ldots$. This iterative process can be concluded when the difference between t_{n+1} and t_n reaches an acceptably small value, and then the latitude is given by

$$\phi = \tan^{-1} t_{n+1} \qquad (50)$$

10. Compute longitude difference ω and longitude λ from

$$\tan\omega = \frac{\sinh\eta'}{\cos\xi'} \qquad (51)$$

$$\lambda = \lambda_0 \pm \omega \qquad (52)$$

11. Compute q and p. See Equations (33) and (34).
12. Compute the point scale factor k. See Equation (35).
13. Compute the grid convergence γ. See Equation (36).

11.1.4 Krueger λ-series equations (Redfearn's formulae)

The Krueger λ-series equations (also known as Redfearn's formulae) may be used to convert between geographic coordinates (latitude, longitude) and grid coordinates (easting, northing and zone) for a transverse Mercator projection, such as the Map Grid of Australia (MGA). These formulae are accurate to better than 1 mm within any zone of the Map Grid of Australia. Further information on the Krueger λ-series equations can be found in the GDA94 Technical Manual.

If you require formulae to provide accurate geographic to / from grid conversion across multiple zones, the Krueger n-series equations are recommended (Chapter 11.1.1).

A number of tools are available to perform conversions using Krueger λ-series equations including:

- Geographic to Grid: (http://www.ga.gov.au/geodesy/datums/redfearn_geo_to_grid.jsp)
- Grid to Geographic: (http://www.ga.gov.au/geodesy/datums/redfearn_grid_to_geo.jsp)
- Spreadsheet (https://github.com/icsm-au/DatumSpreadsheets)

11.1.5 Zone-to-zone transformations

If a point lies within 0.5° of a zone boundary, it is possible to compute the grid coordinate of the point in terms of the adjacent zone. This can be done by:

1. Converting the known grid coordinates to geographic coordinates using Krueger n-series or Krueger λ-series equations, and then converting back to grid coordinates in terms of the adjacent zone, or
2. Using the formulae shown below (Jordan and Eggert 1941; Grossmann 1964). These formulae have an accuracy of 10 mm anywhere within 0.5° of a zone boundary.

11.1.5.1 Formulae

$$\tan J_1 = [\omega_z{}^2 \cos^2\phi_z(1+31\tan^2\phi_z) - 6(1+\varepsilon'^2\cos^2\phi_z)]/[18\omega_z \sin\phi_z(1+\varepsilon'^2\cos^2\phi_z)] \tag{53}$$

$$H_1 = -3\omega_z{}^2 \sin\phi_z \cos\phi_z /(\rho_z \cos J_1) \tag{54}$$

$$E_2 = 500\,000 - E'_z + (E'_1 - E'_z)\cos 2\gamma_z - (N_1 - N_z)\sin 2\gamma_z + H_1 L^2 \sin(2\theta_z + J_1) \tag{55}$$

$$N_2 = N_z + (N_1 - N_z)\cos 2\gamma_z + (E'_1 - E'_z)\sin 2\gamma_z + H_1 L^2 \cos(2\theta_z + J_1) \tag{56}$$

where:

Z	is a point on the zone boundary
E_1, N_1	are the known coordinates of the point to be transformed
E_2, N_2	are the coordinates of the point in terms of the adjacent zone
θ_z	is the plane bearing from Z to the point to be transformed

12. Coordinate computations

12.1 Ellipsoid computations

12.1.1 Reduction of measured distances to the ellipsoid

Due to the effects of atmospheric refraction, the light waves or microwaves used by Electronic Distance Measurement (EDM) devices follow a curved path. Before this curved wave path distance can be used for geodetic computations, it should be reduced to the surface of the ellipsoid by the application of both physical and geometric corrections.

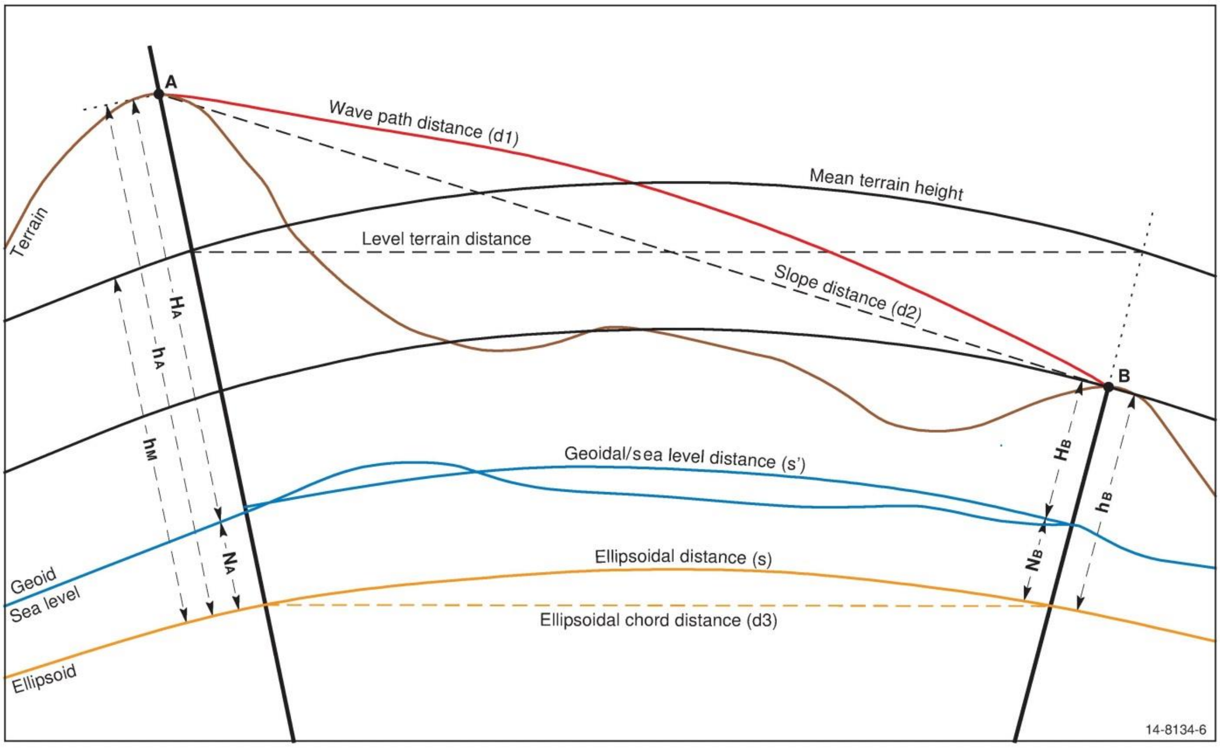

Figure 18: Reduction of distance to the ellipsoid.

The difference between the wave path distance d_1 and the slope distance (wave path chord) d_2 is a function of the EDM equipment used and also of the meteorological conditions prevailing along the wave path at the time of measurement. This difference can often be ignored for distance measurements of up to 15 kilometres, using either light waves or microwaves. Physical corrections, which involve the application of certain velocity corrections to the measured wave path distance, are not discussed in this manual.

12.1.1.1 Combined formula

The reduction of the wave path chord distance d_2, to the ellipsoidal chord distance d_3, can be given as a single rigorous formula (Clark, 1966)

$$d_3 = \sqrt{\left[\left({d_2}^2 - (h_A - h_B)^2\right)/(1 + h_A/R_\alpha)(1 + h_B/R_\alpha)\right]} \quad (57)$$

The ellipsoidal chord distance d_3 can then be reduced to the ellipsoidal arc distance s

$$s = d_3\left[1 + \left({d_3}^2/24{R_\alpha}^2 + 3{d_3}^4/640{R_\alpha}^4 + \ldots\right)\right] \quad (58)$$

where R_α is the radius of curvature in the azimuth of the line.

For a distance of 30 kilometres in the Australian region the chord-to-arc correction is 0.028 m. For a distance of 50 km, the correction reaches about 0.13 m and it is more than 1 m at 100 km. The second term in the chord-to-arc correction is less than 1 mm for lines up to 100 km anywhere in Australia and can usually be ignored.

12.1.1.2 Separate formulae

The combined formula above includes the slope and ellipsoid level corrections. The slope correction reduces the wave path chord d_2 to a horizontal distance at the mean elevation of the terminals of the line (terrain distance) and the ellipsoid level correction reduces the horizontal distance to the ellipsoid chord distance d_3. The chord-to-arc correction is then applied to the ellipsoid chord distance, as with the combined formula, to give the ellipsoidal arc distance s.

Slope correction	$\left({d_2}^2 - \Delta h^2\right)^{1/2} - d_2$	(59)
Ellipsoidal correction	$(h_m/R_\alpha)\left({d_2}^2 - \Delta h^2\right)^{1/2}$	(60)
Chord to arc correction	$+{d_3}^3/24{R_\alpha}^2\{+3{d_3}^5/640{R_\alpha}^4 + \ldots\}$	(61)

Observations using total stations are often reduced to terrain distances, while GNSS observations are reduced to the ellipsoid. These distances can be significantly different depending on the height of the terrain. A change in height of 6.5 m causes approximately a one part per million (1 ppm) effect on distances. For example, at 650 m above the ellipsoid, the difference between terrain and ellipsoidal distances is approximately 100 ppm. Similarly, variations in height across surveys covering a large area may also be significant (DNRM, 2016).

12.1.1.3 Heights in distance reduction

The formulae given in this Chapter use ellipsoidal heights h. If the geoid-ellipsoid separation N is ignored and only the height above the geoid H (orthometric or AHD height) is used, an error of 1 ppm will be introduced for every 6.5 m of N (plus any error due to the change in N value along the line). As the geoid-ellipsoid separation value varies from -35 m in southwest Australia, to approximately 70 m in northeast Australia, errors from -5 to approximately 11 ppm could be expected. In areas where the geoid-ellipsoid separation is small and the corresponding error would also be small.

12.1.1.4 Radius of curvature

The radius of curvature of the ellipsoid is a function of latitude. For many applications the geometric mean radius $R_{m,}$ can be used rather than the radius in the azimuth of the line R_α. However, there can be a large difference between the geometric mean radius and the radius in the azimuth of the line. For high accuracy applications the radius of curvature in the azimuth of the line should be used.

$$R_m = \sqrt{\rho\nu} \quad (62)$$

$$R_\alpha = (\rho\nu)/(\nu\cos^2\alpha + \rho\sin^2\alpha) \qquad (63)$$

where:

$$\rho = a(1-\varepsilon^2)/(1-\varepsilon^2 sin^2\phi)^{3/2} \qquad (64)$$

$$\upsilon = a/(1-\varepsilon^2 sin^2\phi)^{1/2} \qquad (65)$$

12.1.2 Reduction of measured directions to the ellipsoid

When a total station is levelled to make an angular observation (direction or azimuth) it is levelled according to the plumbline at that point, i.e. the normal to the geoid. This is generally different from the normal to the ellipsoid at the same point. This difference is known as the deflection of the vertical. The correction for this deflection is generally small, but should be applied for the highest quality results. Deflection of the vertical can be computed from astronomic and geodetic coordinates at the same point, or they can be produced from a geoid model such as AUSGeoid2020.

A further correction can be made to account for the fact that the normals at each end of the line are not parallel (the skew normal correction). This too is a small correction and except in mountainous country, it can reasonably be ignored (Bomford, 1980).

Because they are related to a particular ellipsoid, deflection of the vertical, like geoid ellipsoid separations, will be different for different datums. Within Australia, the maximum deflection in terms of GDA94 and GDA2020 is of the order of twenty seconds of arc, which could result in a correction to an observed direction or azimuth approaching half a second of arc.

The Laplace correction defines the relationship between an astronomically observed azimuth and a geodetic azimuth. It can be a significant correction, of the order of several seconds of arc, and should always be applied to an astronomic azimuth before computing coordinates.

The formulae for these corrections are often given using the astronomic convention, with east longitude negative. However, the formulae used here have been rearranged to use the geodetic conventions, as used elsewhere in this manual (east longitude positive).

12.1.2.1 Formulae

Direction (reduced) = Direction (measured)

+ Deflection correction

+ Skew normal correction

+ Laplace correction (Laplace for azimuth only)

Deflection correction = $-\zeta \tan e$ *(66)*

where $\zeta = \xi \, sin\, \alpha - \eta \, cos\, \alpha$ *(67)*

If the elevation angle e is not known, an effective estimate can be obtained from:

$$\tan e = [(H_2 - H_1) - 0.067\, D^2]\,/1000D \qquad (68)$$

Skew normal correction $= e'^2 H_2 \cos^2 \phi \sin(2\alpha)/2R$ (69)

Laplace correction $= (\lambda_A - \lambda_G) \sin \phi$ (70)

12.1.3 Positions, azimuth and distances

There are a number of formulae available to calculate accurate geodetic positions, azimuths and distances on the ellipsoid (Bomford, 1980). Vincenty's formulae (Vincenty, 1975) may be used for lines ranging from a few centimetres to nearly 20,000 km, with millimetre accuracy. The formulae have been extensively tested for the Australian region by comparison with results from other formulae (Rainsford 1955; Sodano 1965).

12.1.3.1 Vincenty's inverse formula

Given the latitude and longitude of two points ϕ_1, λ_1 and ϕ_2, λ_2 Vincenty's inverse formula can be used to calculate the ellipsoidal arc distance s and forward and reverse azimuths between the points $(\alpha_{1-2}, \alpha_{2-1})$.

$$\tan U_1 = (1 - f) \tan \phi_1 \quad (71)$$

$$\tan U_2 = (1 - f) \tan \phi_2 \quad (72)$$

Starting with the approximation,

$$\lambda = \omega = \lambda_2 - \lambda_1 \quad (73)$$

iterate the following equations, until there is no significant change in σ:

$$\sin^2\sigma = (\cos U_2 \sin \lambda)^2 + (\cos U_1 \sin U_2 - \sin U_1 \cos U_2 \cos \lambda)^2 \quad (74)$$

$$\cos \sigma = \sin U_1 \sin U_2 + \cos U_1 \cos U_2 \cos \lambda \quad (75)$$

$$\tan \sigma = \sin \sigma / \cos \sigma \quad (76)$$

$$\sin \alpha = \cos U_1 \cos U_2 \sin \lambda / \sin \sigma \quad (77)$$

$$\cos 2\sigma_m = \cos \sigma - (2 \sin U_1 \sin U_2 / \cos^2 \alpha) \quad (78)$$

$$C = (f/16) \cos^2\alpha \, [4 + f(4 - 3\cos^2\alpha)] \quad (79)$$

$$\lambda = \omega + (1 - C) f \sin \alpha \{\sigma + C \sin \sigma [\cos 2\sigma_m + C \cos \sigma (-1 + 2\cos^2 2\sigma_m)]\}$$

(80)

then:

$$u^2 = cos^2\alpha \, (a^2 - b^2)/b^2 \quad (81)$$

$$A = 1 + (u^2/16384) \{4096 + u^2[-768 + u^2(320 - 175u^2)]\} \quad (82)$$

$$B = (u^2/1024) \{256 + u^2[-128 + u^2(74 - 47u^2)]\} \quad (83)$$

$$\Delta\sigma = B \sin \sigma \{\cos 2\sigma_m + (B/4) [\cos \sigma(-1 + 2\cos^2 2\sigma_m) - (B/6) \cos 2\sigma_m(-3 + 4\sin^2\sigma)(-3 + 4\cos^2 2\sigma_m)]\}$$

(84)

$$s = bA(\sigma - \Delta\sigma) \quad (85)$$

$$\tan \alpha_{1-2} = (\cos U_2 \sin \lambda)/(\cos U_1 \sin U_2 - \sin U_1 \cos U_2 \cos \lambda) \quad (86)$$

$$\tan \alpha_{2-1} = (\cos U_1 \sin \lambda)/(-\sin U_1 \cos U_2 + \cos U_1 \sin U_2 \cos \lambda) \quad (87)$$

12.1.3.2 Vincenty's direct formula

Given the latitude and longitude of a point ϕ_1, λ_1 the geodetic azimuth α_{1-2} and ellipsoidal distance to a second point s, Vincenty's direct formula can be used to calculate the latitude and longitude of the second point ϕ_2, λ_2 and the reverse azimuth α_{2-1}.

$$\tan U_1 = (1 - f) \tan \Phi_1 \quad (88)$$

$$\tan \sigma_1 = \tan U_1 / \cos \alpha_{1-2} \quad (89)$$

$$\sin \alpha = \cos U_1 \sin \alpha_{1-2} \quad (90)$$

$$u^2 = \cos^2\alpha \, (a^2 - b^2)/b^2 \quad (91)$$

$$A = 1 + (u^2/16384)\,\{4096 + u^2[-768 + u^2(320 - 175u^2)]\} \quad (92)$$

$$B = (u^2/1024)\,\{256 + u^2[-128 + u^2(74 - 47u^2)]\} \quad (93)$$

Starting with the approximation

$$\sigma = (s/bA) \quad (94)$$

iterate the following three equations until there is no significant change in σ

$$2\sigma_m = 2\sigma_1 + \sigma \quad (95)$$

$$\Delta\sigma = B \sin \sigma \{\cos 2\sigma_m + (B/4)\,[\cos \sigma(-1 + 2\cos^2 2\sigma_m) - (B/6) \cos 2\sigma_m (-3 + 4\sin^2\sigma)(-3 + 4\cos^2 2\sigma_m)]\} \quad (96)$$

$$\sigma = (s/bA) + \Delta\sigma \quad (97)$$

then

$$\tan \phi_2 = (\sin U_1 \cos \sigma + \cos U_1 \sin \sigma \cos \alpha_{1-2}) / \left\{(1 - f)[\sin^2\alpha + (\sin U_1 \sin \sigma - \cos U_1 \cos \sigma \cos \alpha_{1-2})^2]^{\frac{1}{2}}\right\} \quad (98)$$

$$\tan \lambda = (\sin \sigma \sin \alpha_{1-2})/(\cos U_1 \cos \sigma - \sin U_1 \sin \sigma \cos \alpha_{1-2}) \quad (99)$$

$$C = (f/16)\cos^2\alpha[4 + f(4 - 3\cos^2\alpha)] \quad (100)$$

$$\omega = \lambda - (1 - C) f \sin \alpha\{\sigma + C \sin \sigma[\cos 2\sigma_m + C \cos \sigma(-1 + 2cos^2 2\sigma_m)]\} \quad (101)$$

$$\lambda_2 = \lambda_1 + \omega \quad (102)$$

$$\tan \alpha_{2-1} = (\sin \alpha)/(-\sin U_1 \sin \sigma + \cos U_1 \cos \sigma \cos \alpha_{1-2}) \quad (103)$$

“The inverse formulae may give no solution over a line between two nearly antipodal points. This will occur when λ is greater than π in absolute value." (Vincenty, 1975)

In Vincenty (1975) L is used for the difference in longitude, however for consistency with other formulae in this Compendium, ω is used here.

12.1.3.3 Sample Data

Table 8: Sample data to check Vincenty’s calculations

Flinders Peak	-37° 57’ 03.72030"	144° 25’ 29.52440"
Buninyong	-37° 39’ 10.15610"	143° 55’ 35.38390"
Ellipsoidal distance	54,972.271 m	
Forward azimuth	306° 52’ 05.37"	
Reverse azimuth	127° 10’ 25.07"	

12.1.3.4 Ellipsoid computation tools

Tools available to perform ellipsoid computations are:

- Vincenty’s Inverse: (https://geodesyapps.ga.gov.au/vincenty-inverse)
- Vincenty’s Direct: (https://geodesyapps.ga.gov.au/vincenty-direct)
- Spreadsheet (https://github.com/icsm-au/DatumSpreadsheets)

13. Map Grid of Australia 2020

Geodetic coordinates (latitude and longitude) are represented on a map or chart, by mathematically projecting them onto a two-dimensional plane. The Transverse Mercator (TM) projection is a conformal mapping of geodetic coordinates from the ellipsoid onto a plane where the equator and central meridian remain as straight lines and the scale along the central meridian is constant while meridians and parallels are projected as complex curves (Figure 19).

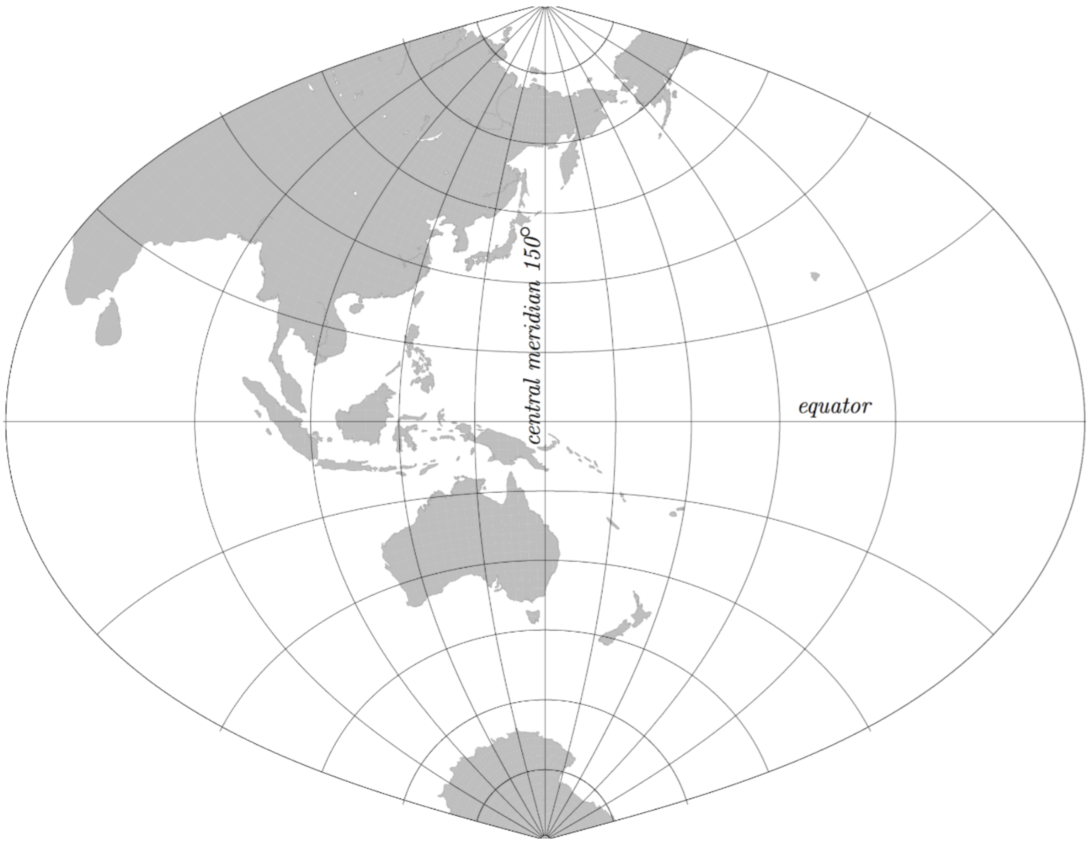

Figure 19: Transverse Mercator projection with central meridian of 150 degrees.

The TM projection is useful to map regions with large extents of latitude; however, distortions increase rapidly away from the central meridian. The UTM coordinate system (Table 9) uses the TM projection and attempts to overcome this limitation by dividing the Earth into 60 zones, each with a width of 6° of longitude. A central meridian is placed in the middle of each longitudinal zone. As a result, within a zone nothing is more than 3° from the central meridian and therefore locations, shapes and sizes and directions between all features are very accurate.

The true origin for each zone is the intersection of the equator and the central meridian, but a false origin is often used to avoid negative coordinates (Figure 20).

