Geocentric Datum of Australia 2020 Technical Manual

Version 1.1.1

Intergovernmental Committee on Surveying and Mapping (ICSM)
Permanent Committee on Geodesy (PCG)

8 January 2018

Foreword

Since the implementation of Geocentric Datum of Australia 1994 (GDA94), many advances have occurred in the fields of space geodesy, which have resulted in the improvement of the International Terrestrial Reference System (ITRS) to better define the shape of the Earth. Furthermore, high performance computing allows for the rigorous adjustment of jurisdictional archives of Global Navigation Satellite System (GNSS) data and terrestrial data.

Recognising the need to align the Australian datum with the reference frame of GNSS in which many current users and future users will access the datum, the Intergovernmental Committee on Surveying and Mapping requested that the Permanent Committee on Geodesy commence work on developing the Geocentric Datum of Australia 2020 (GDA2020) along with the required technical tools, services and documentation.

The Permanent Committee on Geodesy was assisted with contributions from a number of Commonwealth, state and territory representatives and from institutions engaged in the teaching of surveying and geodesy. Many useful suggestions received from these sources have been incorporated into this manual.

The Intergovernmental Committee on Surveying and Mapping thanks those who have contributed to this manual and hope it assists those seeking a definitive explanation of GDA2020.

Permanent Committee on Geodesy

Intergovernmental Committee on Surveying and Mapping

25 July 2017

Document history

DATE	VERSION	AMENDMENTS
25 July 2017	1.0	• New document for the release of GDA2020
13 December 2017	1.1	• Amendments to reflect the signing of the GDA2020 determination • Minor changes to wording to improve clarity • Inclusions to Table 3.4 for South Australian data • Corrections to grammar, table numbers, equation numbers • Added links to datum transformation tools
8 January 2018	1.1.1	• Fixed typographical error on Page 8. Changed “N'+ 10,000,0000 metres” to “false origin N'+ 10,000,000” metres

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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 Greenwich meridian. The angle between the plane of the local geodetic meridian and the Greenwich 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	

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 form 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; the change in the azimuth of a geodesic between two points on the ellipsoid.	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		$R^2{k_0}^2 = \rho\nu{k_0}^2$
${r_m}^2$	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	
$\Delta\alpha$	Meridian convergence; the change in the azimuth of a geodesic between two points on the ellipsoid.	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.	

1 Introduction

1.1 Purpose of the Technical Manual

The purpose of the Geocentric Datum of Australia 2020 (GDA2020) Technical Manual is to:

- define GDA2020;
- provide descriptions, transformation parameters and examples to assist with datum transformations between GDA2020, realisations of the International Terrestrial Reference Frame (ITRF) and historic Australian datums;
- provide descriptions and examples to assist with coordinate conversions between Earth-centred Cartesian, geodetic and map projected coordinates;
- provide descriptions and examples of coordinate computations; and
- define the Australian Height Datum (AHD) and AUSGeoid2020, and describe how to convert between ellipsoidal heights and AHD heights.

1.2 The Geocentric Datum of Australia 2020

Prior to the release of the GDA2020, the Geocentric Datum of Australia 1994 (GDA94) was the only Australian datum that used the acronym GDA. As a consequence, the acronym GDA was often used interchangeably with GDA94. When referring to any documents or software developed prior to the release of GDA2020, the reader can assume GDA refers to GDA94.

1.2.1 Terminology

Table 1.1: GDA2020 terminology.

Datum	Geographic Coordinate Set	Grid Coordinates
GDA2020	GDA2020	MGA2020

1.2.2 Definition

Table 1.2: GDA2020 definition.

Reference frame	Epoch	Ellipsoid	Semi-major axis (m)	Inverse flattening
ITRF2014	2020.0	GRS80	6378137	298.257222101

1.2.3 Legal traceability of position and Australian Fiducial Network

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 3.3).

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 plate motion model (Section 3.3). 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.

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 1.3: 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.

1.2.4 GDA2020 extent

The extent of the GDA2020 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 excludes Heard-McDonald Islands and the Australian Antarctic Territory (AAT) as shown in Figure 1.1. The extent of GDA2020 is the same as the extent of GDA94.