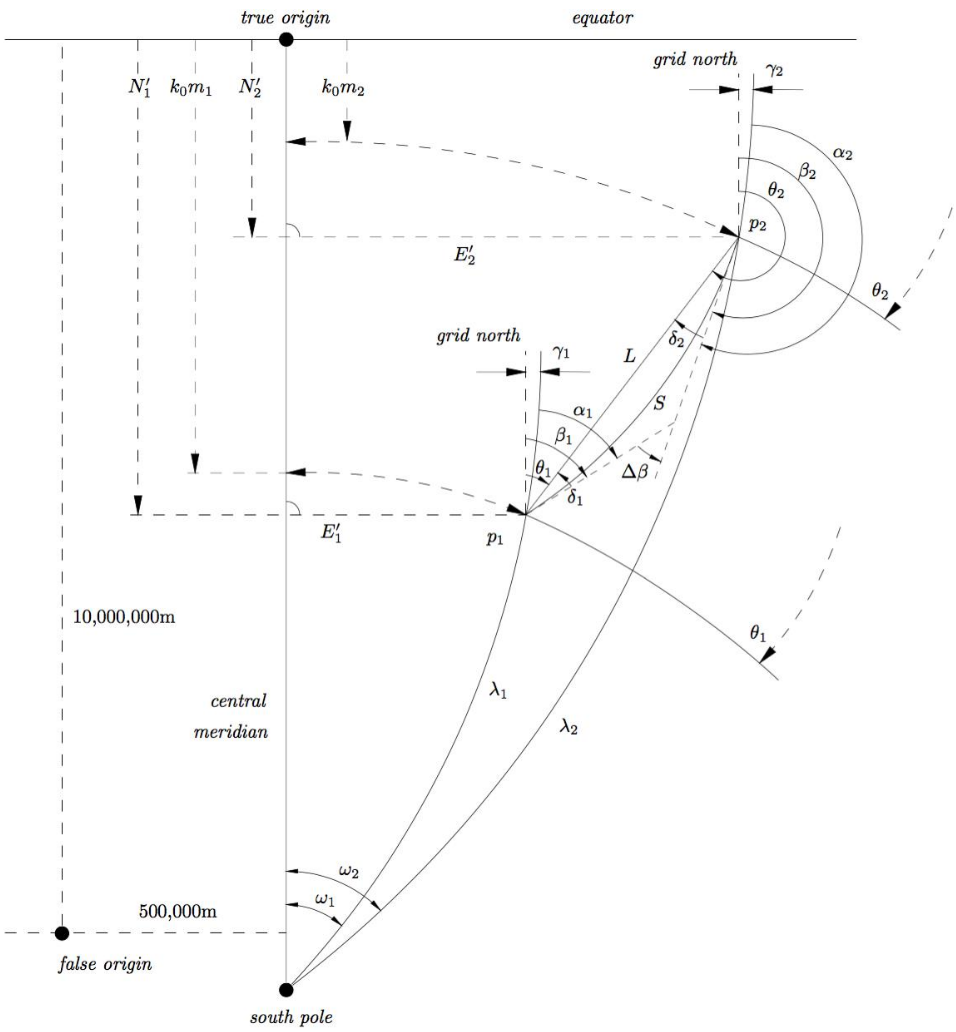

Figure 20: Relationship between geographic coordinates and projected coordinates.

Table 9: UTM coordinate system parameters.

Parameter	Value
Longitude of initial central meridian (Zone 1)	177 degrees west longitude
Zone width	6 degrees
Central scale factor	0.9996
False Easting	500,000 m
False Northing (in the southern hemisphere)	10,000,000 m

The UTM coordinate system has been used with the GRS80 ellipsoid and GDA2020 latitudes and longitudes to define Map Grid of Australia 2020 (MGA2020).

The Krueger n-series or Krueger λ-series formulae are used to convert between UTM (or MGA2020) coordinates and geographic coordinates and vice versa (Chapter 11.1).

Part C: Physical Geodesy

14. Preliminaries

14.1 Physical Height Datums

Fluid will flow from points of higher gravitational potential to points of lower gravitational potential. An ellipsoid does not have equal gravitational potential. In fact, across Australia, the height difference between a surface with equal gravitational potential (called the geoid) and the ellipsoid is between -30 and +80 m (Figure 21).

For this reason, many positioning applications require ellipsoidal heights observed using Global Navigation Satellite Systems (GNSS) to be converted to physical heights (a height with respect to the Earth's gravitational potential) using a geoid model.

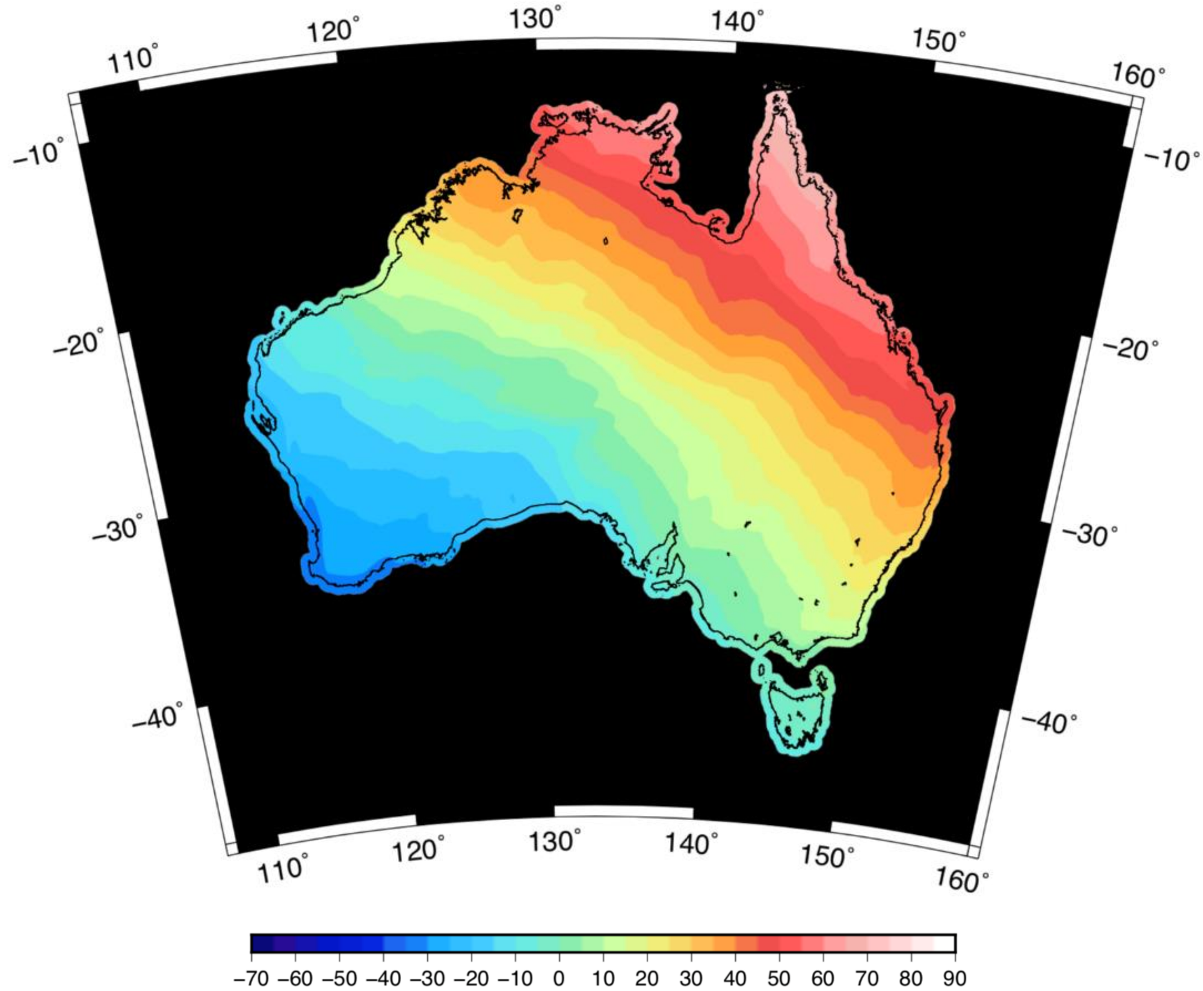

Figure 21: The difference between the geoid and the ellipsoid is between -30 and +80 m across Australia.

14.2 Height Systems and Height Datums

A height system is a coordinate system used to define the height of a point above or below a reference surface. Its definition varies according to the reference surface chosen (e.g. geoid) the path along which the height is measured (e.g. plumbline).

A height datum is the practical realisation of a height system (e.g. Australian Height Datum).

A height system could have many realisations (datums) as new theories, computational process and data become available. Generally, each new height datum is a better (e.g. more accurate, reliable, robust) realisation of the height system.

Although there is only one national height datum in Australia, AHD, there are many other height datums in use (mining, rail, road authorities, water authorities, marine etc.). It is therefore important to clearly define specific elements of a height datum when it is realised. For example:

- the height system, including a reference ellipsoid and theoretically true equipotential surface (e.g. $W_0 = 62{,}636{,}855.69\ m^2/s^2$); and
- the information used in an attempt to physically realise the height system. In the case of AHD, this information includes:
  - Mean Sea Level (MSL) observations at 32 tide gauges around Australia; and
  - Over 200,000 km of levelling used to transfer MSL heights throughout Australia.

14.3 Types of height

Height determination in Australia requires care due to the number, and type, of datums to which heights can be referred (Figure 22), including:

- **Ellipsoid:** Simplified mathematical representation of the Earth often used as a reference surface for positioning, navigation, map projections and geodetic calculations. Ellipsoidal heights h are the distance between the ellipsoid and point of interest measured along the ellipsoid normal.
- **Geoid:** Surface of equal gravitational potential (or equipotential) that closely approximates mean sea level. Heights with respect to the geoid are known as orthometric heights H and are the curved line distance between the geoid and point of interest measured along the plumbline (i.e. the instantaneous direction of gravity).
- **Quasigeoid:** Non-equipotential surface of the Earth's gravity field closely aligned to the geoid with differences up to about 3.4 m in the Himalayas (Rapp, 1997) and 0.15 m in Australia (Featherstone and Kirby, 1998). Heights with respect to the quasigeoid are known as normal heights H^* and are the curved line distance between the quasigeoid and point of interest measured along the plumbline.
- **Mean Sea Level:** Mean Sea Level (MSL) is an observed tidal datum and is used as the conventional reference surface to which heights on the terrain (e.g. contours, heights of mountains, flood plains, etc.) and other tidal datums are related.
- **Mean Sea Surface:** Mean Sea Surface (MSS) is the sum of the geoid (closely approximated by MSL) and Mean Dynamic Topography (MDT) which describes the thermodynamic motion of the oceans.

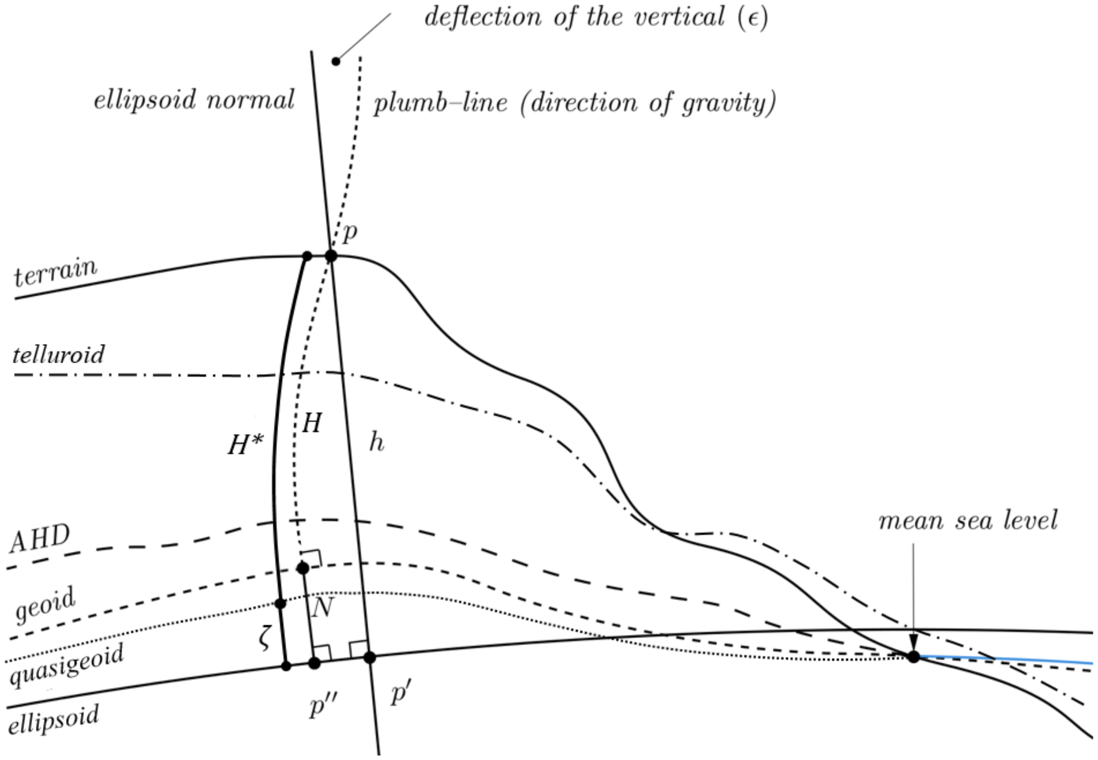

Figure 22: Heights can be observed or derived with respect to an ellipsoid, geoid or quasigeoid surface.

14.4 Gravitational Potential

The gravitational potential energy at a location is equal to the work (energy transferred) per unit mass needed to move an object from one point to another point.

The geopotential number C is the basis of all height systems in physical geodesy. A geopotential number is the difference in gravitational potential energy W_p between a point p (e.g on the Earth's surface) and potential on the reference surface W_0 (e.g. the geoid).

$$C = W_p - W_0 \quad (104)$$

The negative of the geopotential number (m^2/s^2), divided by some value of gravity (m/s^2) yields a unit of length (m).

15. Geoids and quasigeoids

15.1 Geoid

There are an infinite number of surfaces of equal gravitational potential which is the best fit to mean sea level and is denoted by W_0 (units m^2/s^2) (Figure 23).

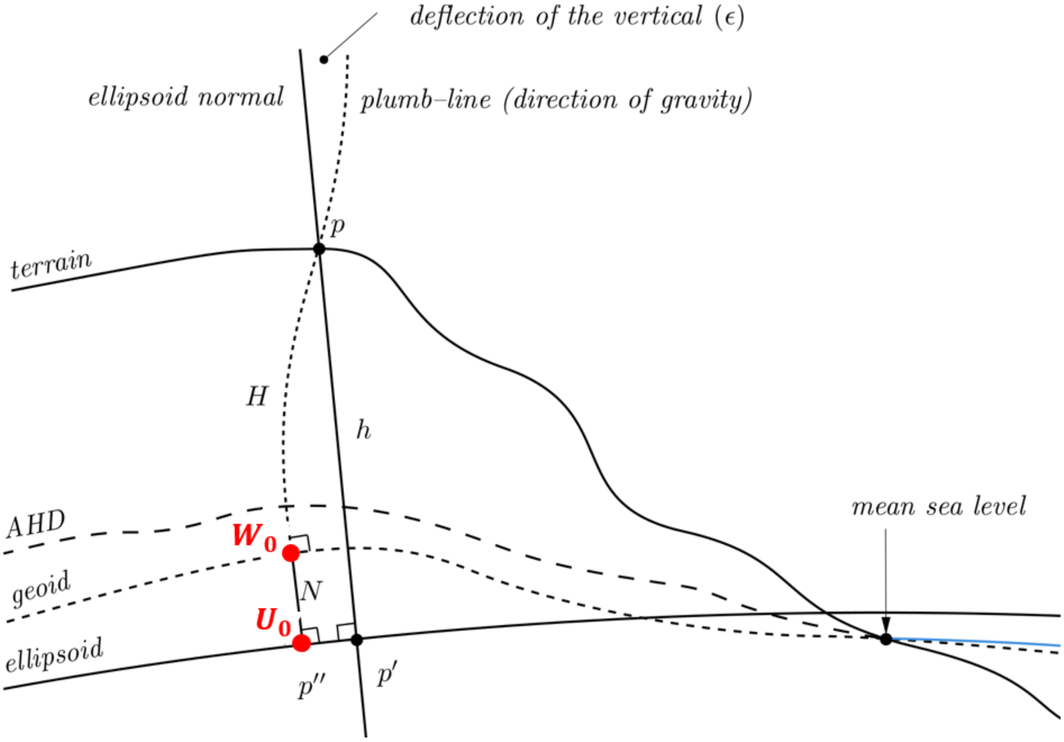

Figure 23: The geoid is the surface of equal gravitational potential which is the best fit to mean sea level and is denoted by W_0.

Heights with respect to the geoid are called orthometric heights H. To approximately compute physical heights from GNSS, the geometric distance between the ellipsoid and the geoid, known as the geoid undulation N, needs to be subtracted from the ellipsoidal height h (Figure 24).

$$H \approx h - N \qquad (105)$$

The error introduced by this approximation is negligible for all practical purposes.

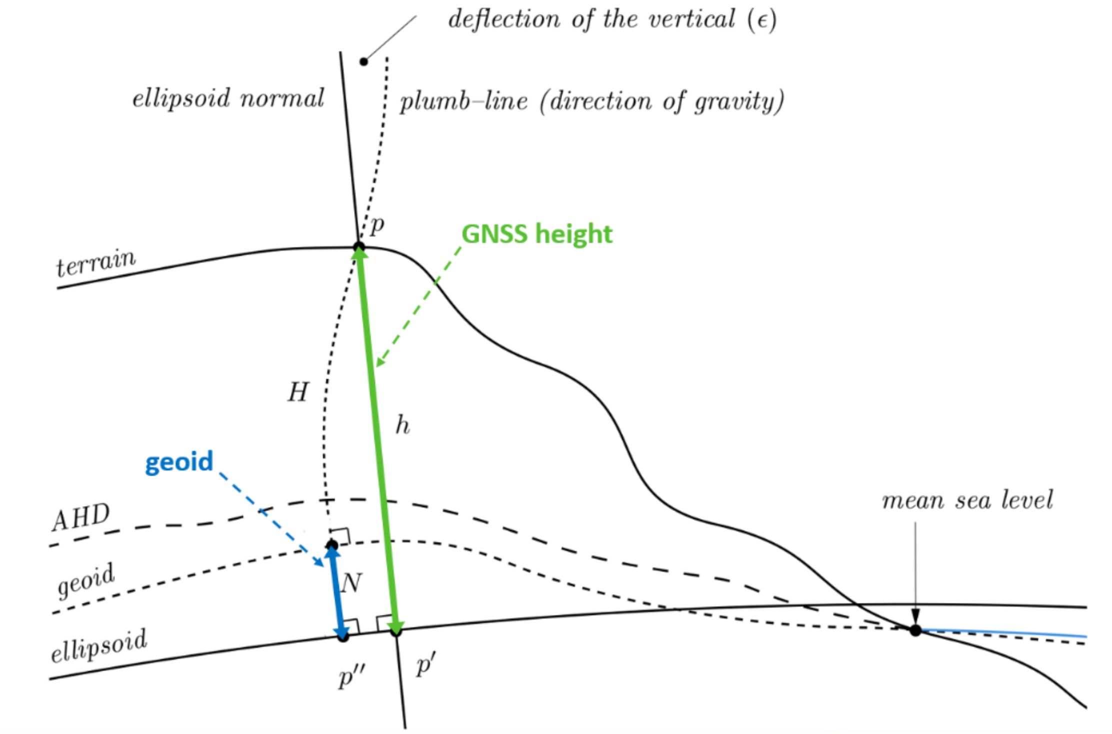

Figure 24: The geometric distance between the ellipsoid and the geoid is the geoid undulation.

There are a wide range of geoid models which have been developed to enable the conversion of geometric ellipsoidal heights to physical heights including global geopotential models such as the Earth Geopotential Model 2008 (EGM2008). EGM2008 has an absolute accuracy of about 20 cm. (Yi and Rummel, 2013). In cases where a more accurate datum for physical heights is required, countries have developed national or local geoid models which use a global geopotential model, and augment it with local data such as terrestrial and airborne gravity data.

15.1.1 Developing a geoid model

The disturbing potential, T is the difference between the Earth's gravitational potential field W and the gravitational potential field of the ellipsoid U.

$$T = W - U \qquad (106)$$

When T is known on the surface of the geoid, the geometric separation / geoid undulation N between the geoid surface and the ellipsoid is given by;

$$N = \frac{T}{\gamma} \qquad (107)$$

where γ is the *normal gravity* (i.e. the gradient of the ellipsoidal potential) evaluated on the surface of the ellipsoid.

The potential W, and therefore the disturbing potential T, cannot be measured directly. But the gradient of the potential, $\frac{dW}{dr}$ (i.e. the familiar gravity value $\approx 9.8\ m/s^2$) can be measured using gravimeters.

We define the *gravity anomaly* Δg as the difference between measured gravity on the geoid surface and normal gravity γ on the ellipsoid surface (Figure 25).

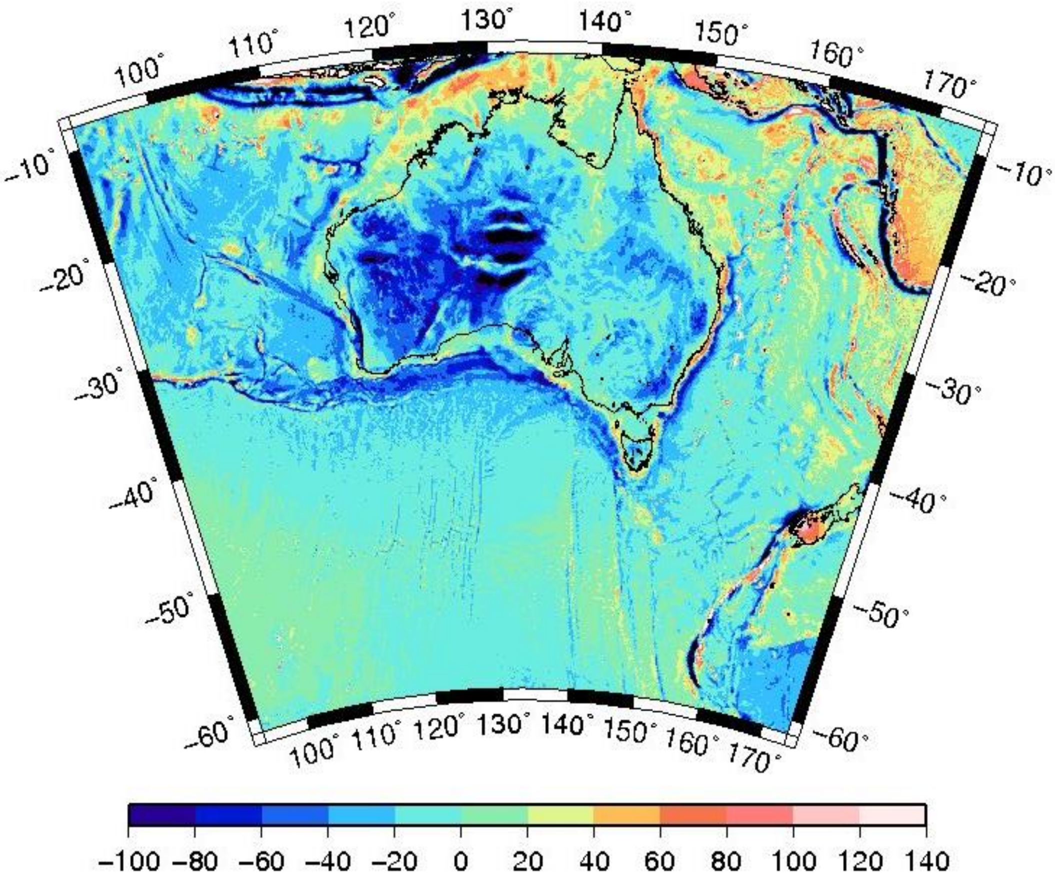

Figure 25: Gravity anomalies over the Australian continent.

When the gravity anomalies are known on the geoid over the surface of the whole Earth, there is a mathematical relationship between them and the disturbing potential. This is known as Stokes integral (Moritz, 1980).

$$T = \kappa \int_{\sigma} \Delta g \, S(\psi) d\sigma \qquad (108)$$

In practice, only long wavelengths of Δg are available over the whole Earth. This means only long wavelength models of the disturbing potential can be determined globally. High resolution geoid models are developed locally via the remove-compute-restore technique, where higher resolution gravity data are available. i.e.

$$T = \kappa \int_{\hat{\sigma}} (\Delta g - \Delta g_{Long}) S(\widehat{\psi}) d\sigma + N_{Long} \qquad (109)$$

Where Δg_{Long} and N_{Long} and gravity anomalies and geoid undulations form a long wavelength global model, $S(\widehat{\psi})$ is a modified form of $S(\psi)$ where long wavelengths have been removed, $\hat{\sigma}$ is the local region for which the higher resolution gravity data are available.

15.1.2 Orthometric Height System

The orthometric height system is compatible with a geoid model. An orthometric height H is the curved line distance between the geoid and point of interest measured along the plumbline and computed by,

$$\mathbf{H} = \mathbf{C}/\bar{\mathbf{g}} \qquad (110)$$

where the geopotential number C is divided by the integral mean of gravity taken along the plumbline $\bar{g}$.

NOTE 1: In the case of an orthometric height system, computation of the geopotential number requires gravity observations.

NOTE 2: Given that orthometric heights require information of the Earth's gravity acceleration along the length of the plumbline through the topography, it is impossible to realise in practice.

NOTE 3: Despite the name, Helmert orthometric heights use an approximation of the Earth's gravity field and are not truly realising an orthometric height systems.

15.2 Quasigeoid

There are advantages and disadvantages to the choice of a geoid model over a quasigeoid model, and vice versa, as a height datum for a country. The choice of the geoid implies an orthometric height system is being used which is practically impossible to implement.

The conundrum is well described by Vanicek (2012), "The problem with the geoid, a physically meaningful surface, is that it is sensitive to the density variations within the Earth. The problem with the quasigeoid, which is not a physically meaningful surface, is that it requires integration over the Earth's surface."

Recognising that evaluating W_p on the geoid is practically impossible, Molodensky (1945) introduced an alternative theoretical surface called the quasigeoid. The determination of the quasigeoid does not require any knowledge of topographic density of the Earth and all the quasigeoid determination computations are done, not on the geoid surface but, on the surface of the Earth (or at an almost identical surface to it, called the telluroid – see the definition below). Molodensky's approach deals only with the external field and needs only to know the geometry of the external field.

- *Referring to Figure 26*: The telluroid is a theoretical surface where the normal gravitational potential is equal to the gravitational potential on the Earth's surface i.e. $U_{p_3} = W_{p_4}$., *the telluroid is a theoretical surface:*
  - *where the normal gravitational potential is equal to the true gravitational potential on the Earth's surface i.e.* $U_{p_3} = W_{p_4}$ *and on the same plumbline; and*
  - *looks like the Earth surface except that it is displaced from the Earth surface by the quasigeoidal height* ζ.

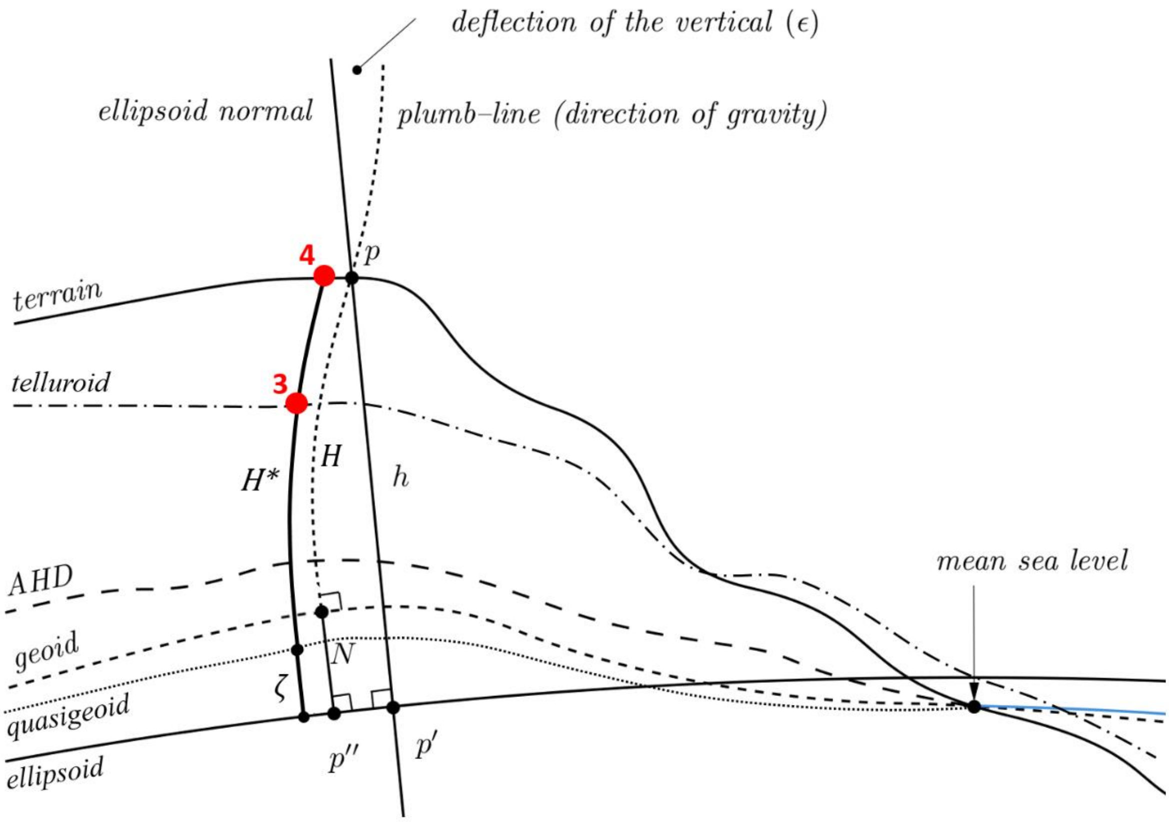

Figure 26: The telluroid is a theoretical surface where the normal gravitational potential is equal to the gravitational potential on the Earth's surface i.e. $U_{p_3} = W_{p_4}$.

The quasigeoid can, in theory, be determined exactly (i.e. without any approximations). It provides the reference surface for normal heights H^* which can be determined from levelling and gravity observations, or derived normal heights from GNSS and a quasigeoid model. Onshore, it differs from the geoid by 1-2 cm in flat terrain and up to 10 cm in steep topography (Figure 27). Offshore, where there is no topography, the quasigeoid agrees with the geoid.

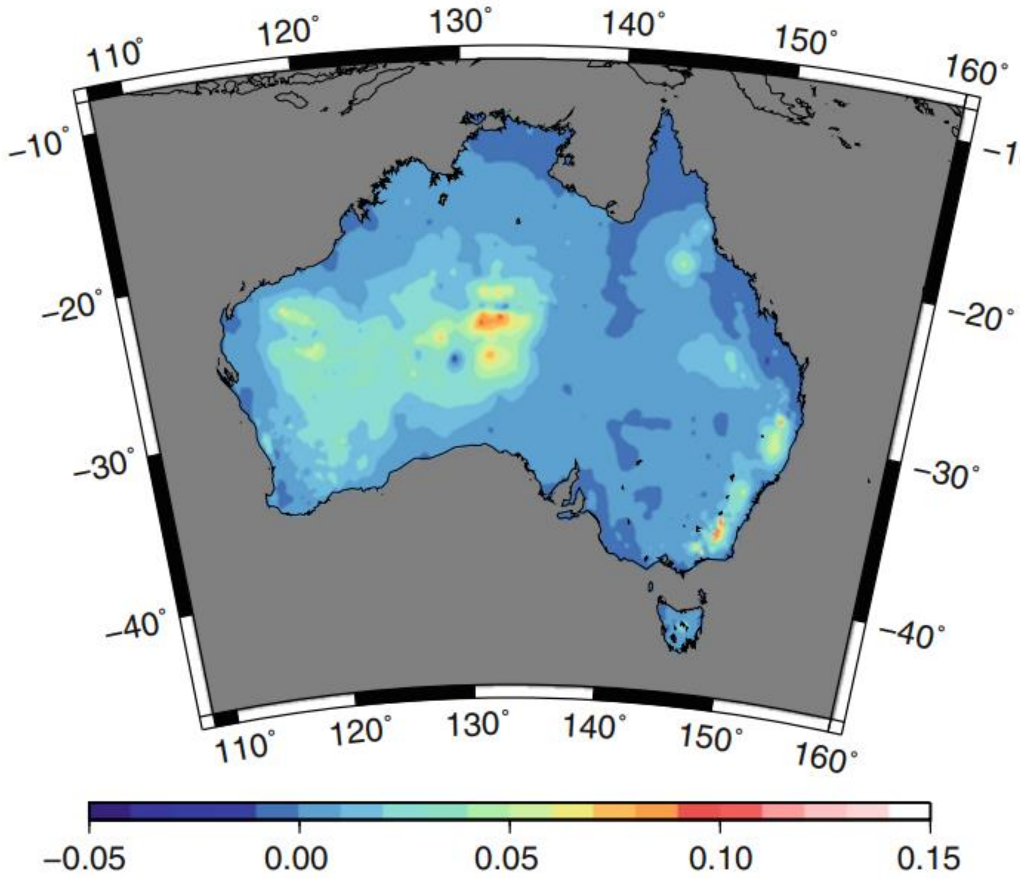

Figure 27: Differences between Helmert orthometric (from geoid) and normal heights (from quasigeoid) (in m) over Australia from Filmer et al. (2010).

To compute normal heights from GNSS, the geometric distance between the ellipsoid and the quasigeoid, known as the height anomaly ζ, needs to be subtracted from the ellipsoidal height h.

$$H^{*} = h - \zeta \tag{111}$$

In the same way that a geoid model gives geoid undulation N at any point, quasigeoid models gives height anomalies ζ at any point. The normal height of a point on the topographical surface is defined as the height of the corresponding point on the telluroid above the reference ellipsoid, measured along the normal plumbline. However, normal heights may equivalently be seen as heights of the topographical surface above the quasigeoid, also measured along the normal plumbline.

15.2.1 Developing a quasigeoid model

The quasigeoid model is determined on the Earth's surface (or to be specific - the telluroid).

On the telluroid, the disturbing potential is given by,

$$T_{p_4} = W_{p_4} - U_{p_3} + \zeta\gamma \quad (112)$$

and so

$$\zeta = \frac{T_{p_4}}{\gamma} \quad (113)$$

Here, γ is the normal gravity, evaluated on the telluroid.

15.2.2 Normal Height System

The normal height system was proposed in 1954 by Molodensky et al. (1962) to overcome the problem in orthometric heights of having to determine the mean value of gravity along the plumbline. The normal height H^* is the distance between the quasigeoid and the point of interest measured along the curved normal and computed by,

$$\boldsymbol{H^* = C/\bar{\gamma}} \quad (114)$$

where the geopotential number $\boldsymbol{C}$ is divided by average normal gravity $\boldsymbol{\bar{\gamma}}$ along the plumbline.

15.2.3 Normal-Orthometric Height System

The normal-orthometric height $\boldsymbol{H^{NO}}$ is the distance between the quasigeoid and the point of interest measured along the curved normal gravity $\boldsymbol{\gamma}$ plumbline and computed by,

$$\boldsymbol{H^{NO} = C_\gamma / \bar{\gamma}} \quad (115)$$

In contrast to orthometric and normal height systems, which require gravity observations to be taken along the levelling traverse in order to derive the geopotential numbers (or normal or orthometric corrections), geopotential numbers, C, are replaced by differences in normal potential C_γ (known as normal-geopotential or spheropotential numbers) and gravity is replaced by normal gravity (integral mean value of normal gravity taken along the normal plumbline between the quasigeoid and point of interest) (Featherstone and Kuhn, 2006).

The difference between normal heights and normal-orthometric heights is due to the gravity correction applied to levelling data. Normal heights require a location-specific gravity value, whereas, normal-orthometric heights are derived using a gravity value based on the normal gravity field (Rapp, 1961). The effect of the difference between these two height systems is shown in Figure 28.

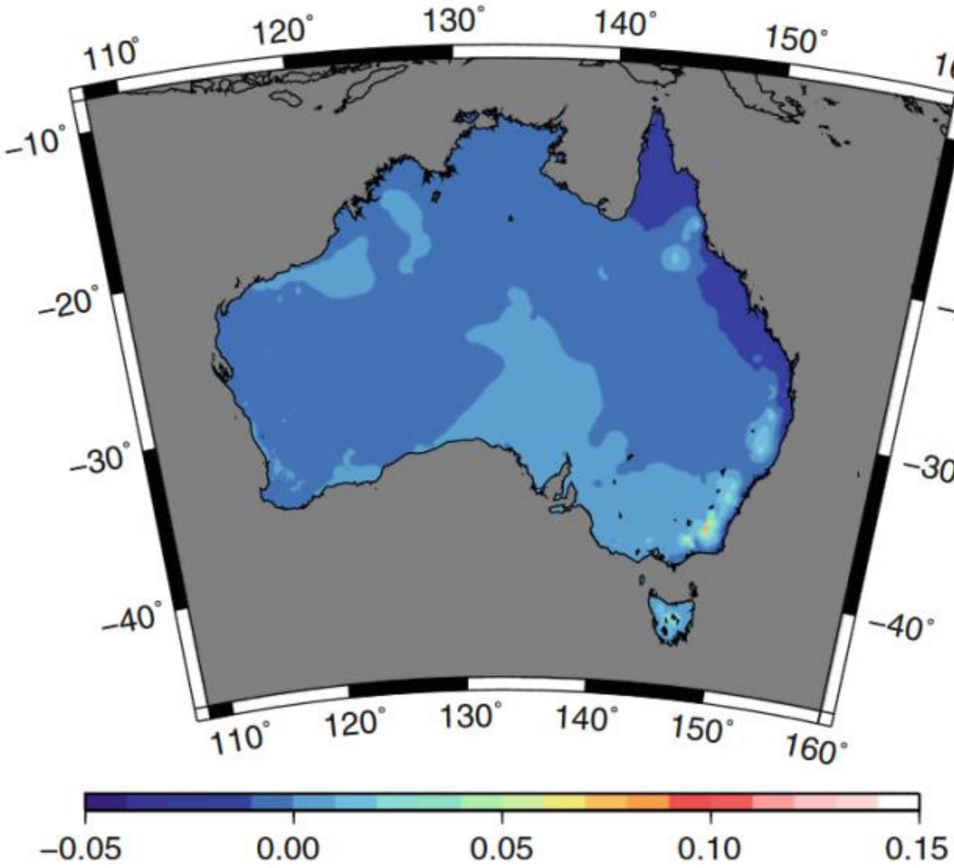

Figure 28: The effect of the difference between normal and normal-orthometric heights over Australia (from Filmer et al, 2010) in metres. Stats: [min: -2.4 cm; max: 17.7 cm; std: 1.2 cm].

16. Australian Height Datum

16.1 Background

The Australian Height Datum (AHD) is the official national vertical datum for Australia and refers to Australian Height Datum 1971 (AHD71; Australian mainland) and Australian Height Datum (Tasmania) 1983 (AHD–TAS83). Prior to AHD, many local height datums were used in the states and territories.

AHD was adopted by the NMC at its 29th meeting in May 1971 as the datum to which all vertical control for mapping was to be referred. The datum surface passes through mean sea level (MSL) realised between 1966 – 1968 at 30 tide gauges around the Australian mainland (Figure 29).

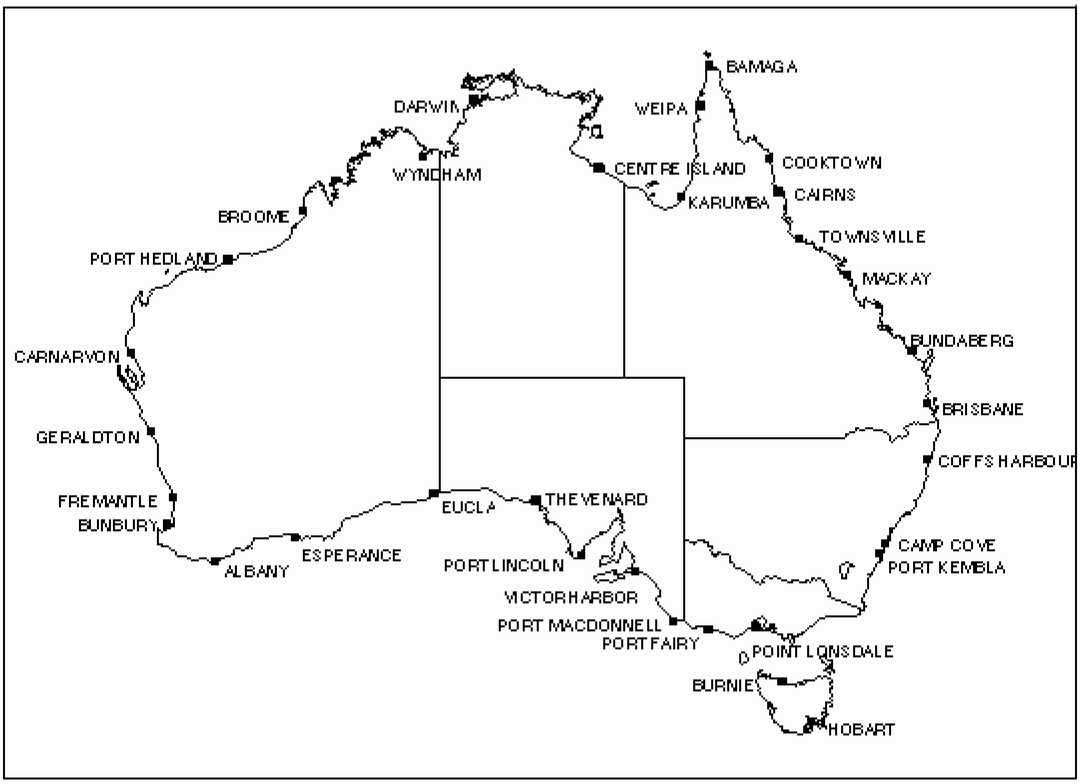

Figure 29: The locations of the tide gauges used to define AHD.

AHD heights were derived across Australia via a least squares adjustment of 97,320 km of 'primary' levelling (used in the original adjustment) and 80,000 km of 'supplementary' levelling (applied in a subsequent adjustment) (Roelse et al., 1971). Levelling observations ran between junction points in the network, and were known as level sections. These level sections were created by combining levelling observations along level runs (usually following major roads). The interconnected network of level sections and junction points was constrained at the 30 tide gauge sites, which were assigned a value of zero AHD. The least squares adjustment propagated mean sea level heights, or AHD, across the level network. Despite the best efforts of surveyors, systematic, gross and random errors crept into the level sections and were distributed across the network within the least squares adjustment.

The Australian Height Datum (Tasmania) 1983 (AHD–TAS83) is based on mean sea level in 1972 at tides gauges in Hobart and Burnie. It was propagated throughout Tasmania using third order differential levelling over 72 sections between 57 junction points and computed via adjustment on 17 October 1983. Mean sea level at both Hobart and Burnie was assigned the value of zero.

16.1.1 Metropolitan and buffer zones

Bench marks within the metropolitan areas of Perth and Adelaide were held fixed at heights assigned by the Surveyors General of Western Australia and South Australia respectively during the adjustment that produced AHD??. The areas in which these heights have been held fixed are termed "Metropolitan Zones". The assigned heights within the Perth Metropolitan Zone are based on mean sea level at Fremantle over a different epoch from that used in the adjustment of 5 May 1971. These heights differed by not more than 40 mm from those computed in the adjustment.

The assigned heights within the Adelaide Metropolitan Zone are based on mean sea level at Port Adelaide and these heights differ by not more than 18 mm from those determined in the National Levelling Adjustment of 5 May 1971 (NMC, 1971)[26].

The small differences between the heights determined by the adjustment of 5 May 1971 and those assigned by the Surveyors General to bench marks on the perimeter of the Metropolitan Zones have been distributed through "Buffer Zones".

Details relating to the limits of the Metropolitan and Buffer Zones, and the levelling sections within these zones may be obtained from the respective State Surveyors General.

The heights of bench marks in the Metropolitan Zones assigned by the Surveyors General and the adjusted heights of bench marks in the Buffer Zones shall be regarded as being on the Australian Height Datum.

16.1.2 Issues with AHD

Although it is still fit for purpose for many applications, AHD has a number of biases and distortions which make it unacceptable for some modern industrial, scientific and environmental activities. The primary bias is due to the manner in which AHD zero was realised; the Australian National Levelling Network (ANLN) was fixed to mean sea level (MSL) observed during 1966-1968 at 30 tide gauges around the Australian mainland. Due to the effect of the ocean's time-mean dynamic topography (MDT), AHD is about 0.5 m above the gravimetric geoid in north-east Australia and about 0.5 m below the gravimetric geoid in south-west Australia (e.g. Featherstone et al., 2006). Secondary biases and errors are uncorrected gross, random and systematic errors in the ANLN (e.g., Roelse et al., 1971; Filmer and Featherstone, 2009) and the use of modified normal-orthometric corrections applied to levelling data based on the GRS67 model ellipsoid (Holloway, 1988). Ignoring the primary bias from MDT, the secondary effects reveal the standard deviation of AHD heights used in the development of AUSGeoid2020 is ±0.038 m (Featherstone et al., 2017), but can reach ±0.5 m in some regions (Filmer and Featherstone, 2009).

These non-gravimetric artefacts are inconsistent over large distances (e.g. greater than 10 km) and mean that GNSS users are only capable of deriving AHD heights with an accuracy of 8-13 cm across Australia (Brown et al., 2018). Uncertainty in the national height datum of this magnitude makes AHD inappropriate for some applications that require a more accurate reference surface. In response to this finding Geoscience Australia led a user requirements study with FrontierSI to investigate current and

[26] The NMC 1971 reference to the Special Publication 8 is a WA annotated version in which the value of 40 mm is written and 4 mm is crossed out. PCG believe the value of 40 mm is correct. The notations match the information in the document "Public Works Department Tidal Information – Western Australian Coast".

future requirements for physical height determination and transfer in Australia (see Section 17; Brown et al. 2019a; Brown et al. 2019b; McCubbine et al. 2019).

Overall, the results of the study indicated that AHD is still fit for purpose for heighting tasks over short distances (less than about 10 km) for projects such as cadastral, civil engineering, construction and mining while users are less satisfied when working over larger areas (greater than about 10 km) for environmental studies (e.g. flood, storm modelling), LiDAR surveys, geodesy, hydrography.

16.2 AUSGeoid2020

16.2.1 Overview

AUSGeoid2020 has been developed to support improved determination of AHD height estimates H_{AHD} from GNSS observations. AUSGeoid2020 provides ellipsoid to AHD separation values ζ_{AHD} onshore accompanied by an estimate of statistical uncertainty.

$$H_{AHD} = h - \zeta_{AHD} \quad (116)$$

Given that AHD is only an onshore datum, the AUSGeoid2020 model should only be used onshore and on islands near to the coast where connections to AHD are known to exist. Christmas Island, Cocos Island and some islands off the coast of north Queensland are exceptions to this rule where AUSGeoid2020 provides ellipsoid to local mean sea level as determined by tidal observations.

Onshore, AUSGeoid2020 is a combined gravimetric - geometric model. The gravimetric component is a $1'$ by $1'$ grid of ellipsoid – quasigeoid separation values created using data from gravity satellite missions (e.g. GRACE, GOCE), re-tracked satellite altimetry, localised airborne gravity, land gravity data from the Australian national gravity database and a Digital Elevation Model to apply terrain corrections.

The geometric component is a $1'$ by $1'$ grid of quasigeoid – AHD separation values and is developed using a dataset of collocated GNSS ellipsoidal height and AHD heights. The geometric component attempts to account for the offset between AHD and the quasigeoid that ranges from about -0.5 m (AHD below quasigeoid) in the south-west of Australia to about +0.5 m (AHD above quasigeoid) in the north-east of Australia. The offset between AHD and the quasigeoid is primarily due to the method by which AHD was realised. Given that the warmer, less dense water off the coast of northern Australia is approximately one metre higher than the cooler, denser water off the coast of southern Australia, by constraining each of the tide gauges to zero AHD, the effects of sea surface topography were propagated into the adjustment.

16.2.2 Format of AUSGeoid2020

AUSGeoid2020 is provided in two formats; ASCII text file (.txt) and NTv2 binary grid (.gsb). Separate ASCII files exist for the ellipsoid to AHD separation (Table 1Table 10) and the uncertainty in the ellipsoid to AHD separation (Table 11).

Table 10: ASCII format of AUSGeoid2020 ASCII file.

ID	ellipsoid to AHD separation (m)	Latitude			Longitude			deflection of the vertical (seconds)	
GEO	ζ_{AHD}	D	M	S	D	M	S	ξ	η

Table 11: ASCII format of AUSGeoid2020 uncertainty ASCII file. The deflection of the vertical are set to zero in the uncertainty file.

ID	uncertainty (1 sigma)	Latitude			Longitude			deflection of the vertical (seconds)	
GEO	$\sigma_{\zeta_{AHD}}$	D	M	S	D	M	S	ξ	η

16.2.3 Differences between AUSGeoid09 and AUSGeoid2020

16.2.3.1 Aligned with GDA2020

The change in the reference frame used for the development of GDA2020 (i.e. ITRF2014 compared to ITRF92 used for GDA94) means the ellipsoidal height of a point in GDA94 is approximately 9 cm higher than GDA2020. As a result, AUSGeoid2020 is incompatible with GDA94. Data referenced to GDA94 is only compatible with AUSGeoid09.

16.2.3.2 Uncertainty provided

AUSGeoid09 provided an estimate of the root mean square error at the input data points used in the construction of the model (Brown et al., 2011). AUSGeoid2020 provides a rigorous uncertainty value associated with the offset between the ellipsoid and AHD, varying as a function of location. This value includes the uncertainty from the gravimetric component and geometric component of the model.

16.2.4 AUSGeoid2020 tools and services

A web application is available on the Geoscience Australia website[27] to perform AUSGeoid computations using AUSGeoid98, AUSGeoid09 and AUSGeoid2020.