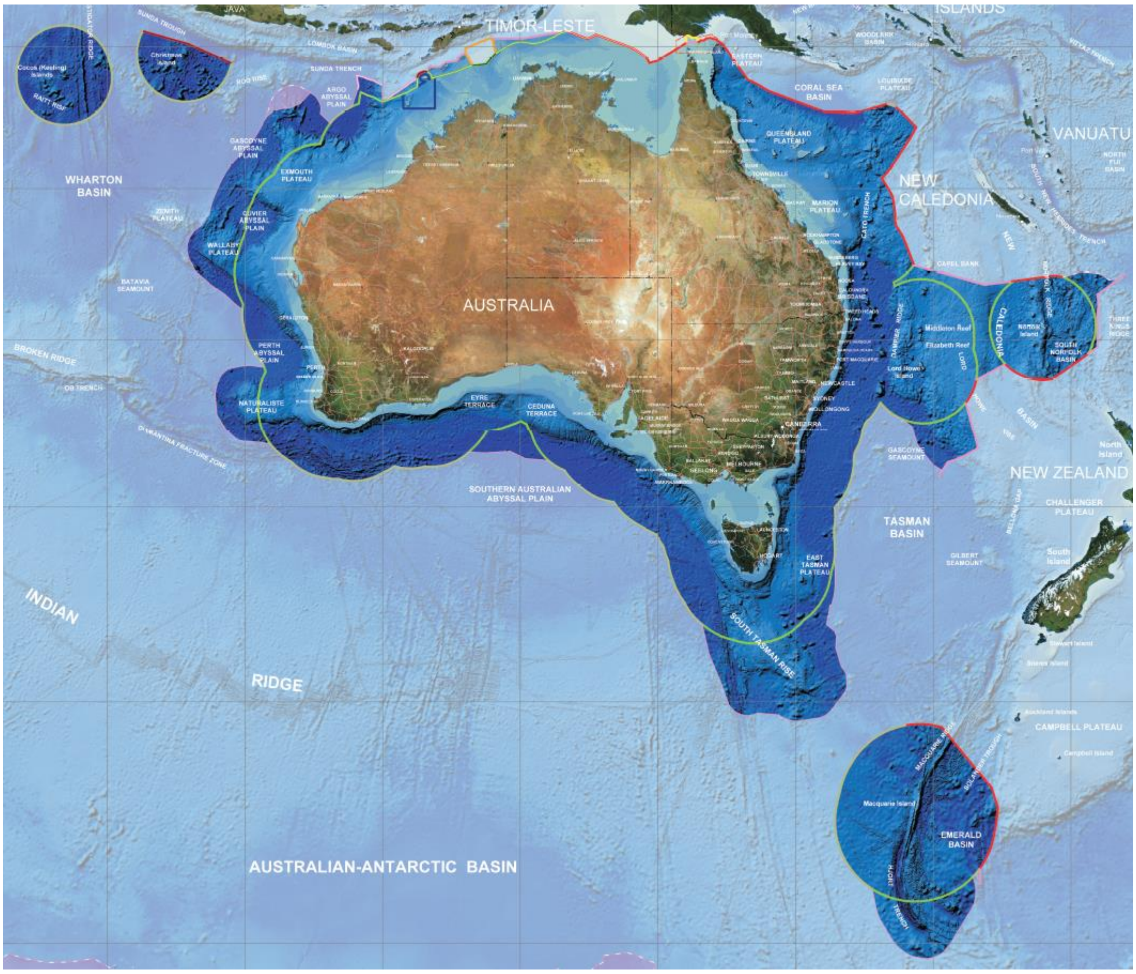

Figure 1.1: The area shown in dark blue is the GDA2020 extent. The colours of the lines represent different types of jurisdictional boundaries or proposed jurisdictional boundaries. For more information on the type of boundary, please refer to http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_70362

1.3 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.

For example, “EPSG::1168 Geodetic datum” refers to the defining elements of the Geocentric Datum of Australia GDA2020 held in the EPSG registry.

1.3.1 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.

1.3.2 ISO Registry

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 will ultimately replace the functions of the EPSG registry. Once ISO Registry codes are available they will be referenced in future updates to this manual.

1.4 History of Australian datums

1.4.1 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 spheroid the Australian National Spheroid (ANS; see Table 1.6) (NMC, 1966).

1.4.2 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 on 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 is defined by the following coordinates of Johnston Geodetic Station:

Table 1.4: 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.

1.4.3 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 1.5: 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.

1.4.4 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 Global Navigation Satellite System Service (IGS) campaign (previously known as the International GPS Service), 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 et al., 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 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 the Dawson and Woods (2010) transformation parameters. For those stations with multiple coordinate estimates in ITRF2008 the most recent coordinate estimate was adopted.

1.4.5 Geocentric Datum of Australia 2020

Since the realisation of GDA94, there have been significant developments in technology that provide ready access to accurate positioning systems. In the near future it is anticipated that GNSS will be capable of providing positioning services with centimetre accuracy in real-time to the mass market on mobile devices. Given that data from GNSS is referenced to a global reference frame, it is appropriate that the Australian datum be closely aligned to ITRF2014.