27 https://www.ga.gov.au/scientific-topics/positioning-navigation/australian-geospatial-reference-system/agrstoolsandmodels

17. Australian Vertical Working Surface

17.1 User requirements for height datums in Australia

The Positioning Australia program will provide accurate and reliable positioning for all Australian's at the centimetre level. The coordinates received from GNSS are cartesian coordinates with respect to the centre of the Earth which can be converted to latitude, longitude and ellipsoidal height. Many users, however, require heights with respect to the Earth's gravity field to ensure fluid will always flow downhill.

AUSGeoid2020 is a model of the offset between the GDA2020 ellipsoid and AHD. It is a hybrid gravimetric - geometric quasigeoid model where the geometric component attempts to model the effects of MDT and systematic levelling errors. As shown in Brown et al., 2018, AUSGeoid2020 has uncertainty (one sigma) of 8-13 cm throughout Australia. Uncertainty of this magnitude makes GNSS and AUSGeoid2020 inappropriate to compute physical heights for some applications that require more accurate heighting control.

In 2018, Geoscience Australia led an investigation into user requirements for height datums in Australia (Brown et al., 2019a, 2019b) and explored technical options (McCubbine et al., 2019) which could be implemented to meet the identified user requirements. Results of the study indicated that AHD is still fit for purpose for tasks over short distances (less than about 10 km) for projects such as cadastral surveying, civil engineering, construction and mining, however, users are less satisfied with AHD and AUSGeoid when working over larger areas (greater than about 10 km) for environmental studies (e.g. flood, storm modelling), LiDAR surveys, geodesy and hydrography.

Based on the results of the survey, Geoscience Australia led the development and implementation of the Australian Vertical Working Surface (AVWS), as an alternative to AHD. AVWS heights are realised by subtracting the geoid – ellipsoid separation value from the Australian Gravimetric Quasigeoid (AGQG) model where AGQG is the gravimetric component of AUSGeoid2020.

In comparison to AHD, AVWS is:

- Internally consistent, being defined solely from gravity field measurements i.e. it is not contaminated with non-gravimetric artefacts due to mean dynamic topography and local distortions in levelling networks.
- Not reliant upon benchmark heights.
- Defined seamlessly on and offshore.

For these reasons it better meets the needs identified during the user requirements survey to establish or transfer accurate heights over long (>10 km) distances. Additionally, the AGQG model is provided with a corresponding map of uncertainty values formally propagated from the raw data sources through each stage of the computation (Featherstone et al., 2018).

17.2 User choice: AHD or AVWS

A recommendation of the user requirements study was to adopt a “two-frame” approach similar to that done with GDA2020 and ATRF2014 where AHD remains the official national height datum and Geoscience Australia would introduce the AVWS for those who would like to or need to use it.

The AVWS, like AHD, is vertical reference surface for heights, realised by subtracting an Australian Gravimetric Quasigeoid (AGQG) model value from a GDA2020 ellipsoidal heights. The AGQG model provides the height difference between the ellipsoid and the AVWS. It differs from AUSGeoid2020, which provides the offset between the ellipsoid and Australian Height Datum (AHD), by between -1 to 1 m throughout Australia.

17.3 Australian Gravimetric Quasigeoid

Like AUSGeoid2020, which is used to derive AHD heights from GNSS ellipsoid heights, the AGQG can be used to compute AVWS heights. GNSS-derived GDA2020 ellipsoidal heights can be converted to AVWS heights by subtracting the height anomaly ζ provided by AGQG. This is advantageous since GNSS ellipsoidal heights are relatively cheap and easy to obtain in comparison to large-scale levelling campaigns.

The difference between AHD and AVWS (Figure 30) is a combination of biases and distortions due to:

- The ocean’s time-mean dynamic topography (MDT) not accounted for in the realisation of AHD.
- The relatively short tide gauge observation periods used to define MSL for the AHD, the zero reference of the AHD is not coincident with an equipotential surface (e.g. the geoid). The differences largely manifest in a north-south tilt of ~0.7 m in the AHD relative to the geoid across the continent. This tilt can be eliminated by the use of MDT models at tide gauges to correct for the offset between the sea surface recorded at the tide gauges and the geoid.
- The presence of unaccounted for systematic and gross errors in the Australian National Levelling Network (ANLN).

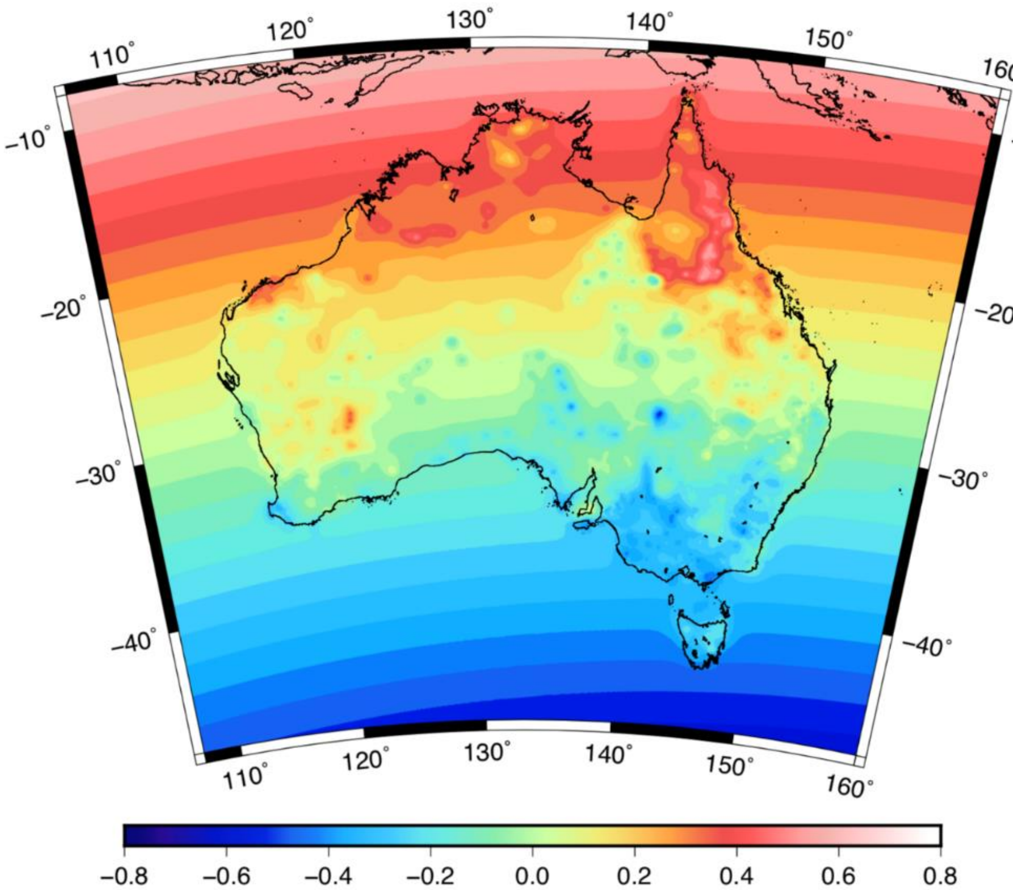

Figure 30: Offset between AHD and AVWS. Units in metres.

The biases and distortions associated with AHD mean GNSS users are only capable of deriving AHD heights from AUSGeoid2020 with accuracy of 6-13 cm across Australia. The accuracy of AGQG is between 4-8 cm across Australia.

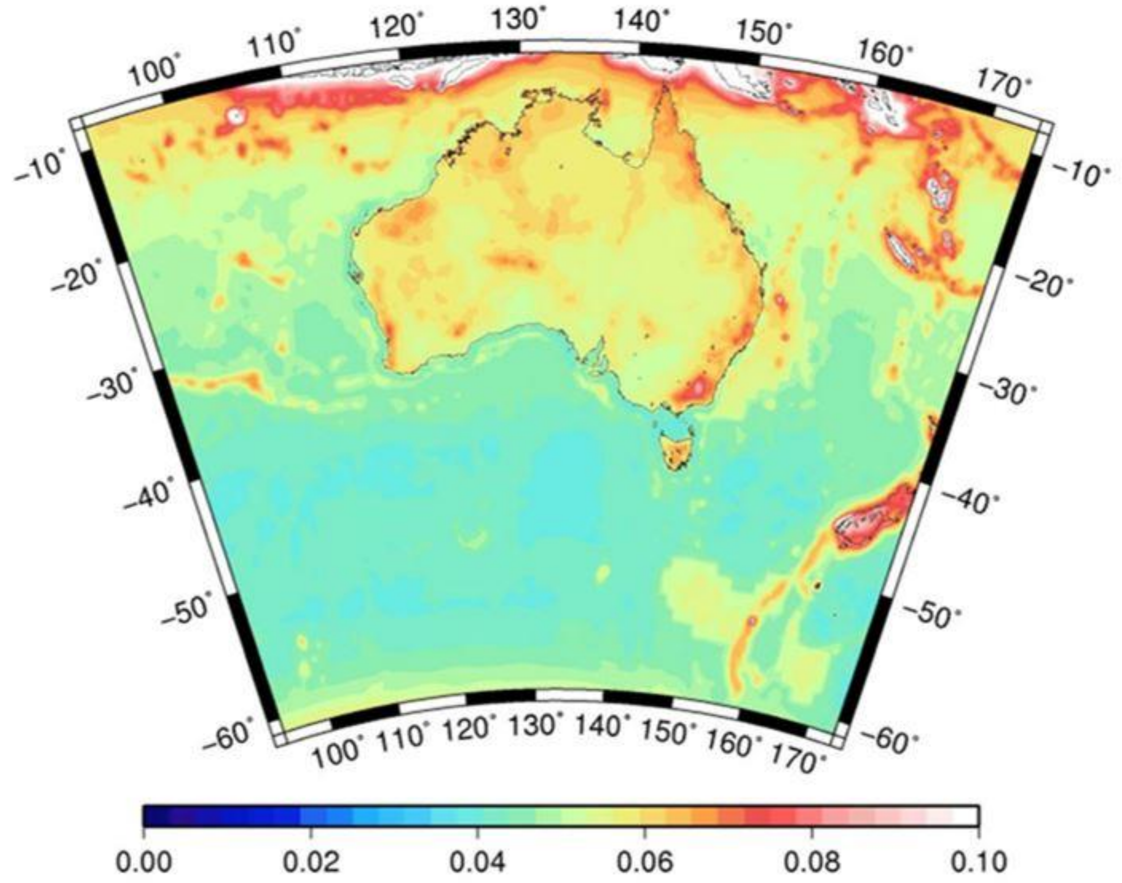

Figure 31: Accuracy of AGQG2020. Units in metres.

This addresses one of the biggest concerns from the users who have noticed the quality of their data (e.g. LiDAR) was starting to become more accurate than the datum (AHD) when they applied AUSGeoid. Geoscience Australia will be working with all the states and territories to continuously improve AGQG as new gravity data is included and modelling techniques are refined.

17.3.1 Computing derived AHD and AVWS heights from GNSS

AVWS heights H^*_{AVWS} can be computed by subtracting the corresponding AGQG model value from GNSS ellipsoidal height observation.

$$H^*_{AVWS} = h - \zeta_{AGQG} \qquad (117)$$

Derived AHD heights H_{AHD} can be computed by subtracting the corresponding AUSGeoid model value from GNSS ellipsoidal height observation.

$$H_{AHD} = h - \zeta_{AUSGeoid} \qquad (118)$$

NOTE: If you have GDA94 ellipsoid heights, use AUSGeoid09.

NOTE: If you have GDA2020 ellipsoidal heights, use AUSGeoid2020.

17.3.2 Computing AVWS heights from levelling

To determine AVWS heights via levelling, ζ_{AGQG} reference point/s must first be established from GNSS height/s h and AGQG model value/s.

$$H^*_{AVWS} = h - \zeta_{AGQG} \tag{118}$$

Heights can then be transferred via levelling. Formally, normal corrections should be applied to the relative levelling heights. The normal correction applied to levelling height differences at points A and B, is given by,

$$NC_{AB} = \sum_A^B \frac{g-\gamma_0}{\gamma_0} dn + \frac{\bar{\gamma}_A - \gamma_0}{\gamma_0} H_A - \frac{\bar{\gamma}_B - \gamma_0}{\gamma_0} H_B \tag{119}$$

where g are surface gravity measurements between A and B and $\bar{\gamma}_A$ and $\bar{\gamma}_B$ are the average normal gravity along the curved normal plumbline, between the ellipsoid and telluroid. In practice this requirements can generally be neglected at the cost of introducing a small amount of error (c.f. Filmer et al. (2010)).

For example, suppose we have two points A at [latitude -24.6500; longitude 153.1667] and B at [latitude -24.6167; longitude 115.3333] with uncorrected normal heights H_A [180.8741 m] and H_B [181.1234 m].

The differential height of the points is $dn = 0.2493\ m$. The average gravity between the points is $g = 9.7885607011$. The average normal gravity of point A is $\gamma_A = 9.7890357117$ and the average normal gravity of point B is $\gamma_B = 9.7890125308$. With $\gamma_0 = 9.8061992115$ the normal gravity at 45 degrees latitude, the normal correction applied to the differential height between A and B is

$$\begin{aligned} NC_{AB} &= \frac{g-\gamma_0}{\gamma_0} dn + \frac{\bar{\gamma}_A - \gamma_0}{\gamma_0} H_A - \frac{\bar{\gamma}_B - \gamma_0}{\gamma_0} H_B \\ &= \frac{9.7885607011 - 9.8061992115}{9.8061992115} 0.2493 + \frac{9.7890357117 - 9.8061992115}{9.8061992115} \\ &\quad \times 180.8741 - \frac{9.7890357117 - 9.8061992115}{9.8061992115} \times 181.1234 = 0.0004\ \mathrm{m} \end{aligned}$$

17.3.3 Computing AVWS height uncertainties

Uncertainty values of heights above the AVWS, $\sigma(H^*_{AVWS})$ should be modelled as the square root of the sum of GNSS ellipsoidal height uncertainties squared, $\sigma(h)^2$, output from GNSS processing software and AGQG uncertainty value, $\sigma(\zeta_{AGQG})^2$ interpolated from the AGQG uncertainty model (Featherstone et al., 2018).

$$\sigma(H^*_{AVWS}) = \sqrt{\sigma(h)^2 + \sigma(\zeta_{AGQG})^2} \tag{120}$$

For example:

- We have a GNSS observation at [Lat: -23.6701, Long: 133.8855] with ellipsoidal height $h = 603.244$ m, the standard deviation of the ellipsoidal heights after post processing is $\sigma(h) = 0.0035\ m$.
- The AGQG value at the respective latitude and longitude is $\zeta_{AGQG} = 15.201\ m$ and has uncertainty value $\sigma(\zeta_{AGQG}) = 0.06$.

- The AVWS height is then given by $H_{AVWS} = h - \zeta_{AGQG} = 588.043\ m$
- The AVWS height uncertainty is given by $\sigma(H_{AVWS}) = \sqrt{\sigma(h)^2 + \sigma(\zeta_{AGQG})^2} = \sqrt{0.06^2 + 0.004^2} = \pm 0.06\ m$
- i.e. the AVWS height at our point is $H^*_{AVWS} = 588.043\ \pm 0.06\ m$

17.3.4 Access to AGQG models

Table 12: The AGQG model, and corresponding uncertainty model, is available from the links below in a range of formats (TIF, GSB (binary) and Windows Text).

AGQG TIF	Ellipsoid-AVWS separation	https://s3-ap-southeast-2.amazonaws.com/geoid/AGQG/AGQG_20201120.tif
AGQG TIF	Ellipsoid-AVWS separation uncertainty (1 sigma)	https://s3-ap-southeast-2.amazonaws.com/geoid/AGQG/AGQG_uncertainty_20201120.tif
AGQG Binary	Ellipsoid-AVWS separation	https://s3-ap-southeast-2.amazonaws.com/geoid/AGQG/AGQG_20201120.gsb
AGQG Binary	Ellipsoid-AVWS separation uncertainty (1 sigma)	https://s3-ap-southeast-2.amazonaws.com/geoid/AGQG/AGQG_uncertainty_20201120.gsb
AGQG Winter ASCII	Ellipsoid-AVWS separation	https://s3-ap-southeast-2.amazonaws.com/geoid/AGQG/AGQG_20201120_Win.dat
AGQG Winter ASCII	Ellipsoid-AVWS separation uncertainty (1 sigma)	https://s3-ap-southeast-2.amazonaws.com/geoid/AGQG/AGQG_uncertainty_20201120_Win.dat

- To download the files, click on the link, or paste the link in an internet browser and hit Enter. The file should download automatically.
- Geoscience Australia has also developed an online tool to determine AVWS heights from GNSS observations (and vice versa) with 1σ uncertainties.
- See here: https://geodesyapps.ga.gov.au/avws
- The tool has a batch processing capability.

17.3.5 AGQG zero degree term

The Earth's gravitational potential field W is closely approximated by that of an ellipsoid with its own gravitational potential field U.

On the surface of the geoid the value of the Earth's potential is constant, $W = W_0$.

When modelling the Earth's gravity field with a spherical harmonic model (SHM) (e.g. EGM2008), a reference ellipsoid is chosen to (i) have a mass (M) that is equal to that of the Earth (which is equal to the mass of the EGM2008 SHM) and (ii) ensure that on the surface of the ellipsoid the ellipsoidal gravitational potential is equal to the Earth's gravitational potential on the geoid i.e. $U = U_0 = W_0$. The surface of the geoid is described relative to the surface of the reference ellipsoid. With these particular specifications for the reference ellipsoid, the ellipsoid-geoid separation is zero on average, in a global sense.

However, the choice of M and U_0 used to define the reference ellipsoid for a SHM can differ to other ellipsoids commonly used in positioning. For example, the SHM for EGM2008 uses a Mean Earth Ellipsoid (MEE), not GRS80. Therefore $M_{MEE} \neq M_{GRS80}$ and $U_{0_{MEE}} \neq U_{0_{GRS80}}$.

The different values of M and U_0 for EGM2008 and GRS80 cause a constant bias which affects the scale of the reference ellipsoid's gravitational field. This constant bias is the amount which needs to be added or subtracted to EGM2008 SHM ellipsoid-geoid separation values to align them with GRS80.

This bias is known as "the zero degree term" (Figure 32Figure 32: The zero degree term must be applied to convert the EGM2008 ellipsoid-geoid separations to GRS80 ellipsoid-geoid separations.), here denoted ζ_z.

The zero degree term can be approximated, from the generalised Bruns equation,

$$\zeta_z = \frac{GM - GM_0}{r\gamma} - \frac{W_0 - U_0}{\gamma} \tag{121}$$

where:

- GM – Newton's Gravitational constant multiplied by the mass of the Earth as chosen for the production of the SHM.
- GM_0 – Newton's Gravitational constant multiplied by the mass of the reference ellipsoid
- γ – Normal (i.e. due to the ellipsoid) gravity
- r – Radius of computation point
- W_0 – Earth gravitational potential value on the geoid surface from SHM
- U_0 – Normal (i.e. due to the ellipsoid) gravitational potential on the ellipsoid

Long wavelengths of AGQG models are based on the EGM2008 SHM. To account for the bias between EGM2008 and GRS80 it is necessary to apply the zero degree term bias to AGQG. This enables the accurate conversion of GDA2020 ellipsoidal heights to AVWS heights.

The following constants were used to compute this value.

EGM2008	GM	3.9860044E+14	m^3s^{-2}	Ince, 2011
	W_0	62636855.69	$m^2\ s^{-2}$	
GRS80	GM_0	3.9860050E+14	m^3s^{-2}	Moritz, 1980b
	U_0	62636860.85	$m^2\ s^{-2}$	
	γ	9.797644656	ms^{-1}	Mean gravity over the surface of the GRS80 ellipsoid
	r	6378137	m	

This yields a zero degree term of -0.41 m.

The software used to create AGQG applies the zero degree term ζ_z (-0.41 m) to all EGM2008 ellipsoid-geoid separations $\zeta_{EGM2008}$ (which were previously referenced to the EGM2008 MEE) to convert them to AGQG ellipsoid-geoid separations ζ_{AGQG}.

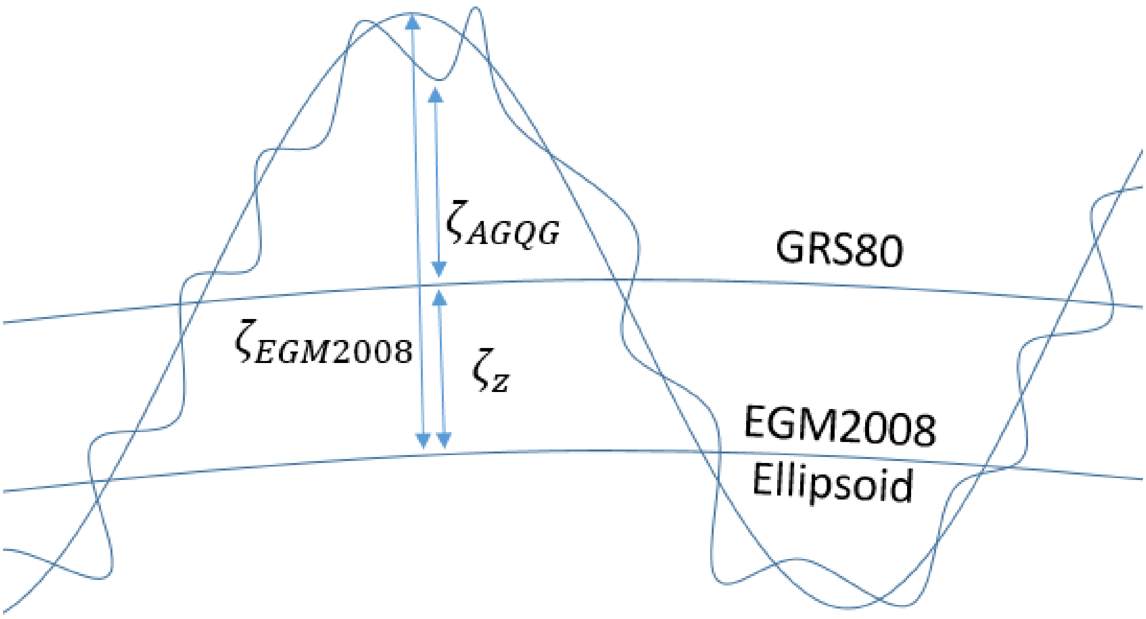

Figure 32: The zero degree term must be applied to convert the EGM2008 ellipsoid-geoid separations to GRS80 ellipsoid-geoid separations.

17.3.6 AGQG version control

17.3.6.1 AGQG_20201120 model

- This is the current version of the AGQG model.
- The zero degree term offset between AGQG_20201120 and GRS80 is 0 m. This means there AGQG_20201120 will work seamlessly with GDA2020.

17.3.6.2 AGQG_20191107 model

- The zero degree term offset between AGQG_20201120 and AGQG_20191107 is 0.93 m. Heights above AGQG_20191107 will be 0.93 m larger than heights above AGQG_20201120.

For the 20191107 release of AGQG (AGQG_20191107) Geoscience Australia applied a -1.34 m zero degree term instead of -0.41 m. This error is due to Geoscience Australia accounting for the bias between EGM2008 and GRS80 in two steps. First, accounting for the 0.41 m offset between EGM2008 and WGS84, then applying a 0.93 m offset between GRS80 and WGS84 (From ICGEM FAQ Q17). The second correction only accounts for the mass difference between WGS84 and GRS80 but not for the difference between the GRS80 and WGS84 U_0 values (i.e. the second term of Eq. 121). The proper inclusion of the second term makes the GRS80 to WGS84 bias almost equal to zero. For this reason there is a 0.93 m bias between AGQG_20201120 and AGQG_20191107.

For those who have used the AGQG_20191107 model, the relative heights between points will be unaffected. However, to ensure alignment with future AGQG models (including AGQG_20201120), it is recommended that users identify the original ellipsoidal height data (with respect to GDA2020), and convert the data to AVWS heights using the AGQG_20201120 model.

17.3.6.3 AGQG_2017 model

- The zero degree term offset between AGQG_20201120 and AGQG_2017 is -0.41 m. Heights above AGQG_2017 will be 0.41 m smaller than heights above AGQG_20201120.

For the 2017 release of AGQG (Featherstone et al. 2018), no zero degree term was applied. For this reason the AGQG2017 model is aligned with the EGM2008 ellipsoid so there is a -0.41 m bias between AGQG_20201120 and AGQG_2017.

For those who have used the AGQG_2017 model, the relative heights between points will be unaffected. However, to ensure alignment with future AGQG models (including AGQG_20201120), it is recommended that users identify the original ellipsoidal height data (with respect to GDA2020), and convert the data to AVWS heights using the AGQG_20201120 model.

Part D: Standards & Policies

18. Standards

18.1 Geodetic Parameter Registries

Internationally there are a number of geodetic registries that are relied upon as the source of information for defining geodetic datums and the transformations between them. A registry is a database of coordinate reference system information including ellipsoids, units, datums, projections and transformations. Each database element is assigned a code to identify it uniquely. The registry name, code number and type of registry element provide a shorthand method for defining the relevant coordinate reference system information.

To ensure users can access the upgraded elements of the AGRS, the ICSM GWG has engaged with the team from the European Petroleum Survey Group (EPSG) and ISO Geodetic Register to update, and create new EPSG codes for the new AGRS elements. Below is a complete list of the codes for AGRS datums, coordinate reference frames and transformations.

18.1.1 Updates to EPSG Registry

The EPSG registry (http://www.epsg-registry.org/) is a reliable, freely available registry of geodetic and transformation information. It is maintained on a “best effort” basis by the Geomatics Committee of the International Association of Oil and Gas Producers (IOGP; previously known as the European Petroleum Survey Group or EPSG). It is updated on a needs basis, which generally equates to two full release amendments per year.

Datum elements in this manual are identified by EPSG codes and registry element type where they exist at the time of publication and the manual will be revised when additional codes are available.

A number of organisations reproduce content from the EPSG registry but the IOGP site http://www.epsg-registry.org/ is the only official EPSG dataset.

18.1.2 EPSG Datum Codes

EPSG Code	Name	Type
5111	Australian Height Datum	Vertical
1168	GDA2020	Geodetic
6283	GDA94	Geodetic
1292	Australian Vertical Working Surface	Vertical
1291	Australian Terrestrial Reference Frame 2014	Dynamic geodetic

18.1.3 EPSG Coordinate Reference System Codes

EPSG Code	Name	Type
7844	GDA2020	Geographic 2D
4283	GDA94	Geographic 2D
7843	GDA2020	Geographic 3D
4939	GDA94	Geographic 3D
7842	GDA2020	Geocentric, Cartesian CS

4938	GDA94	Geocentric, Cartesian CS
5711	AHD height	Vertical
9309	ATRF2014	Geographic 2D
9308	ATRF2014	Geographic 3D
9307	ATRF2014	Geocentric, Cartesian CS
9458	AVWS height	Vertical

18.1.4 EPSG Transformation Codes

EPSG Code	Name	Type	Accuracy
8048	GDA94 to GDA2020 (1)	7 Parameter transformation	0.01 m
8447	GDA94 to GDA2020 (2)	NTv2 Conformal and Distortion transformation	0.05 m
8446	GDA94 to GDA2020 (3)	NTv2 Conformal transformation	0.05 m
8448	GDA2020 to WGS 84 (1) (WGS84: G1762)	3 parameter plate rotation to account for motion. Assumes WGS84 = ITRF14 = GDA2020 at epoch 2020.0	0.2 m
8450	GDA2020 to WGS 84 (2)	Null Transformation	3 m
1150	GDA94 to WGS 84 (1)	Null Transformation Approximation at the +/- 3m level using inappropriate assumption that GDA94 is equivalent to WGS 84. Accuracy changed from 1m to 3m due to tectonic plate motion over more than 15 years (Revised 2014-08-20)	3 m
5656	GDA94 to AHD height (49)	AusGeoid09 model; Replaces AusGeoid98 model.	n/a
8451	GDA2020 to AHD height (1)	AUSGeoid2020	Via GSB file
8049	ITRF2014 to GDA2020 (1)	3 parameter plate rotation to account for motion.	0.001 m
6276	ITRF2008 to GDA94 (1)	(7 parameter transformation. 2008 is latest available)	0.001 m
9460	ATRF2014-ITRF2014	7 Parameter transformation (NULL)	0.01 m
9459	ATRF2014-GDA2020	3 parameter plate rotation to account for motion.	0.03 m
9461	GDA2020 to AVWS height	Australian Gravimetric Quasigeoid (AGQG)	0.1
8049	ITRF2014 to GDA2020 (1)	3 parameter plate rotation to account for motion.	0.03 m
5656	GDA94 to AHD height (49)	AusGeoid09 model; Replaces AusGeoid98 model.	0.15 m
8451	GDA2020 to AHD height (1)	AUSGeoid2020	0.15 m

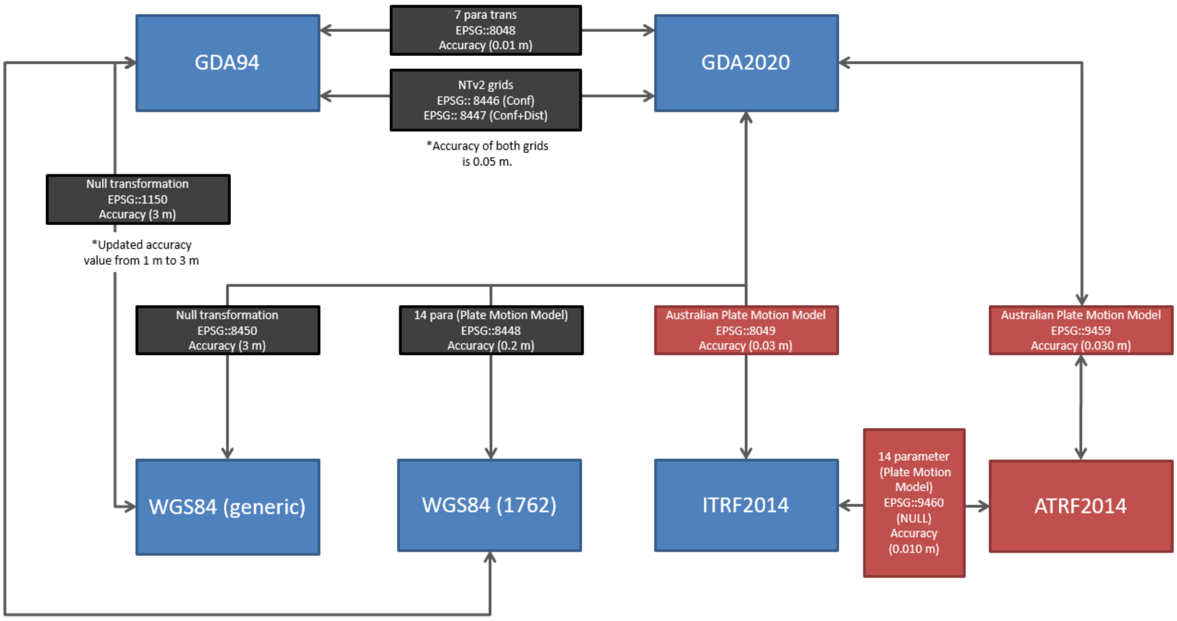

Figure 33: EPSG codes of AGRS geometric datums and transformations

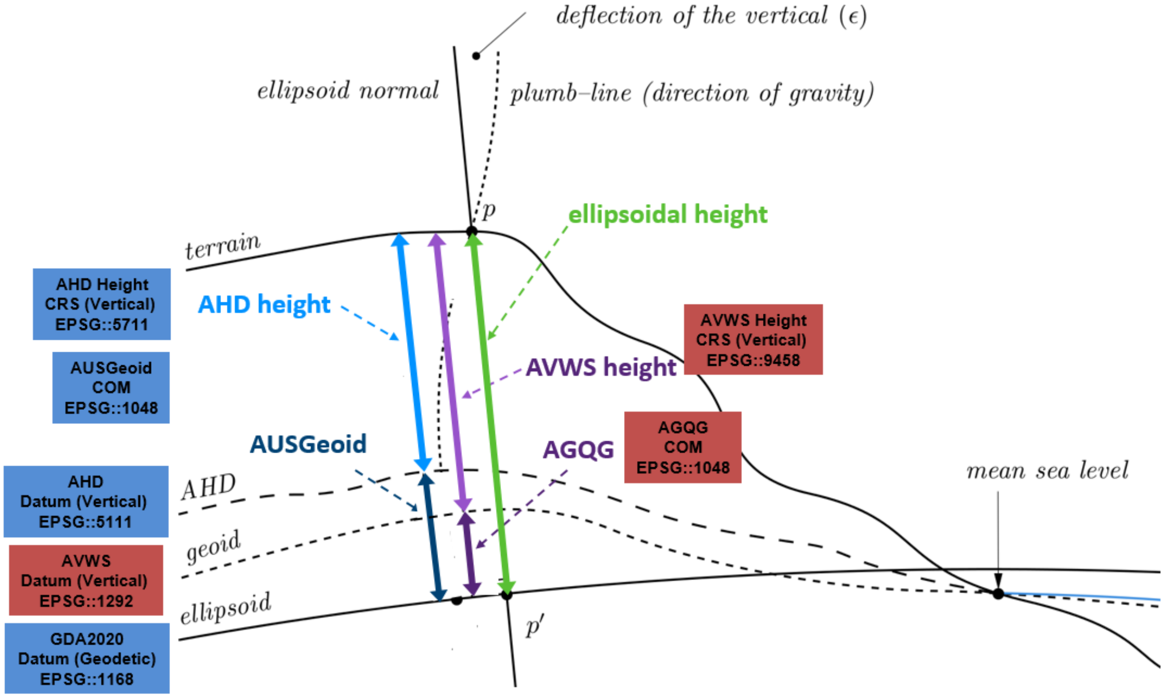

Figure 34: EPSG codes of AGRS physical datums and transformations.

18.2 ISO Geodetic Register

The International Standards Organisation Technical Committee 211 Geographic information / Geomatics (ISO/TC 211) is responsible for the ISO geographic information series of standards. ISO/TC 211 is developing an ISO Geodetic Registry (ISO 19127) that provides an authoritative register of datum and transformations as supplied by national representatives.

18.3 GeodesyML

- Current standards for delivering geodetic data will not adequately serve the needs of new (non-geodetic) users, who will emerge on account of the rapid growth in precise positioning services.
- Broad, multi-domain, standards are important for combining geodetic data with data from other domains.
- Internationally, several groups (e.g. Inspire, DCAT, ESIP, CODATA) are working on defining standards for geospatial and geophysical metadata and enhancing interoperability.
- However, there is no international strategy to ensure geodetic data is **Findable, Accessible, Interoperable and Reusable (FAIR).**
- **Lack of expertise** and **limited capacity** within the geodetic community to tackle this problem. We would be better served by combining resources and knowledge to adopt (and where necessary adapt) existing international standards wherever possible.
- There are a range of efforts being made, but are we working efficiently?
- UNGGIM, ISO, IAG GGOS, EOS, FIG …
- GML provides a rich set of primitive objects like (geometry, coordinate reference system, time etc.)
- But not detailed / specific standards
- e.g. GML can not be used to describe everything about a GNSS, VLBI, SLR, DORIS site.
- The geodetic standard needs objects like antenna, receiver, cable, adjustments etc.
- GML Application Schemas extend GML to meet the needs of a specific community of interest (e.g. SensorML, GeoSciML, GeodesyML (proposed))
- GeodesyML (www.geodesyml.org) goes some way to dealing with the issues of making GNSS data and the associated metadata available to the new and emerging user base in a standardised, discoverable and interoperable way.
- However, GeodesyML doesn't deal with all metadata requirements for precise positioning (e.g. compatibility with Intelligent Transport Systems and mobile phone standards).
- Furthermore, GeodesyML requires further development from people with experience working on OGC and ISO standards to ensure it can interface with complementary standards (e.g. SensorML, TimeseriesML, etc.)

19. Policy and Legal

19.1 Geoscience Australia is a Verifying Authority for Position

The National Measurement Institute (NMI) administers the National Measurement Act 1960 and has the authority to appoint legal metrology authorities to verify reference standards of measurement. Geoscience Australia is appointed as a Verifying Authority for Position. As a Verifying Authority for Position, Geoscience Australia can issue certificates of verification under Regulation 13 of the National Measurement Regulations 1999. These are commonly referred to as Regulation 13 Certificates.

Regulation 13 Certificates provide coordinates and their uncertainty with respect to the Recognized-value standard of measurement of position (RVS) in Australia, which is the Australian Fiducial Network (AFN). The AFN was updated in October 2017 and includes 109 stations from the Australian Global Navigation Satellite System network which:

- are operated by Geoscience Australia or similar agency;
- are located on the Australian Tectonic Plate, within Australia's jurisdiction and on a high quality survey monument; and
- have residuals less than 1 mm/yr relative to the Australian plate motion model (Section 0).

To define GDA2020, International Terrestrial Reference Frame 2014 (ITRF2014) coordinates and velocities of the 109 AFN stations were mapped forward to the epoch of January 1, 2020 using the Australian PMM (Section 0). GDA2020 is determined with respect to the RVS with crustal velocities and their uncertainties. These velocities enable coordinates to be mapped to any epoch. The list of 109 AFN stations including their coordinates and velocities, and the equation for coordinate conversion is shown in Appendix A of the GDA2020 Technical Manual.

More information on Regulation 13 Certificates including the application process can be found on the Geoscience Australia website (http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/regulation-13-certificates).

Table 13: Verifying Authority for Position scope of accreditation and least uncertainty.

Physical Quantity	Range of Measurement	Least Uncertainty (95%CI)
Position (horizontal & vertical)	Australia and its Territories	7 mm horizontal 15 mm vertical

Note: "Least uncertainty" is synonymous with "best measurement capability". It is the smallest uncertainty of measurement that can realistically be expected under ideal conditions.

Historically, RVS Determinations have only included coordinates (X, Y, Z), however, the 2017 Determination also included coordinate uncertainty (Type A and Type B), coordinate velocity and coordinate velocity uncertainty. Eqn. 2 enables the coordinates from the RVS Determination sites (shown in GDA2020) to be propagated to ATRF2014 and expressed at any epoch t (years) in a legally traceable manner through the application of the following linear model using the coordinates (X, Y, Z) and velocities (V_x, V_y, V_z):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_t = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2020} + (t - 2020) \begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix}$$

The above equation is valid for 15 years either side of 2020: $|\mathrm{t} - 2020| \leq 15$. This limitation is required because the velocities become increasingly unreliable as the time gap increases.

The GDA2020 coordinates in the 2017 RVS Determination were taken from the cumulative APREF solution of October 2016 and propagated to 2020 using the Australian PMM. The velocities of the sites in the RVS Determination were computed using the Australian PMM. The Australian PMM or the linear model (Eqn.2) can therefore be used to propagate coordinates in time. Both techniques are legally traceable and produce identical results, however, Eqn. 2 only applies where you have velocities and therefore only at the RVS sites, while the Australian PMM can be used anywhere.

19.2 Quality checking of RVS Determination

Regular checks (at least yearly) will be undertaken to ensure the RVS Determination coordinates, velocities and uncertainties remain valid (coordinates and velocities are within the bounds of uncertainty). If site coordinates and velocities are found to have deviated from the RVS Determination, GA will work with the National Measurement Institute (NMI) to update the RVS Determination as required.

19.2.1 Testing procedure

- Cumulative APREF solutions provide updated GDA2020 (and ATRF2014) site coordinates, velocities and uncertainties.
- Compare updated site coordinates, velocities and uncertainties to the RVS Determination values.
- If updated site coordinates, velocities and uncertainties exceed the RVS Determination values (beyond the 95% CI), GA will advise NMI, and update the RVS Determination.

19.3 Quality checking of Regulation 13 Certificates

NOTE: Coordinates for Regulation 13 Certificates are currently derived using the GA weekly APREF solution (i.e. seven days of data; not the cumulative solution). This process is under review and may be updated in the near future to use the cumulative APREF solution and align with the process as used to update GDA2020 and ATRF.

Weekly checks are undertaken to ensure the coordinates provided in Regulation 13 Certificates remain valid. If Regulation 13 coordinates are found to have deviated from the cumulative APREF solution (over more than four weeks), GA will work with the site owner to update the Regulation 13 Certificate. This may be to update the coordinates, the coordinate uncertainties, or both.

20. Standards and Guidelines

The Standard for the Australian Survey Control Network – Special Publication 1 (the Standard) and associated guidelines provide an outcomes based framework that supports the highest level of rigour and integrity in the delivery and maintenance of Australia's survey control mark network.

The purpose of the Standard is to specify the minimum requirements for the determination of one, two or three dimensional position and associated uncertainty of Australia's survey control marks. This Standard prescribes ICSM's requirements for control surveys that define, extend, improve or connect to the AGRS.

The following control surveys are within the scope of the Standard:

a. Datum Control Surveys: These surveys define, extend or improve the AGRS. These control surveys are included in AGRS adjustments (State, Territory and Australian Government) to allow for the most rigorous estimation and testing of position and uncertainty for new and existing survey control marks in the AGRS.
b. General Purpose Control Surveys: These surveys are not included in AGRS adjustments, but connect to the AGRS for the purpose of estimating the position and uncertainty of new survey control marks relative to the AGRS. These control surveys may be grouped into two categories according to the method used to estimate position and uncertainty, being:
    - least squares; or
    - other reliable statistical methods.

The provisions in this Standard for expressing uncertainty have been developed primarily for Datum Control Surveys, but are also intended to be adopted, where possible, for all forms of General Purpose Control Surveys. Government and private sector organisations undertaking Datum Control Surveys shall comply with this Standard. ICSM recommends that government and private sector organisations undertaking General Purpose Control Surveys comply with this Standard. Information on how to use this Standard, together with additional technical detail and commentary, is provided in the technical manuals and Guidelines listed in the reference section.

Version 2 of the Standard completed the transition from CLASS and ORDER to uncertainty as the basis for evaluating and expressing the quality of measurements and positions. The Standard's definition of uncertainty is intended to be consistent with the ISO definition. The use of the term Local Uncertainty as defined in SP1 version 1.7 has been discontinued in this Standard.

Version 2.2 of the Standard and associated guidelines includes:

- Standard for Australian Survey Control Network v2.2
- Guideline for Adjustment and Evaluation of Survey Control v2.2
- Guideline for Continuously Operating Reference Stations v2.2
- Guideline for Control Surveys by GNSS v2.2
- Guideline for Control Surveys by Differential Levelling v2.2
- Guideline for Conventional Traverse Surveys v2.2
- Guideline for Installation and Documentation of Survey Control Marks v2.2

were released in December 2020 and are available from the ICSM website[28]. This version contains updates to guide best practice methods of working in the Australian Geospatial Reference System (including GDA2020).

28 https://www.icsm.gov.au/publications/standard-australian-survey-control-network-special-publication-1-sp1

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Appendix A – Australian Plate Motion Model Estimation Results

The following steps were used to estimate the Australian Plate Motion Model for the 2017 Determination of the Recognized-Value Standard of Measurement of Position.

+ working on: XVSOLFIN14_ver05.SNX.AUSONLY.AUSCOPE_ARGN

+ making CRD file: XVSOLFIN14_ver05.SNX.AUSONLY.AUSCOPE_ARGN.crd

+ making VCV file: XVSOLFIN14_ver05.SNX.AUSONLY.AUSCOPE_ARGN.vcv

Longitude	Latitude	E (mm/yr)	N (mm/yr)	U (mm/yr)	X (mm)	Y (mm)	Z (mm)	Site ID
133.8098	-31.8667	0.17	-0.03	-0.61	0.25	-0.5	0.3	CEDU
131.1327	-12.8437	-0.28	0.21	-0.94	0.78	-0.47	0.41	DARW
149.0101	-35.3155	-0.13	0.09	-1.03	0.74	-0.29	0.67	STR1
151.1504	-33.7809	-0.2	0.06	-0.33	0.31	0.06	0.24	SYDN
148.98	-35.3992	-0.17	0.05	-0.98	0.75	-0.25	0.61	TID1
147.4387	-42.8047	-0.05	-0.27	-0.79	0.67	-0.37	0.34	HOB2
144.9753	-37.8294	0.21	0.27	-0.93	0.34	-0.5	0.79	MOBS
148.2646	-32.9988	-0.15	-0.86	1.59	-0.66	0.58	-1.59	PARK
115.7386	-31.8255	0.28	-0.6	-2.88	0.94	-2.61	1.01	HIL1

152.321	-24.9082	0.05	0.06	-1.13	0.86	-0.5	0.53	BNDY
121.4593	-30.7844	0.05	0.35	-0.77	0.21	-0.44	0.7	KALG
167.9388	-29.0433	-0.53	-0.21	-0.87	0.96	0.34	0.25	NORF
117.8102	-34.9502	-0.06	-0.17	-1.09	0.52	-0.85	0.48	ALBY
145.9149	-41.0501	0.79	-0.35	-0.31	-0.06	-0.91	-0.06	BUR2
146.6731	-41.9023	-0.02	-0.29	-0.72	0.62	-0.38	0.26	LIAW
117.1746	-30.5255	-0.05	0.24	-0.9	0.34	-0.56	0.66	BURA
117.7026	-31.6223	-0.11	0.27	-1.04	0.45	-0.6	0.77	KELN
121.7872	-32.26	0.01	0.27	-1.24	0.46	-0.77	0.89	NORS
118.8919	-32.4494	-0.34	0.48	-1.21	0.67	-0.51	1.06	HYDN
128.2962	-25.0372	0	0.12	-1.15	0.61	-0.78	0.6	WARA
136.0587	-32.8104	0.14	-0.1	-1.2	0.67	-0.84	0.57	BBOO
146.6577	-36.3464	0.12	0.01	-1.09	0.66	-0.58	0.65	BEEC
135.7844	-34.1442	0.22	0.07	-0.73	0.25	-0.55	0.46	YEEL
137.9343	-32.4703	0.05	0.16	-1.07	0.57	-0.59	0.71	SA45
147.3217	-33.7034	0.11	0.05	-1.16	0.73	-0.6	0.69	WWLG
147.656	-37.7586	-0.18	-0.01	-0.9	0.71	-0.23	0.54	BDLE
150.9137	-34.4755	-0.1	0.19	-0.53	0.34	-0.07	0.46	PTKL
131.1868	-13.8346	-0.32	-0.02	-0.46	0.54	-0.12	0.09	DODA
151.9285	-27.5344	-0.67	0.68	-1.44	1.17	0.14	1.27	TOOW
137.1601	-30.4533	0.19	-0.06	-0.83	0.41	-0.65	0.37	ANDA
149.9152	-37.5681	-0.18	0	-0.77	0.62	-0.15	0.47	GABO

134.7226	-29.0347	0.05	0.13	-1.12	0.61	-0.68	0.66	COOB
132.1533	-14.376	0.05	0.2	-0.9	0.52	-0.64	0.42	KAT1
117.4101	-33.3331	-0.03	0.09	-1.38	0.53	-0.97	0.83	WAGN
120.0709	-33.5967	-0.12	-0.1	-1.25	0.66	-0.89	0.6	RAVN
133.2067	-25.9457	0.09	0.12	-0.84	0.42	-0.57	0.48	MTCV
120.2184	-26.6257	-0.02	0.28	-1.21	0.5	-0.82	0.79	WILU
142.0574	-29.4502	0.01	0.12	-0.17	0.07	-0.07	0.19	TBOB
143.4921	-32.8641	0.21	0.1	-0.15	-0.07	-0.21	0.17	IHOE
122.2091	-18.004	-0.18	0.54	-1	0.57	-0.57	0.82	BRO1
141.646	-36.3084	-0.24	-0.09	0.77	-0.3	0.54	-0.53	NHIL
134.3545	-19.9334	-0.24	0.58	-1.52	1.03	-0.71	1.06	WMGA
117.8431	-28.1153	-0.32	0.31	-0.85	0.56	-0.39	0.67	MTMA
133.2128	-15.5732	-0.08	-0.01	-0.65	0.49	-0.4	0.16	LARR
121.3191	-28.8784	-0.01	0.09	-1.22	0.54	-0.88	0.67	LONA
150.1222	-36.0351	-0.16	-0.01	-1.2	0.93	-0.34	0.69	TURO
144.204	-36.0314	0.21	0.03	-0.4	0.12	-0.35	0.26	BROC
142.2962	-10.5904	-0.4	-0.5	-0.23	0.5	0.12	-0.45	HNIS
143.4489	-37.5876	-0.19	0.74	1.16	-0.99	0.97	-0.12	MTEM
145.214	-38.3752	-0.03	-0.24	-0.04	0.16	-0.08	-0.16	STNY
133.8855	-23.6701	0.11	0.25	-0.19	-0.03	-0.13	0.31	ALIC
150.7901	-23.161	-0.22	-0.39	-0.17	0.38	0.04	-0.29	RSBY
130.8247	-12.4555	-0.34	0.29	-0.91	0.8	-0.4	0.48	LKYA

141.4701	-31.9963	-0.46	0.45	-0.52	0.44	0.23	0.66	BKNL
147.0557	-19.2693	-0.01	-0.13	-0.4	0.36	-0.22	0.01	TOW2
120.6435	-19.7786	-0.22	0.32	0.86	-0.28	0.9	0.01	WLAL
147.9309	-42.5464	0.11	-0.02	-0.76	0.43	-0.4	0.5	SPBY
128.8832	-31.6796	-0.27	0.65	0.03	-0.02	0.46	0.54	UCLA
149.2696	-31.3333	0.22	-0.15	-1.02	0.7	-0.67	0.4	CNBN
125.9244	-31.8091	0.02	0.13	-1.21	0.55	-0.78	0.75	ARUB
123.8681	-32.4608	-0.05	0.06	-1.54	0.75	-1.03	0.88	BALA
134.0929	-14.0462	-0.77	0.02	-0.24	0.71	0.37	0.08	MAIN
151.6523	-32.4118	0.33	0.12	-0.68	0.29	-0.53	0.47	BING
141.6135	-38.3444	0.06	-0.48	-1.07	0.85	-0.75	0.29	PTLD
137.8348	-19.9676	-0.54	0.15	-0.88	0.94	-0.12	0.44	RKLD
133.6968	-32.1286	-0.24	0.66	-1	0.51	-0.2	1.09	THEV
114.1134	-21.9607	0.04	0.26	0.01	-0.08	0.08	0.24	EXMT
125.8005	-18.126	0.16	0.46	-0.52	0.07	-0.38	0.6	FROY
115.8853	-31.802	0.1	0.25	-1.74	0.5	-1.26	1.13	PERT
148.2416	-40.2144	-0.05	-0.13	-0.48	0.41	-0.19	0.21	FLND
116.1927	-31.0487	0.08	0.35	-0.18	-0.08	-0.01	0.39	NNOR
117.4003	-22.8465	-0.1	-0.07	0.1	0.06	0.11	-0.11	TOMP
150.4441	-29.0455	0.17	0.24	-0.7	0.35	-0.39	0.55	NSTA
145.6803	-26.7421	0.64	-0.33	-1.39	0.79	-1.31	0.33	COOL
139.3479	-25.9004	0.35	0.46	-1.12	0.39	-0.79	0.91	BDVL

139.9031	-22.9135	0.04	-0.07	-1.51	1.06	-0.95	0.53	BULA
144.2045	-20.9474	-0.43	0.06	0.21	0.08	0.48	-0.02	HUGH
141.739	-20.6693	-0.02	0.03	-0.38	0.28	-0.2	0.16	JLCK
133.97	-21.4572	-0.32	0.2	0.46	-0.12	0.58	0.02	NTJN
134.0629	-26.9386	-0.02	-0.1	-1.14	0.75	-0.75	0.43	LAMB
131.4927	-22.1328	-0.27	0.64	-0.75	0.5	-0.16	0.88	MTDN
136.1007	-22.8605	-0.29	0.47	-1.11	0.8	-0.37	0.87	JERV
143.1767	-13.9588	-0.16	-0.46	-0.7	0.72	-0.35	-0.28	COEN
144.457	-15.5775	0.09	-0.04	-0.7	0.5	-0.47	0.15	LURA
116.1233	-34.7084	0.16	0.24	-0.16	-0.15	-0.07	0.29	NCLF
152.2521	-26.0842	0.14	-0.12	-1.22	0.95	-0.66	0.42	KILK
114.6096	-26.7574	0.03	0.13	0.59	-0.28	0.52	-0.15	MEDO
115.347	-29.0466	-0.14	0.21	-0.09	0.11	0.08	0.22	YAR2
145.814	-29.6772	-0.07	-0.06	-0.28	0.27	-0.1	0.09	NBRK
117.0972	-20.9814	-0.04	0.3	0.35	-0.16	0.4	0.16	KARR
118.6789	-20.5398	-0.32	-0.02	1.13	-0.22	1.07	-0.42	PTHL
116.6375	-26.6966	-0.08	0.16	-0.95	0.43	-0.66	0.57	MRO1
115.3386	-24.6326	-0.34	-0.3	-0.3	0.48	-0.22	-0.15	GASC
141.0692	-17.6717	-0.18	-0.57	-0.69	0.76	-0.38	-0.33	NMTN
143.8471	-39.9419	0.8	0.97	-0.68	-0.55	-0.58	1.18	KGIS
152.4869	-30.3266	-0.13	-0.85	-1.93	1.92	-0.85	0.24	HERN
105.6885	-10.45	0.78	0.04	0.19	-0.81	-0.02	0	XMIS

159.0612	-31.5199	-0.02	0.13	-1.45	1.1	-0.4	0.87	LORD			
151.1198	-25.3758	0.46	-0.59	-1.36	1.07	-1.11	0.05	EDSV			
148.6986	-21.6403	-0.49	0.59	1.28	-0.95	1.15	0.07	NEBO			
145.2455	-22.9568	-0.23	0.32	-0.16	0.15	0.18	0.35	ARMC			
146.2841	-24.7717	-0.98	-0.56	0.28	0.53	0.83	-0.63	TMBO			
134.0586	-30.282	0.02	0.41	-0.83	0.34	-0.38	0.77	MULG			
130.9555	-16.1177	0.66	-0.09	-2	0.78	-1.9	0.47	KMAN			
133.8165	-18.3879	0.26	-0.54	3.35	-2.27	1.99	-1.57	RNSP			
121.8943	-33.8743	0	0.06	-1.34	0.57	-0.92	0.8	ESPA			
132.8945	-12.6602	-0.49	-0.12	-1.58	1.43	-0.82	0.23	JAB2			
119.6458	-31.2907	-0.09	-0.04	-1.34	0.65	-0.96	0.66	YELO			
135.6433	-17.7763	0.22	-0.95	2.29	-1.5	1.17	-1.61	WALH			
			-0.04	0.05	-0.62	mm/yr	ENU	0.39	-0.31	0.35	MEAN
			0.29	0.34	0.85	mm/yr	ENU	0.55	0.62	0.5	STD
			0.29	0.34	1.05	mm/yr	ENU	0.67	0.69	0.61	RMS
			0.98	0.97	3.35	mm/yr	ENU	2.27	2.61	1.61	MAX
			29.01	57.19	-0.15	mm/yr	ENU				MEAN
			40.8	59.14	-0.07	mm/yr	ENU				MAX
			14.11	45.47	-0.19	mm/yr	ENU				MIN

+ no. stations: 109

+ dof: 215

+ varf: 32.313

+ sigma0: 5.684

+ Estimated plate model: 1.50379 +/- 0.00417 1.18346 +/- 0.00401 1.20716 +/- 0.00370 mas

Appendix B – GDA94 to GDA2020 transformation grids development summary

B.1 Overview

There are vast quantities of digital spatial data stored throughout Australia. This data is collected, managed and used by a wide variety of organisations and for a diverse range of applications. Until recently, most spatial data in Australia has been related to the Geocentric Datum of Australia 1994 (GDA94). In October 2017, the new Geocentric Datum of Australia 2020 (GDA2020) [EPSG: 1168] was officially defined in the National Measurement (Recognized-Value Standard of Measurement of Position) Determination 2017. ANZLIC – the Spatial Information Council of Australia and New Zealand announced 30 June 2020 as the date by which Australian State and Territories will support the delivery and receipt of foundational spatial data on the GDA2020 datum.

The transition from GDA94 to GDA2020 will see coordinates shift by approximately 1.5m - 1.8m in a north-easterly direction due to the motion of the Australian tectonic plate. In adopting GDA2020, those involved in the collection, management, distribution and provision of spatial data will need to manage the issues associated with the transformation of data between the old and new datum.

To support transformation of spatial data between GDA94 and GDA2020, transformation products were developed that were simple to apply, computationally efficient, unique in terms of the solution and rigorous in application. The Intergovernmental Committee on Surveying and Mapping (ICSM) developed three transformation products, including:

- 3D 7-parameter similarity (Helmert) transformation (conformal) [EPSG: 8048]
- 2D conformal NTv2 grid file [EPSG: 8446]
- 2D conformal + distortion NTv2 grid file [EPSG: 8447]]

Figure B.1 shows the extents of the two national transformation grids.

Please note, due to the way Queensland maintained the GDA94 coordinates of survey control marks, there is effectively no distortion modelled in Queensland and the conformal + distortion grid reverts to the conformal-only grid across the state.

Additional two-dimensional conformal-only transformation grids were developed for the Indian Ocean Territories:

- Christmas Island [EPSG: 8444]
- Cocos (Keeling) Islands [EPSG: 8445]

Conformal + distortion transformation grids were not developed for the Indian Ocean Territories.

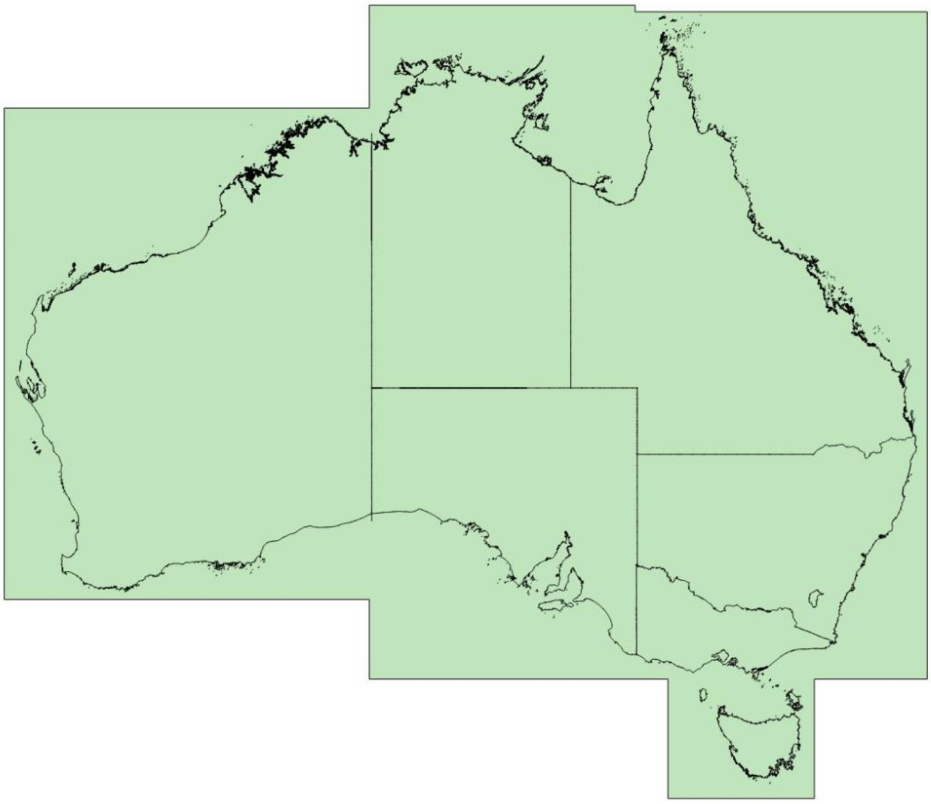

Figure B.1: National transformation grid extents.

In addition to the transformation products, ICSM also prepared the Geocentric Datum of Australia 2020 Technical Manual to summarise technical information related to the definition of GDA2020, transformation and coordinate conversion options, and the relationship to the Australian Height Datum (AHD). In addition to the GDA2020 Technical Manual summary of coordinate transformation, this report details the development of the conformal + distortion grid, including refinements to the input data, parameters and modelling approach.

The GDA2020 Technical Manual includes recommendations for selecting the appropriate transformation method. Additional advice is provided in section 2 of this report, with a flow chart presented to identify the most suitable transformation option based on spatial data accuracy and origin.

B.2 Selection of transformation grid

The spatial accuracy and origin of spatial data are important considerations when selecting the appropriate transformation approach. This includes the option to not transform data if it is considered GDA2020 compatible.

The seven-parameter conformal transformation is a three-dimensional transformation and is applied to three-dimensional data (Cartesian XYZ or latitude, longitude and ellipsoidal height). It accounts for tectonic plate motion and is recommended for transforming spatial data directly related to Global Navigation Satellite System (GNSS) observations, with no influence from the local survey control mark network.

For two-dimensional data, the conformal-only grid replicates the behaviour of the seven-parameter conformal transformation and is designed to suit the transformation of data derived from GNSS observations, with no influence from the local survey control mark network.

The conformal + distortion grid supports transformation of two-dimensional data derived through a connection to the survey control mark network and thus subject to the influence of distortion that exists between adjusted GDA94 and GDA2020 survey control mark coordinates. The two-dimensional transformation grids are applied to geographical coordinates (latitude and longitude).

The conformal-only grid is most suitable when transforming two-dimensional spatial data within Queensland, and the conformal + distortion grid is identical to the conformal-only grid, one grid cell within the Queensland state border. Care should be exercised when transforming spatial data that overlaps two kilometres within the Queensland border.

Spatial data accuracy is also an important consideration when selecting which GDA94-GDA2020 transformation method to apply. Figure B.2 supports the selection of the appropriate transformation option for two-dimensional datasets, taking into account spatial data horizontal accuracy and origin.

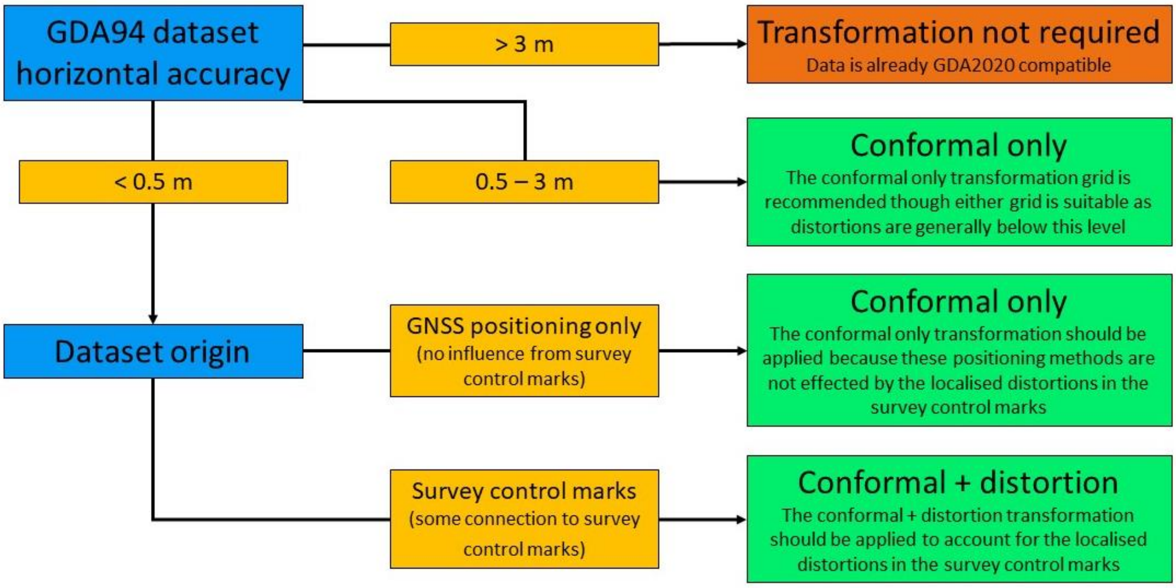

Figure B.2: Transformation decision making flow chart.

Please note that all transformation methods have a degree of uncertainty which flows through to the final transformed spatial data. Also, AHD remains the official national height datum. The datum transformation options should not affect the orthometric height of spatial data.

The following sections summarise the development of the primary transformation products between GDA94 and GDA2020.

B.3 Seven-parameter conformal transformation

Geoscience Australia derived official conformal transformation parameters between GDA94 and GDA2020. The seven transformation parameters were derived in the Combination and Analysis of Terrestrial Reference Frame (CATREF) software. The best-fit parameters were computed for the transformation between 18 nationally distributed GNSS Continuously Operating Reference Stations (CORS) that feature in both the GDA94 and GDA2020 National Measurement Institute (NMI) Recognised Value-Standard of Measurement of Position Determinations.

The seven-parameter conformal transformation represents the fundamental change in the datum, defined by the official GNSS CORS positions. This effectively accounts for the observed 70 mm per year motion of the Australian tectonic plate between 1994 and 2020 and change in underlying reference frame from ITRF1992 to ITRF2014. It is important to note that the scale change between ITRF1992 and ITRF2014 resulted in a 90mm – 100mm reduction in ellipsoidal heights across Australia with the transition from GDA94 to GDA2020. This consistent change in ellipsoidal height is accommodated in the AUSGeoid2020 model. For this reason, AUSGeoid2020 is the model required to derive AHD heights from GDA2020 ellipsoidal heights and is not compatible with GDA94. To derive AHD heights from GDA94 ellipsoidal heights the AUSGeoid09 model is required.

The seven transformation parameters consist of three translations, three rotations and one scale, and are published in the GDA2020 Technical Manual. This coordinate transformation approach is designed for three-dimensional data which is free from the distortion in the survey control mark network, such as GNSS positioning data.

B.4 Conformal-only transformation grid

The conformal-only grid replicates the behaviour of the seven-parameter transformation. This 1’ x 1’ national grid is provided in the Canadian National Transformation version 2 (NTv2) format.

The conformal-only grid is suitable for the transformation of two-dimensional data derived from GNSS data aligned to a CORS network (e.g. CORSnet-NSW, GPSnet, AUSPOS) and not corrected for localised distortions related to the survey control mark network.

B.5 Conformal + distortion transformation grid

The conformal + distortion grid attempts to extend upon the conformal-only grid, accounting for the distortion that exists between the realisation of GDA94 and GDA2020 in the survey control mark network. The conformal + distortion grid was developed using survey control network marks at which both GDA94 and GDA2020 coordinates were defined. The distortion component was modelled from the difference between nationally adjusted GDA2020 coordinates and GDA2020 coordinates derived by applying the conformal-only transformation to jurisdiction supplied GDA94 coordinates.

Distortion = GDA2020 (national adjustment) – GDA2020 (conformal-only transformed GDA94)

With the move to GDA2020, Australia is transitioning from a state-based GDA94 adjustment approach to a national GDA2020 adjustment approach. One of the motivating drivers behind this modernisation was to mitigate the occurrence of distortion in GDA94. In some cases, the magnitude of distortion between GDA94 and GDA2020 is in the order of decimetres and can be attributed to a range of factors, including:

- change in the least-squares adjustment approach from non-contiguous, jurisdiction based to a contiguous national adjustment
- application of constraints in different ways for jurisdictional GDA94 adjustments
- influence of additional measurements and changed network geometry

- influence of additional measurements from neighbouring jurisdictions in the GDA2020 national adjustment
- surface deformation and monument instability over time

The objective of including modelled distortion is to account for changes in network shape (represented in the survey control mark adjusted coordinates) and thereby improve the level of agreement between the adjusted and transformed coordinates. The conformal + distortion grid is recommended for GDA94 data aligned with survey control network marks.

Modelling of distortion between adjusted survey control mark coordinates across Australia was complicated as distortion can be highly variable in magnitude, direction and distribution. The conformal + distortion grid went through several revisions during development, with changes made to input data, modelling parameters and strategies. These revisions were performed to improve the national model by removing outliers and/or incorporating additional control marks into the distortion modelling procedure.

There are various distortion modelling techniques available, such as minimum curvature surfaces, least squares collocation and multiple regression equations. The least squares collocation distortion modelling approach was adopted for development of the GDA94 to GDA2020 conformal + distortion grid. Throughout this document references to the “model” or “modelling approach” refer to the least squares collocation method used by the GDAGrid software to estimate distortion at each grid node. This distortion modelling approach was deemed most suitable for modelling network distortion in the Australian context and was the same technique used to develop the AGD66/84 and GDA94 transformation grids.

GDAGrid is scientific software and not publicly available. The software was originally developed through the University of Melbourne for distortion modelling and creation of the transformation grids between AGD66/84 and GDA94. The GDAGrid software was upgraded by a consultant to support the development of the conformal + distortion grid between GDA94 and GDA2020.

B.5.1 Least squares collocation

Least squares collocation, when applied to distortion modelling, is a weighted interpolation process. This technique applies weighted distortion at surrounding survey marks to estimate distortion at grid nodes. The approach involves development of a distance-dependent covariance function to represent the spatial behaviour of distortion in two-dimensions (East and North). The computation of the covariance function was based on assigned parameters determined through a cross validation testing process.

B.5.2 Outlier detection and removal

The accuracy of the distortion model is dependent on the consistency (in magnitude and direction) of the distortion at the informing marks selected to predict the distortion at a grid node. Occasional outliers or “non-conforming points” have been found to impact the distortion modelling in unpredictable and counterintuitive ways.

An outlier detection and removal process were conducted before the distortion modelling procedure was undertaken. A mark was considered an outlier if the GDA94 coordinates transformed to GDA2020 using the conformal-only grid were different to the GDA2020 national adjustment coordinates by more than a specified value. Initially this value was set at 250 mm. Whilst under normal circumstances 250 mm would be considered an outlier, such magnitudes could be considered a true representation of the distortion in some areas. The net result of the arbitrary outlier removal approach was that the distortion grid nodes in those areas were produced with a conformal-only component and thereby, the transformation failed to apply the expected distortion in the GDA94 coordinates.

To overcome this problem, all State and Territory jurisdictions were supplied a list of detected outliers. Jurisdictions confirmed which of these survey marks represented genuine outliers and which survey marks should be maintained in the distortion modelling procedure.

B.5.3 Weighting of distortion

The survey marks supplied across Australia in the distortion modelling procedure were highly variable in spatial distribution. After the outlier detection and removal process a thinning process was performed on marks which were within 5 m of each other. This thinning process was performed to reduce the influence of highly clustered networks of survey marks.

If two marks were within 5 m of each other, the GDA2020 national adjustment uncertainty for both marks were compared. The mark with the lower uncertainty estimate was retained and the other mark removed from the model. However, if two marks were more than 5 m from each other, they were both retained in the model and contributed the same level of influence on the distortion model. That is, there was no weighting applied based on the GDA2020 uncertainty estimates. As such, State and Territory jurisdictions identified survey marks with high uncertainty to be withdrawn so they did not influence the distortion model.

B.5.4 Correlation length

An empirically derived covariance function was not applied in the distortion modelling procedure. Rather a correlation length parameter (32 km) and search radius parameter (80 km) were specified for the covariance function. The correlation length parameter (32 km) used in the model effectively determined the distance (~45 km) within which an informing survey mark would influence the predicted grid node and the other informing marks. The search radius parameter (80 km) limited the range within which informing survey marks could contribute to the distortion modelling at each grid node.

A best-fitting distortion correlation length of approximately 6 km was originally computed for the national dataset, based on a statistical analysis to determine the distance at which the distortion of marks was correlated. However, areas without marks within the reach of the distortion correlation length, reverted to the conformal-only transformation component. This led to a relatively spotty looking distortion grid, particularly in regional areas where marks were sparsely distributed. Further, there were cases where distortion modelling was not being performed around marks, even though those marks were not considered outliers. This was due to a step in the distortion modelling which prevented the determination of an estimate of distortion if only one mark fell within a grid area.

To expand the modelling of distortion and include more marks in the distortion modelling procedure, the statistically determined correlation length and search radius parameters were over-written to be 32 km and 80 km, respectively. These parameters were selected based on distortion modelling cross validation tests.

B.5.5 Cross validation testing

The choice of a suitable correlation length was difficult for a national dataset such as this where there are densely clustered marks (such as in towns and cities) and sparsely distributed marks (such as in regional areas), as well as inconsistent levels of distortion (magnitude and direction).

Distortion modelling cross validation testing was performed for ten different combinations of correlation length (4 km, 8 km, 16 km, 32 km, 64 km) and search radius (20 km, 80 km) parameters. These parameters were varied to improve the distortion modelling and capture more points in the model. Results from the separate cross validation tests were compared to identify the optimum parameter combination.

Table B.1. Summary statistic for different parameter combinations

	Mean		Sdev		Min		Max		No Result		Outliers
Name	**Lat**	**Long**	**Lat**	**Long**	**Lat**	**Long**	**Lat**	**Long**	**Lat**	**Long**	**Count**
Xval_4k_20k	0.000	-0.004	0.023	0.032	-0.126	-0.187	0.140	0.197	6662	6662	389
Xval_4k_80k	0.000	-0.004	0.023	0.032	-0.126	-0.187	0.140	0.197	6390	6390	385
Xval_8k_20k	-0.001	-0.003	0.021	0.027	-0.180	-0.165	0.125	0.120	2848	2848	578
Xval_8k_80k	-0.001	-0.003	0.021	0.027	-0.203	-0.179	0.125	0.120	2479	2479	595
Xval_16k_20k	0.001	0.002	0.018	0.022	-0.092	-0.158	0.124	0.126	1384	1384	803
Xval_16k_80k	0.001	0.003	0.018	0.021	-0.092	-0.158	0.124	0.126	410	410	922
Xval_32k_20k	0.001	0.002	0.016	0.019	-0.111	-0.148	0.120	0.140	1384	1384	911
Xval_32k_80k	**0.001**	**0.002**	**0.017**	**0.019**	**-0.154**	**-0.146**	**0.120**	**0.140**	**46**	**46**	**1067**
Xval_64k_20k	0.000	0.001	0.016	0.018	-0.135	-0.147	0.119	0.142	1384	1384	917
Xval_64k_80k	0.000	0.001	0.016	0.018	-0.104	-0.147	0.119	0.142	25	25	1068

The mean and standard deviation values for the different tests were quite similar. Likewise, there was little variation in the max and min differences. The “no result” counts were quite large for many of the combinations ranging from 1000 to 6000 points not being included in the distortion modelling. The larger correlation lengths (16 km, 32 km and 64 km) reduced the number of “no result” points. However, this led to an increase in the count of outliers (distortion difference greater than 3-sigma).

A correlation length of 32 km and search radius of 80 km were selected. The larger correlation length of 32 km included more marks in the model and allowed the influence of distortion at marks to extend over distances larger than 45 km, out to the limit of the search radius of 80 km (Figure B.3). This led to an increase in the number of marks exhibiting inconsistent distortion behaviour. Whilst the influence of an outlier (in terms of geometry) may have been weak, it could have unpredictable effects.

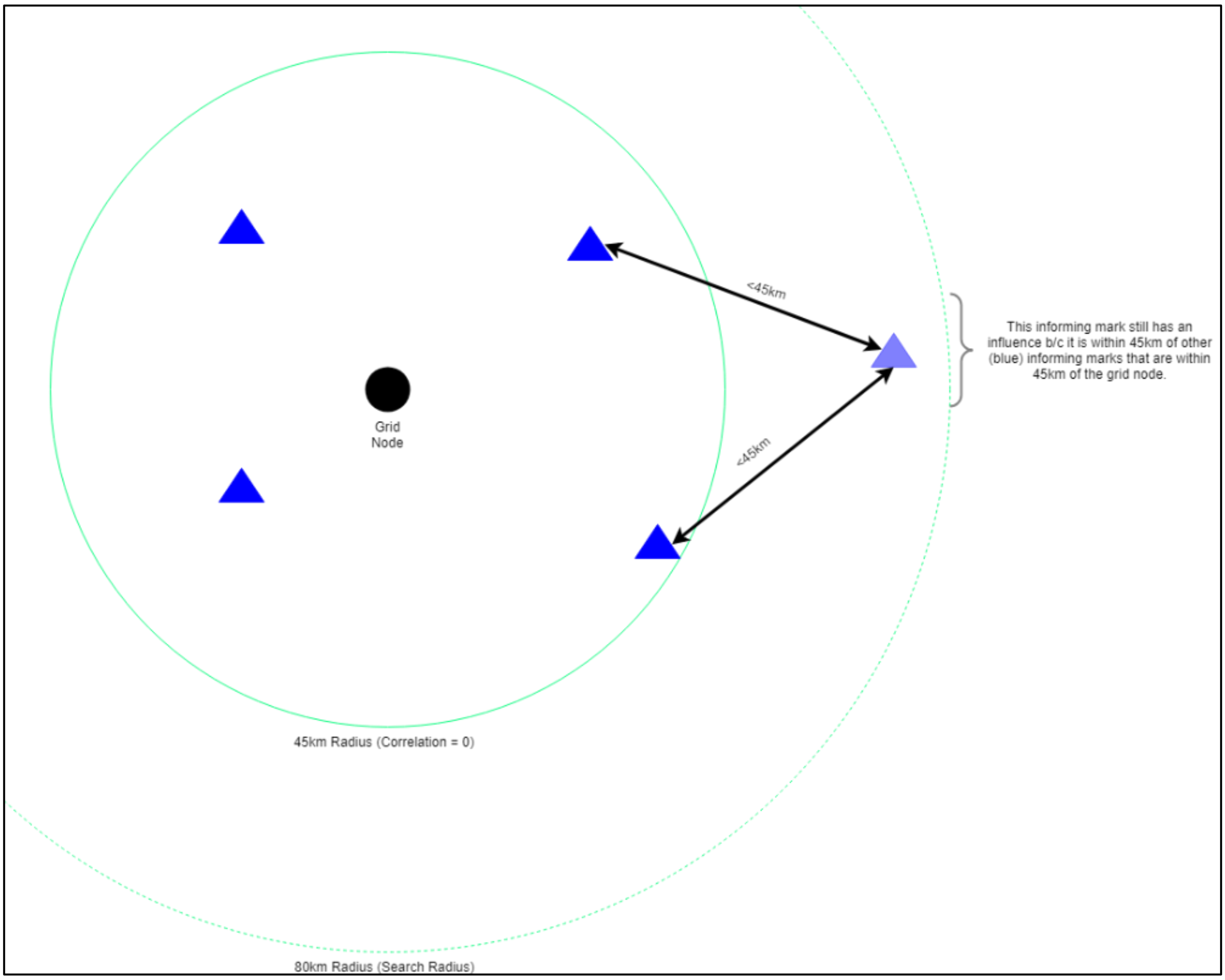

Figure B.3. Correlation length and search radius.

During this analysis it was observed, that in areas where distortion is consistent in direction and magnitude the distortion is modelled well (Figure B.4). However, if the distortion is inconsistent in direction and magnitude then the distortion can be modelled poorly (Figure B.5).

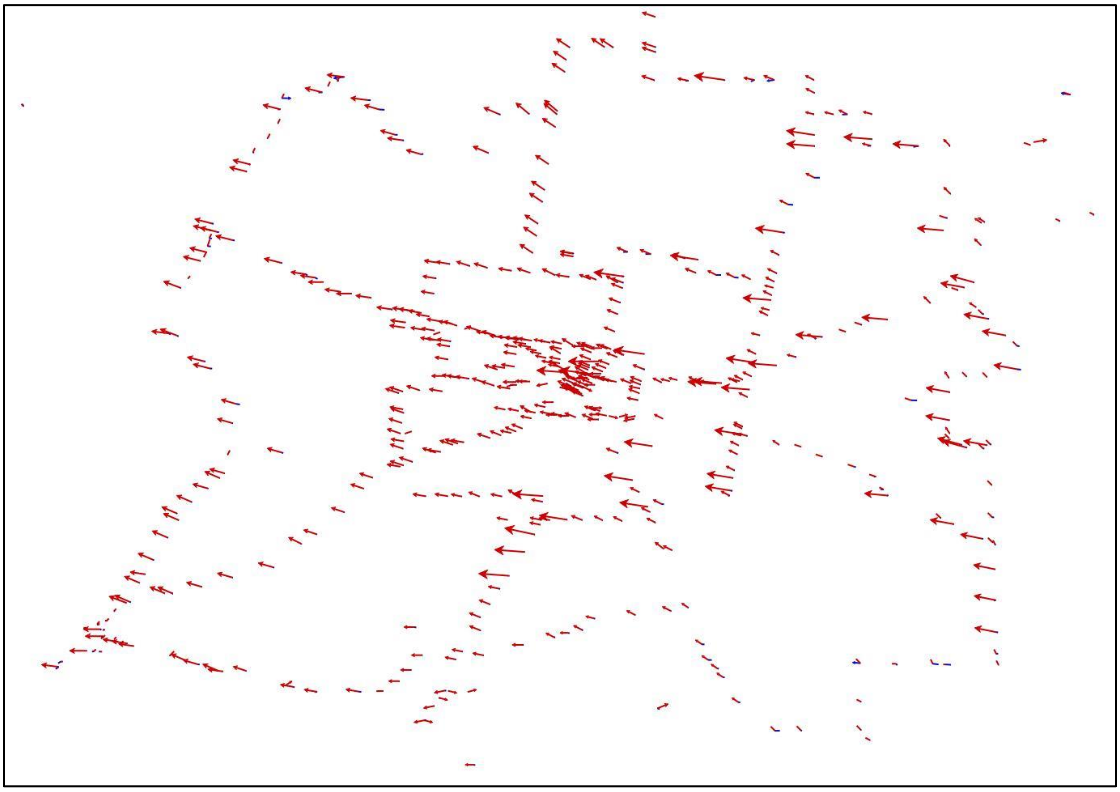

Figure B.4. Example of consistent distortion behaviour and the minimal influence on modelled distortion (Hamilton, VIC).

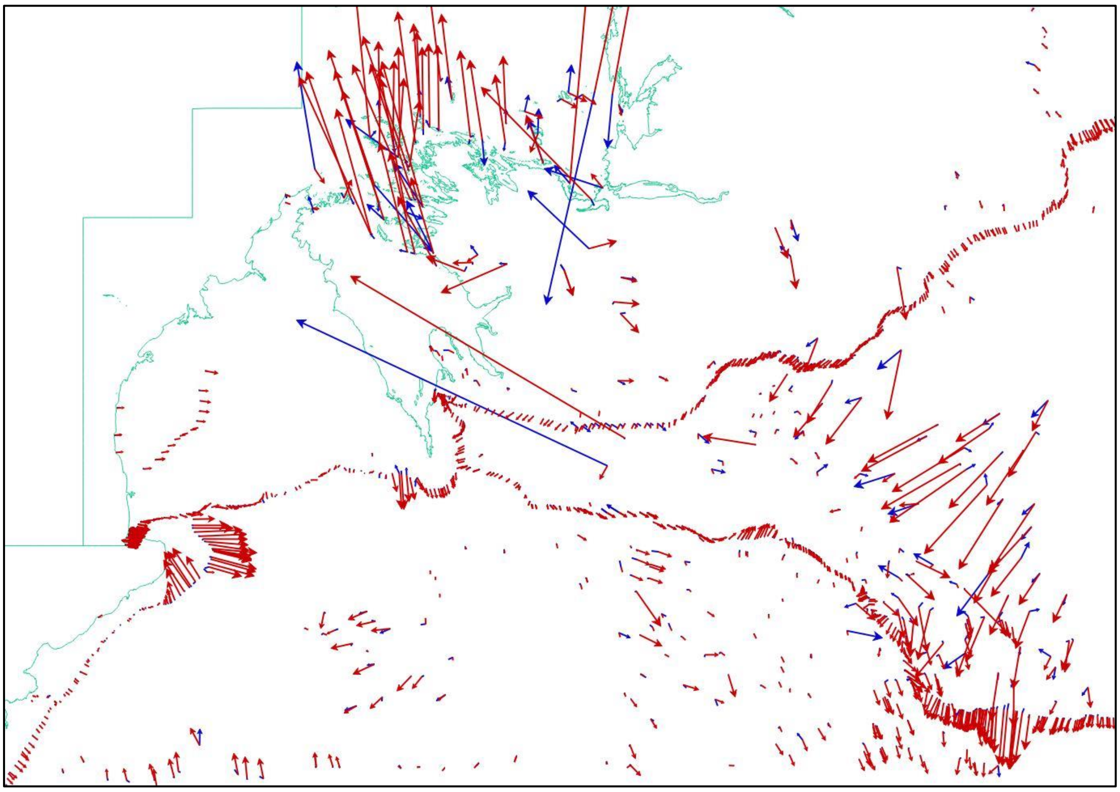

Figure B.5. Example of consistent and inconsistent distortion behaviour and the influence on modelled distortion (North West WA).

B.5.6 Point selection

To predict the distortion at a grid node the software selects a number (5) of informing marks to use in the prediction. The algorithm used to perform this task is shown in Figure B.6 and described below:

3. All informing marks within a certain radius (80 km) of the grid node are identified.
4. Identify the closest informing mark to the grid node and record its quadrant (e.g. Quadrant 1)
   a. Select this informing survey mark for use in the prediction.
5. Loop through the remaining quadrants (Q2, Q3, Q4)
   a. Identify the closest informing survey mark to the grid node in the current quadrant
   b. Select this informing survey mark for use in the prediction.
   c. If there is no informing mark in this quadrant, move to the next quadrant.
6. Continue Step 3 until the required number of informing marks are selected.
   a. Or, stop if there are no more informing marks to check within the 80km.

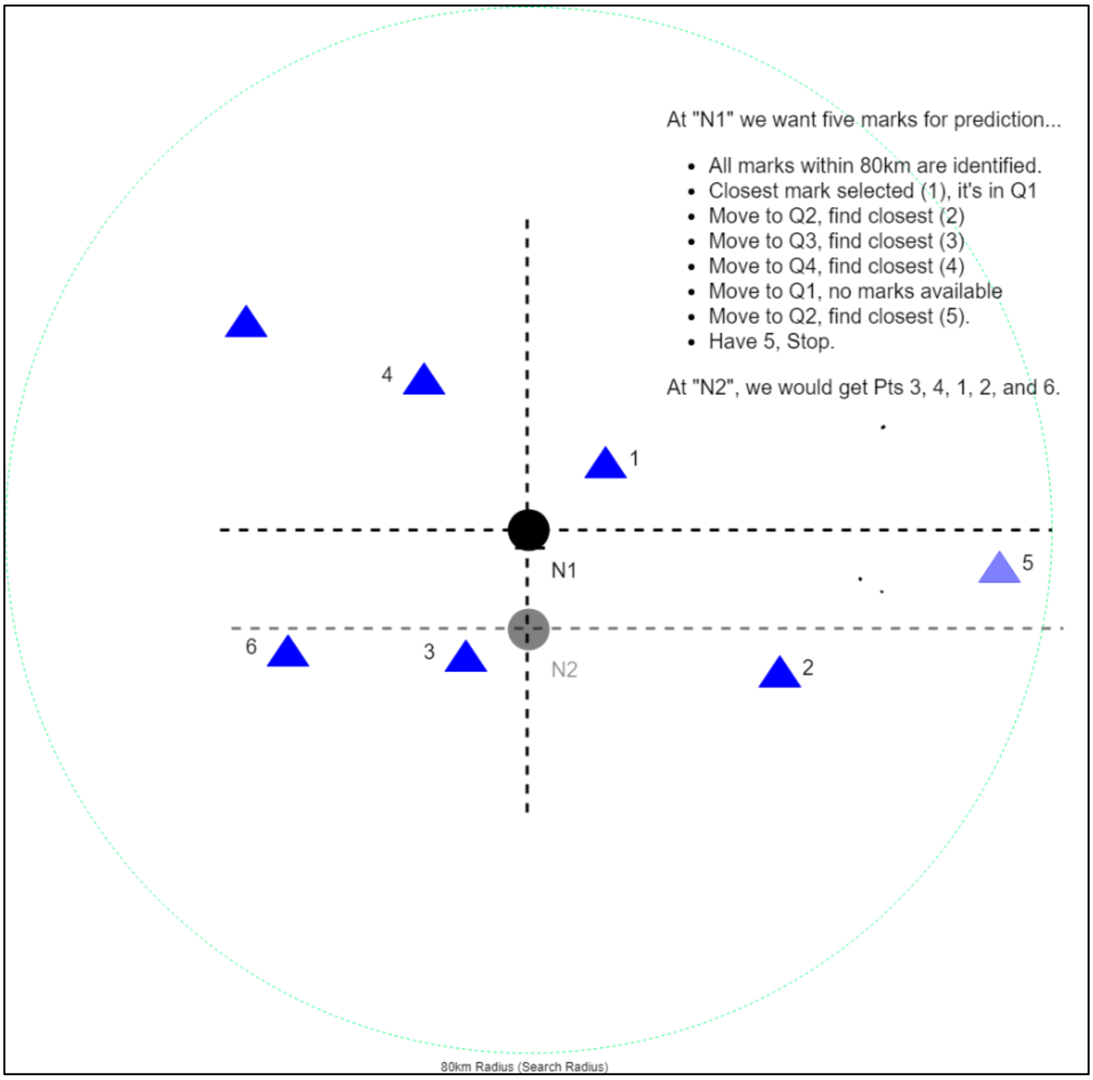

Figure B.6: Point Selection.

The purpose of quadrant control in this algorithm is to ensure (where possible) that the selected informing marks have a good geometric spread.

The quadrant control process has had an influence in the creation of apparent linear artefacts, caused by the discontinuous selection of informing mark. The inclusion of outliers exacerbated the unpredictable behaviour seen in the distortion modelling.

B.5.7 Least squares collocation prediction equation

After developing the covariance function, the least squares collocation prediction equation was used to compute the grid of distortion values over Australia.

B.5.8 National grid

The GDAGrid software and NTv2 grid file format are capable of supporting sub grids. The AGD66/AGD84-GDA94 distortion grids included sub grids. However, in the early development stages of the GDA94-GDA2020 transformation grids, it was decided to generate only one national grid.

Initially the transformation grids were developed as a series of regional grids, covering one or two states/territories. This was done to keep the file sizes small during the development and testing phases. Towards the end of the grid development all the grids were merged into one national grid file (conformal-only, conformal + distortion).

B.5.9 Queensland conformal-only

The conformal + distortion grid combination was complicated by the requirement for Queensland to only be covered by the conformal-only grid. This is due to the approach Queensland employed for the maintenance of GDA94 survey control mark coordinates via a least-squares adjustment aligned to the most current solution for the GNSS CORS. This approach effectively removed the requirement for the modelling of distortion across Queensland.

The official Queensland state border was used to remove Queensland from the conformal + distortion grid, leaving the conformal-only grid to cover the state. This strategy ensured that distortion would be modelled entirely within neighbouring states and territories. However, the first grid cell within the Queensland border retained the modelled distortion. Therefore, care should be exercised when transforming spatial data that overlaps two kilometres within the Queensland border. The conformal-only transformation grid is recommended for the transformation of two-dimensional spatial data within Queensland.

B.5.10 Territory transformation grid

Additional two-dimensional conformal-only transformation grids were developed for the Indian Ocean Territories, Christmas Island and Cocos (Keeling) Island. Conformal + distortion transformation grids were not developed for the Indian Ocean Territories.

B.5.11 Pseudo points

To overcome problems associated with an insufficient number of points, pseudo points were used in the AGD66/AGD84-GDA94 transformation grids development procedure. Pseudo points were not used in the GDA94-GDA2020 distortion modelling procedure. The extended correlation length and search radius overcame the need for introducing pseudo points.

B.6 Performance of the transformation grids

Analysis was performed by each State and Territory jurisdiction to assess the performance of the two transformation grids. The survey control mark data supplied to create the conformal + distortion grid and additional survey control mark data, withheld from the conformal + distortion grid, were used to test the transformation grids.

The transformation grids were found to be fit for purpose, although it was noted that the distortion modelling using the least squares collocation technique was impeded when the distortion was erratic and non-homogenous in behaviour.

B.7 Summary

The transformation grids were accepted by all States and Territories at the end of 2017. The grids were distributed as part of the release and implementation of GDA2020. The conformal-only grid was accepted as a satisfactory product for performing a seven-parameter transformation between GDA94 and GDA2020.

The conformal + distortion grid was developed to provide a best fitting solution across Australia and was deemed fit for purpose by all States and Territories. Various factors and decisions influenced the distortion modelling process, including:

- Variability in distortion (magnitude and direction)
- Variability in the distribution of marks
- Avoidance of sub-grids and adoption of one national grid
- Expectations that distortion be modelled across areas of sparse coverage, beyond the distance at which the distortion of marks was estimated to be correlated (increased the correlation length and search radius)
- Lack of weighting of distortion
- Intentional retention of marks exhibiting inconsistent distortion (e.g. outliers)

The conformal + distortion grid was deemed fit for purpose by all States and Territories. The GDA2020 national adjustment continues to extend and improve as new measurements are introduced, and outliers are resolved. As such the national adjustment derived GDA2020 coordinates of survey control marks are subject to ongoing revision. However, there are no plans to continually revise the conformal + distortion grid. This will slowly degrade the alignment of the conformal + distortion grid with the survey control mark coordinates.

B.8 References

ICSM, 2020, Geocentric Datum of Australia 2020 Technical Manual, Version 1.5.

Appendix C – AGD66 / AGD84 to GDA94 transformations

C.1 Transformation grid details

Initially State and Territories produced individual NTv2 transformation grids. These files transformed from either AGD66 or AGD84 to GDA94, depending on which version of AGD was previously adopted by that jurisdiction. Subsequently combined grids were produced and ultimately two national transformation grid files (one each for AGD66 and AGD84) were developed. It is these grids that are available under a BSD 3-Clause licence from the ICSM GitHub repository (https://github.com/icsm-au) and recommended for use as the preferred method to transform from AGD66 and AGD84 to GDA94. The uncertainty of each of these transformations grids is estimated to be approximately 0.1 m.

See Tables C-1 and C-2 for details of various transformation files related to respective EPSG transformation codes and names.

Table C-1: AGD66 to GDA94 NTv2 Transformation Grids

NTv2 Transformation file name	EPSG Transformation Code	EPSG transformation name	Comments
A66 National (13.09.01).gsb	1803	AGD66 to GDA94 (11)	Coverage - national. Replaces Codes 1506, 1507, 1596
SEAust_21_06_00.gsb	1596	AGD66 to GDA94 (10)	Coverage - ACT, NSW, VIC. Replaced code 1464
nt_0599.gsb	1507	AGD66 to GDA94 (7)	Coverage - NT.
tas_1098.gsb	1506	AGD66 to GDA94 (6)	Coverage – Tas
Vic_0799.gsb	1464	AGD66 to GDA94 (5)	Coverage – Vic

Table C-2: AGD84 to GDA94 NTv2 Transformation Grids

Transformation file name	EPSG Transformation Code	EPSG transformation name	Comments
National 84(02.07.01).gsb	1804	AGD84 to GDA94 (5)	Coverage – Qld, SA, WA. Replaces Code 1593
wa_0700.gsb	1593	AGD84 to GDA94 (4)	Coverage - WA. Replaced code 1559

C.2 National transformation grid coverage

Transformation file *A66 National (13.09.01).gsb* provides a complete national coverage from AGD66 to GDA94. In NSW and Victoria the on-shore and close coastal areas of the earlier combined State grid were included in the national grid, but elsewhere there may be differences. These differences are generally small but may be larger near the state borders and in areas where there was little or no common data (e.g. offshore). The AGD66 national file also covers the offshore areas out to the

Exclusive Economic Zone (EEZ). Although still in NTv2 format, a simple conformal transformation was used to generate the shifts in these offshore areas.

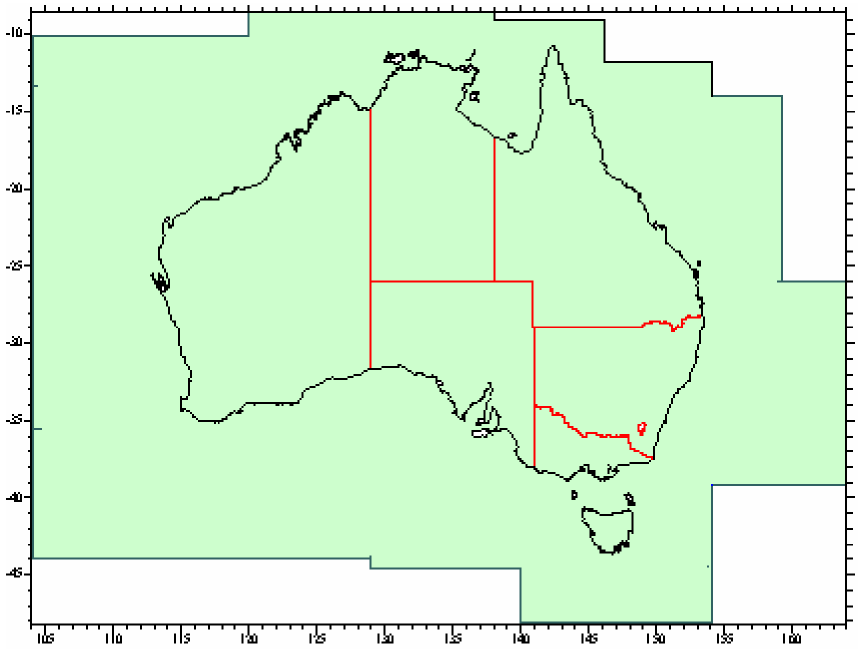

Figure C-1: AGD66 to GDA94 Transformation Grid Coverage.

Transformation file *National 84(02.07.01).gsb* has coverage for the states that previously adopted AGD84 (Queensland, South Australia and Western Australia). This coverage was produced by merging individual Queensland, South Australian and West Australian transformation files, and differs slightly from the previous state files only near the merged borders.

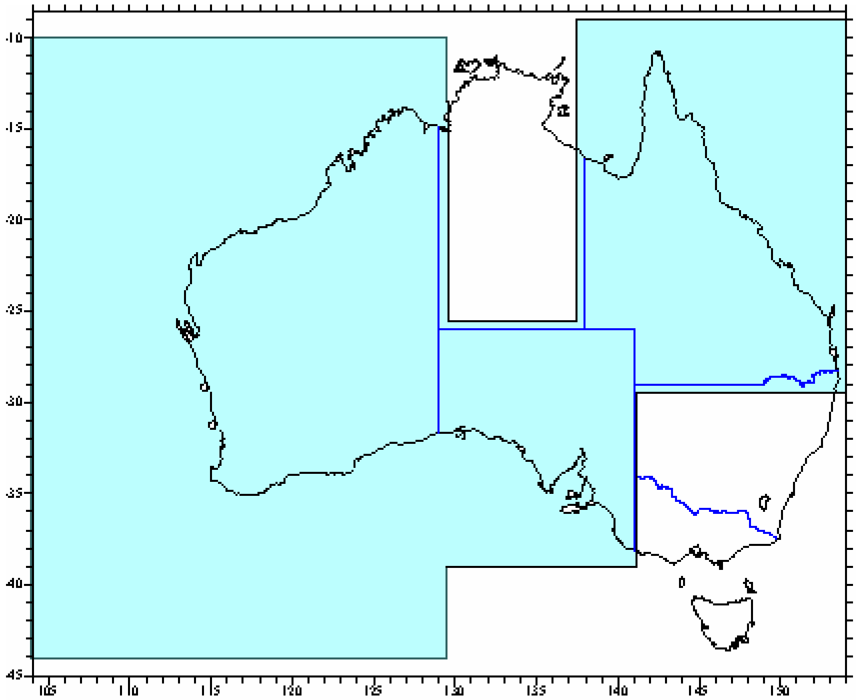

Figure C-2: AGD84 to GDA94 Transformation Grid Coverage.

For mathematical convenience and to suit the rectangular convention of the NTv2 format, the national grids extend outside the Australian EEZ in some places, but these extents do not infer any rights, nor do they imply the use of AGD or GDA94 coordinates in these areas.

C.3 National 7 parameter similarity transformations

National similarity transformation parameters to convert between AGD66 / AGD84 and GDA94 were developed (Table C-3 and C-4). Due to the inconsistent nature of the AGD66 coordinate set, it is not possible to perform a highly accurate 7-parameter similarity transformation. The estimated uncertainty of the national AGD66 parameters is 3 metres and they are only recommended for use in offshore environments. The estimated uncertainty of 7-parameter similarity transformation for AGD84 to GDA94 parameters is about 1 metre.

The parameters to transform between AGD84 and GDA94 were computed from 327 points across Australia, which had both AGD84 and GDA94 coordinates.

Table C-3 National transformation parameters for AGD84 and AGD66 to GDA94. Units are in m for the translation, parts-per-million (ppm) for scale, and arc-seconds (as) for the rotations.

Datum	EPSG Code	t_x	t_y	t_z	s_c	r_x	r_y	r_z
AGD84	1280	-117.763	-51.510	139.061	-0.191	-0.292	-0.443	-0.277
AGD66	15979	-117.808	-51.536	137.784	-0.290	-0.303	-0.446	-0.234

Refer to Chapter 10.1 for an explanation of the rotation matrix sign convention.

Table C-4 EPSG details of national transformations for AGD84 and AGD66 to GDA94.

EPSG Transformation Code	EPSG transformation name	Comments
1280	AGD84 to GDA94 (2)	AGD84 officially adopted only in QLD, SA and WA
15979	AGD66 to GDA94 (12)	Recommended for use in offshore areas only.

C.4 Regional 7 parameter similarity transformations for AGD66

Although it is possible to compute national similarity transformation parameters between AGD84 and GDA94 that provide an estimated accuracy of transformation of 1 metre, AGD66/GDA94 similarity transformation parameters can only be accurately computed for smaller areas where AGD66 is more consistent.

The parameters shown in Table C-5 are only valid for transformation between AGD66 and GDA94 for the jurisdiction indicated.

Table C-5 Regional transformation parameters for AGD66 to GDA94. Units are in m for the translation, parts-per-million (ppm) for scale, and arc-seconds (as) for the rotations.

Region	EPSG Code	t_x	t_y	t_z	s_c	r_x	r_y	r_z
ACT	5827	-129.164	-41.188	130.718	-2.955	-0.246	-0.374	-0.329
ACT	1458	-129.193	-41.212	130.730	-2.955	-0.246	-0.374	-0.329
TAS	1594	-120.271	-51.536	137.784	2.499	-0.217	0.067	0.129
VIC/NSW	1460	-119.353	-48.301	139.484	-0.613	-0.415	-0.260	-0.437
NT	1595	-124.133	-42.003	137.400	-1.854	0.008	-0.557	-0.178

Table C-6 EPSG details of regional transformations for AGD66 to GDA94.

EPSG Transformation Code	EPSG transformation name	Comments
5827	AGD66 to GDA94 (19)	Coverage – ACT
1458	AGD66 to GDA94 (10)	Coverage – ACT. Parameters replaced in Code 5827
1594	AGD66 to GDA94 (8)	Coverage - Tas
1460	AGD66 to GDA94 (4)	Coverage – VIC/NSW
1595	AGD66 to GDA94 (9)	Coverage – NT

Appendix D Grid bearings and ellipsoidal distance

The following formulae provide the only direct method to obtain grid bearings and ellipsoidal distance from MGA2020 coordinates.

$$tan\,\theta_1 = (E_2' - E_1')/(N_2 - N_1) = cot\,\theta_1 = (N_2 - N_1)/(E_2' - E_1')$$

where E_1' E_2' are the easting values measured positive eastwards from the central meridian (i.e. does not include the false easting) of points 1 and 2 respectively

$$L = (E_2' - E_1')/\sin\theta_1 = (N_2 - N_1)/\cos\theta_1$$

$$K = k_0\{1 + [(E_1'^2 + E_1'E_2' + E_2'^2)/6{r_m}^2][1 + (E_1'^2 + E_1'E_2' + E_2'^2)/36{r_m}^2]\}$$

$$s = L/K$$

$$\delta_1{}^{"} = -(N_2 - N_1)(E_2' + 2E_1')[1 - (E_2' + 2E_1')^2/27{r_m}^2]/6{r_m}^2 \text{ (radians)}$$

$$\delta_1{}^{"} = 206264.8062\,\delta_1 \text{ (seconds)}$$

$$\delta_2{}^{"} = (N_2 - N_1)(2E_2' + E_1')[1 - (2E_2' + E_1')^2/27{r_m}^2]/6{r_m}^2 \text{ (radians)}$$

$$\delta_2{}^{"} = 206264.8062\,\delta_2 \text{ (seconds)}$$

$$\beta_1 = \theta_1 - \delta_1$$

$$\beta_2 = \theta_1 \pm 180° - \delta_2$$

The mean radius of curvature can be calculated as shown below, using an approximate value for the mean latitude (ϕ_m'). The approximate mean latitude can be calculated in two steps, with an accuracy of about two minutes of arc, using the formulae shown below. This approximation is derived from the formulae for meridian distance used with Krueger λ series equations (Redfearn's) and the constants shown are the values aA_1 and aA_2, computed for GDA2020.

$$N' = N - False\ Northing$$

- $N_m' = (N_1' + N_2')/2$
- $\phi_m'(1st\ approx) = (N_m'/k_0)/111132.952$
- $\phi_m'(2nd\ approx) = ((N_m'/k_0) + 16038.508\ \sin 2\phi_m')/111132.952$
- $\rho_m = a(1 - e^2)/(1 - e^2 \sin^2\phi_m')^{3/2}$
- $\nu_m = a/(1 - e^2 \sin^2\phi_m')^{1/2}$
- ${r_m}^2 = \rho_m \nu_m {k_o}^2$

D.1 MGA2020 coordinates from grid bearing and ellipsoidal distance

This computation is commonly used when the coordinates of one station are known and the grid bearing and ellipsoidal distance from this station to an adjacent station have been determined. The bearing and distance are applied to the coordinates of the known station to derive the coordinates of the unknown station and the reverse grid bearing. The formulae shown are accurate to 0.02" and 0.1 ppm over any 100 kilometre line in an MGA zone. For lower order surveys:

- • the underlined terms are often omitted
- • the latitude function $1/6r^2$ becomes a constant and
- • the formulae for K and δ are replaced by simplified versions

Formulae

First calculate approximate coordinates for the unknown station:

$$E_1' = E_1 - 500\,000$$

$$E_2' \approx E'_1 + k_1 s \sin\beta_1$$

$$N_2 - N_1 \approx k_1 s \cos\beta_1$$

If not already known the point scale factor (k_1) may be approximated by:

$$k_1 \approx 0.9996 + 1.23E'^2 10^{-14}$$

$$K = k_0\left\{1 + \left[\left(E_1'^2 + E_1'E_2' + E_2'^2\right)/6r_m^2\right]\underline{\left[1 + \left(E_1'^2 + E_1'E_2' + E_2'^2\right)/36r_m^2\right]}\right\}$$

$$L = sK$$

$$\sin\delta_1 = -(N_2 - N_1)(E_2' + 2E_1')\left[\underline{1 - (E_2' + 2E_1')^2/27r_m^2}\right]/6r_m^2$$

$$\theta = \beta_1 + \delta_1$$

$$\sin\delta_2 = (N_2 - N_1)(2E_2' + E_1')\left[\underline{1 - (2E_2' + E_1')^2/27r_m^2}\right]/6r_m^2$$

$$\beta_2 = \theta \pm 180° - \delta_2$$

$$\Delta E = L\sin\theta$$

$$\Delta N = L\cos\theta$$

$$E_2 = E_1 + \Delta E$$

$$N_2 = N_1 + \Delta N$$

The mean radius of curvature can be calculated as shown below, using an approximate value for the mean latitude (ϕ_m'). The approximate mean latitude can be calculated in two steps, with an accuracy of about two minutes of arc, using the formulae shown below. This approximation is derived from the formulae for meridian distance used with Krueger λ series equations (Redfearn's) and the constants shown are the values aA_0 and aA_2, computed for GDA2020.

$$N' = N - False\ Northing$$

$$N_m' = (N_1' + N_2')/2$$

$$\phi_m'(1st\ approx) = \left(N_m'/k_0\right)/111132.952$$

$$\phi_m'(2nd\ approx) = \left(\left(N_m'/k_0\right) + 16038.508\sin 2\phi_m'\right)/111132.952$$

$$\rho_m = a(1 - e^2)/\left(1 - e^2\sin^2\phi_m'\right)^{3/2}$$

$$\nu_m = a/\left(1 - e^2\sin^2\phi_m'\right)^{1/2}$$

$$r_m{}^2 = \rho_m \nu_m k_0{}^2$$

D.2 Traverse computations using arc-to-chord corrections and scale factors

Traverses can be rigorously computed on the ellipsoid, using formulae such as those shown in Chapter 12. The geographic results from these computations can then be rigorously converted to grid coordinates using Krueger equations. However if necessary, the computation can be varied to suit the requirements of the project. For example:

- the arc-to-chord corrections and line scale factors can be ignored and the traverse computed using the formulae of plane trigonometry;
- if approximate MGA2020 coordinates of the traverse stations are available, compute of the arc-to-chord corrections and line scale factors; or
- the arc-to-chord corrections and line scale factors can be computed precisely, and the method becomes first order anywhere in a MGA2020 grid zone.

The precision obtained should be closely balanced against the labour involved, though with modern computers and software, the difference between a rigorous and approximate calculation is trivial. Prior to precise computation, approximate coordinates and bearings may be carried through the traverse, using uncorrected field measurements, to ensure that the observations are free of gross errors.

D.2.1 Basic outline

There are many ways of arranging the computation. Essentially, the work is split into stages:

1. approximate eastings and northings are computed from observed angles and distances
2. arc-to-chord corrections and line scale factors are computed from the approximate coordinates and applied to the observations to give plane angles and plane distances
3. precise coordinates are computed by plane trigonometry
4. misclosure in grid bearing and position is analysed and the traverse is adjusted as required.

For precise computation, each line is rigorously computed before the next line is calculated, so that errors in the approximate coordinates do not accumulate. True eastings E' and differences in northing ΔN are the quantities carried through the computation. Sign conventions can be disregarded and signs determined by inspection of a traverse diagram.

D.2.2 Formulae and symbols

Formulae for arc-to-chord corrections δ and line scale factors K are given above. If the underlined terms are omitted, the errors for a 100 km line running north and south on a zone boundary do not exceed 0.08” in bearing and 0.25 ppm in distance. As the final coordinates of a precise traverse will nearly always be computed and adjusted by least squares. For short lines near a central meridian it may be possible to omit the arc-to-chord corrections and line scale factors and compute the traverse with observed angles and distances, using the formulae of plane trigonometry.

If the symbol δ_{21} is used for the arc-to-chord correction at station 2 to station 1 and δ_{23} for the correction at station 2 to station 3 and the angles are measured clockwise from station 1 to station 3, then the plane angle P_2 at station 2 is obtained from the observed angle O_2 by

$$P_2 = O_2 + \delta_{23} - \delta_{21}$$

where angles are measured clockwise only.

D.2.3 Computations of arc-to-chord corrections and scale factors

Although there are several ways of arranging the computation, the following procedure, is recommended:

1. compute the grid bearing to the "forward" station by applying the observed horizontal angle at the "occupied" station to the known grid bearing of the "rear" station
2. compute the point scale factor at the "occupied" station and multiply the ellipsoidal distance to the "forward" station by this factor
3. using the distance obtained and the forward grid bearing, compute approximate coordinates of the "forward" station by plane trigonometry
4. using the coordinates of the "occupied" station and the approximate coordinates of the "forward" station, compute the arc-to-chord correction at the "occupied" station and the line scale factor. If the line crosses the central meridian, $E_1'\ E_2'$ is negative
5. add the arc-to-chord correction to the forward grid bearing to obtain the plane bearing and multiply the ellipsoidal distance by the line scale factor to obtain the plane distance
6. using the plane bearing and plane distance, compute the coordinates of the "forward" station by plane trigonometry
7. compute the arc-to-chord correction from the new station to the previously occupied station and add this to the plane bearing reversed by 180° to obtain the reverse grid bearing from the new station.

The above process is repeated for each new line of a traverse with the reverse grid bearing of the previous line becoming the known grid bearing to the rear station.

The traverse diagram shown in Figure D-2 should be referred to with the above text.

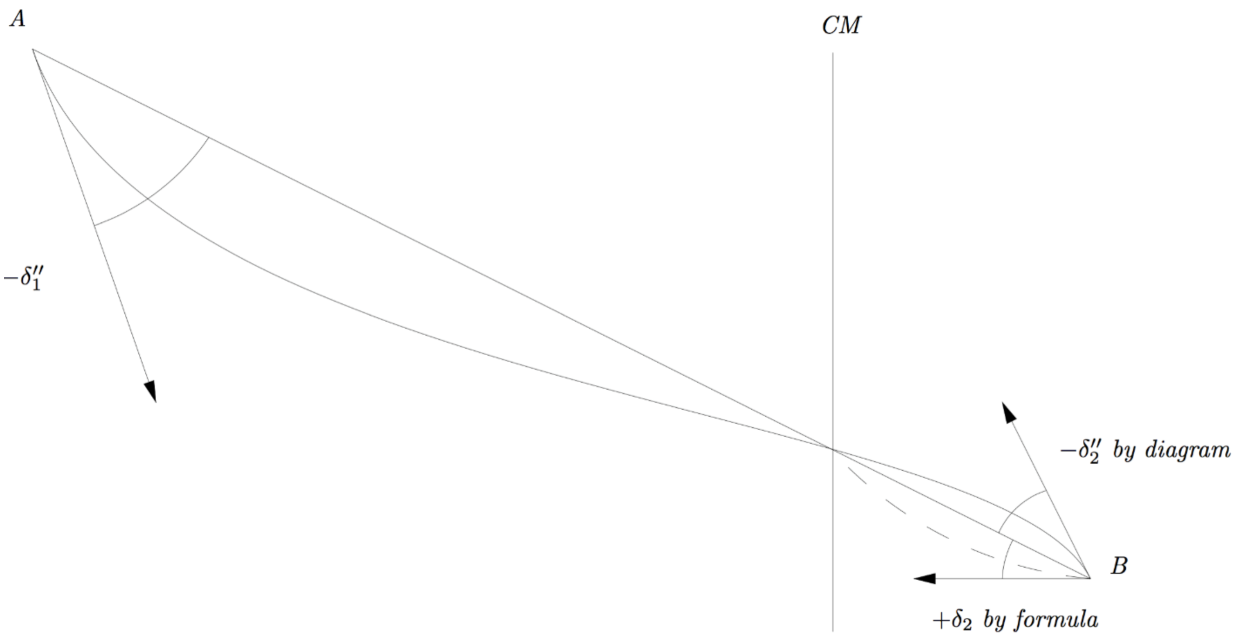

Figure D-1 Arc-to-chord correction.

Table D-1 Sample data to check grid calculations.

	Flinders Peak	Buninyong
MGA2020 (zone 55)	E 273 741.297 N 5 796 489.777	E 228 854.051 N 5 828 259.038
Ellipsoidal Distance (m)	54972.271	
Plane Distance (m)	54992.279	
Grid Bearing	305° 17’ 01.72"	125° 17’ 41.86"
Arc to chord	+19.47"	-20.67”
Line scale factor	1.000 363 97	

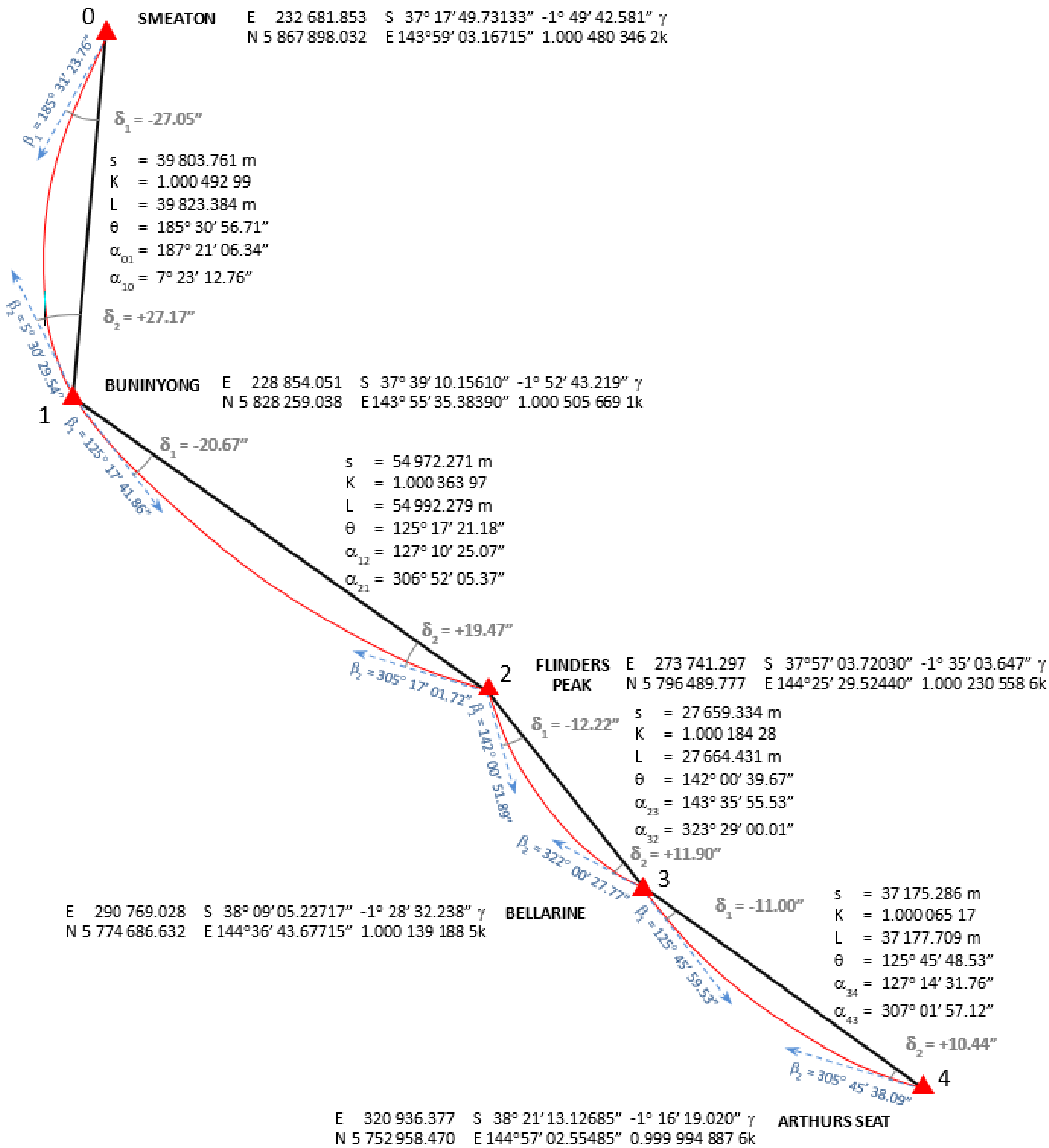

Figure D-2: Traverse diagram. All MGA2020 Eastings and Northings are in Zone 55.

Appendix E Grid references

The Universal Transverse Mercator (UTM) Grid, of which the Map Grid of Australia 2020 (MGA2020) is a part, provides the ability for the locations of features on the Earth to be uniquely defined via a single grid reference. Grid references can be used with maps and with online mapping systems, such as Google Maps.

Grid references are generalised forms of MGA2020 grid coordinates that consist of two parts. The first part is an alphanumeric code that uniquely defines a rectangular region of the Earth. The second part consists of the numerical location that defines the easting and northing for the location within the region.

E.1 Grid zones

A grid reference uses the UTM Grid Zones of 6° longitude bands together with the Military Grid Reference System (MGRS) of 8° latitude bands (except for the most northerly band, X, which covers 12 degrees of latitude from 72°N to 84°N). An extended MGRS can also be used where the zones are further divided into 100 000 metre square regions identified by a two letter code.

The Universal Polar Stereographic Grid is used north of the 84°N latitude and south of the 80°S latitude, but will not be discussed in this manual as it is outside the extents of GDA2020 and thus beyond the limits of MGA2020.

The numbering of the longitude bands starts at the 180° meridian with zone 1 and proceeds easterly with 6° intervals to define the 60 bands for the whole 360° around the Earth.

The 8° bands of latitude are lettered from C to X (X is a 12° latitude band), omitting the letters I and O, so as not to confuse them with the numbers one and zero. The southern value of the first latitude band is 80°S and with each band proceeding northwards to 84°N. There are 20 bands.

Each grid zone is thus one rectangle of the grid pattern established by these bands and is designated by the figure of the longitude band followed by the letter of the latitude band.

E.2 100 000 metre square identification

To further subdivide the 6° x 8° grid zones, an extended MGRS has been defined where the zones are divided into 100 000 metre square regions that are bounded by grid lines of eastings and northings and identified by a two letter code.

Each column and each row is identified by a letter which are combined to identify the 100 000 metre square. The letter pattern of 100 000 metre squares covers an area 18° east to west by 2 000 000 metres north to south, and is not repeated within this area.

Starting at the 180° meridian and proceeding easterly along the equator for 18°, the 100 000 metre columns, including partial columns along grid junctions, are consecutively lettered A to Z, with I and O being omitted. This is repeated at 18° intervals.

The 100 000 metre rows are lettered A to V with I and O being omitted and reading from south to north, with this partial alphabet being repeated every 2 000 000 metres. Every odd-numbered UTM zone has the alphabet of the 100 000 metre row letters beginning at the equator; the even-numbered UTM zones have the alphabet of the 100 000 metre row letters beginning at the northing grid line 500 000 metres south of the equator. So for even numbered easting zones the northing designators are offset by five characters, starting at the equator with the letter F. This staggering lengthens the distance between 100 000 metre squares of the same identification.

For the extents of GDA2020, which lies wholly below the equator, the 100 000 metre row letters also read from south to north, tying into the letters above in the same zone.

E.3 The grid reference

A grid reference will consist of a group of letters and numbers which indicate:

1. The Grid Zone Designation.
2. The 100 000 metre square identification.
3. The grid coordinates of the point expressed to the desired accuracy.

A reference will be written as a continuous number without spaces, parenthesis, dashes or decimal points.

To assist in explaining how to define a grid reference, the GDA2020/MGA2020 location of the Australian Fiducial Network site at Alice Springs (ALIC) is used as the example:

	Latitude (DMS)	Longitude (DMS)
	-23° 40’ 12.39650”	133° 53’ 07.87779”

Zone	Easting	Northing
53	386 353.2343	7,381,852.2986

This point would define the following grid references with increasing levels of accuracy:

1. 53KLP locating a point within a 100 000 metre square
2. 53KLP88 locating a point within a 10 000 metre square
3. 53KLP8681 locating a point within 1 000 metres
4. 53KLP863818 locating a point within 100 metres
5. 53KLP86358185 locating a point within 10 metres
6. 53KLP8635381852 locating a point within 1 metre

The Google Map reference for Alice Springs (ALIC) is 53KLP8635381852. Lower accuracy grid references are not recognised by the web service, other than by adding zeros.