GDA2020 is based on a realisation of the ITRF2014 (ITRF2014; Altamimi et al., 2016) at epoch 2020.0. The Geocentric Datum of Australia 1994 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 will be approximately 1.8 m;
- there have been many improvements and realisations of the 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); and
- parts of the Australian crust have deformed (e.g. subsidence).

These refinements to the reference frame and local scale distortions have not been reflected in changes to the Australian datum; some of which will begin to be noticeable to some users of positioning services.

1.4.5.1 Computation of GDA2020 coordinates

GDA2020 coordinates were computed using a rigorous, 3D network adjustment of all available GNSS and terrestrial data from Commonwealth, state and territory jurisdictional archives. This adjustment enables the determination of GDA2020 coordinates and supports the computation of positional uncertainty and relative uncertainty between any survey control marks in Australia. The national GDA2020 adjustment was undertaken by Geoscience Australia with input from geodetic specialist representatives from all jurisdictional survey organisations.

The national GDA2020 network adjustment involved a rigorous least squares adjustment of all data. In the past, adjustments were undertaken with higher order data being held fixed in lower order adjustments. This resulted in distortions in the datum that have become more apparent when compared with high accuracy GNSS data observed in ITRF2008 or ITRF2014 and transformed back to 1994 using a 7-parameter similarity transformation. By performing a single national rigorous adjustment these distortions have been reduced and relative uncertainty can be computed for any given points on the datum.

The national GDA2020 network adjustment includes all available GNSS and terrestrial data from the jurisdictional archives, constrained using the Asia-Pacific Reference Frame (APREF) time series combination solution. This solution is calculated weekly by Geoscience Australia for approximately 450 APREF stations within Australia's jurisdiction and it provides a link between ITRF2014 and GDA2020. The development of GDA2020 has also seen the creation of the National GNSS Campaign Archive stored at Geoscience Australia.

This archive contains all GNSS observations provided by state and territory jurisdictions greater than six hours duration. The data was processed (and will continue to be as new data is available) by Geoscience Australia to create a national high quality GNSS network.

1.4.6 Summary of Australian horizontal datums

A summary of the Australian datums is provided in Table 1.6. In some previous documentation, GDA and AGD have been documented as the name of the datum and the epoch has been appended to describe the coordinate set (e.g. AGD66). To avoid confusion, it is recommended that the epoch be appended when describing the name of the datum so users can differentiate between them (e.g. GDA94 and GDA2020). The EPSG codes for the datums are shown in Table 1.7.

Table 1.6: Summary of the parameters of Australian datums.

Datum	Geographic Coordinate Set	Grid Coordinates	Reference Frame	Ellipsoid / Spheroid	Semi-major axis (m)	Inverse Flattening
GDA2020	GDA2020	MGA2020	ITRF2014	GRS80	6378137.0	298.257222101
GDA94	GDA94	MGA94	ITRF1992	GRS80	6378137.0	298.257222101
AGD84	AGD84	AMG84		ANS	6378160.0	298.25
AGD66	AGD66	AMG66		ANS	6378160.0	298.25

Table 1.7: EPSG codes of Australian datums.

Datum	Geographic Coordinate Set	EPSG Code Geodetic Datum	EPSG Code Geodetic CRS (Geocentric)	EPSG Code Geodetic CRS (Geographic 3D)	EPSG Code Geodetic CRS (Geographic 2D)
GDA2020	GDA2020	1168	7842	7843	7844
GDA94	GDA94	6283	4938	4939	4283
AGD84	AGD84	6203	-	-	4203
AGD66	AGD66	6202	-	-	4202

1.5 Overview of the differences among GDA2020, ITRF2014 and GNSS reference frames

1.5.1 GDA2020 and ITRF2014

GDA2020 is aligned with ITRF2014 (Altamimi et al., 2016) at epoch 2020.00. 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).

On January 1 2020, ITRF2014 at epoch 2020.0 will coincide with GDA2020. From January 1 2017 until January 1 2020, the difference between ITRF2014 coordinates (at the observed epoch) and GDA2020 coordinates will continually converge as the Australian tectonic plate moves 7 cm per year in a north-easterly direction. Until 2020, there will be an increasing convergence in the coordinates of GDA2020 and ITRF2014. From January 1 2020, there will be an increasing divergence in the coordinates of the GDA2020 and ITRF2014.

1.5.2 World Geodetic System 1984

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 been revised several times since its conception and is at present 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 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 the United Nations Office of Outer Space Affairs (UNOOSA, 2016).

1.6 Map Grid of Australia 2020 (MGA2020)

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 1.2).

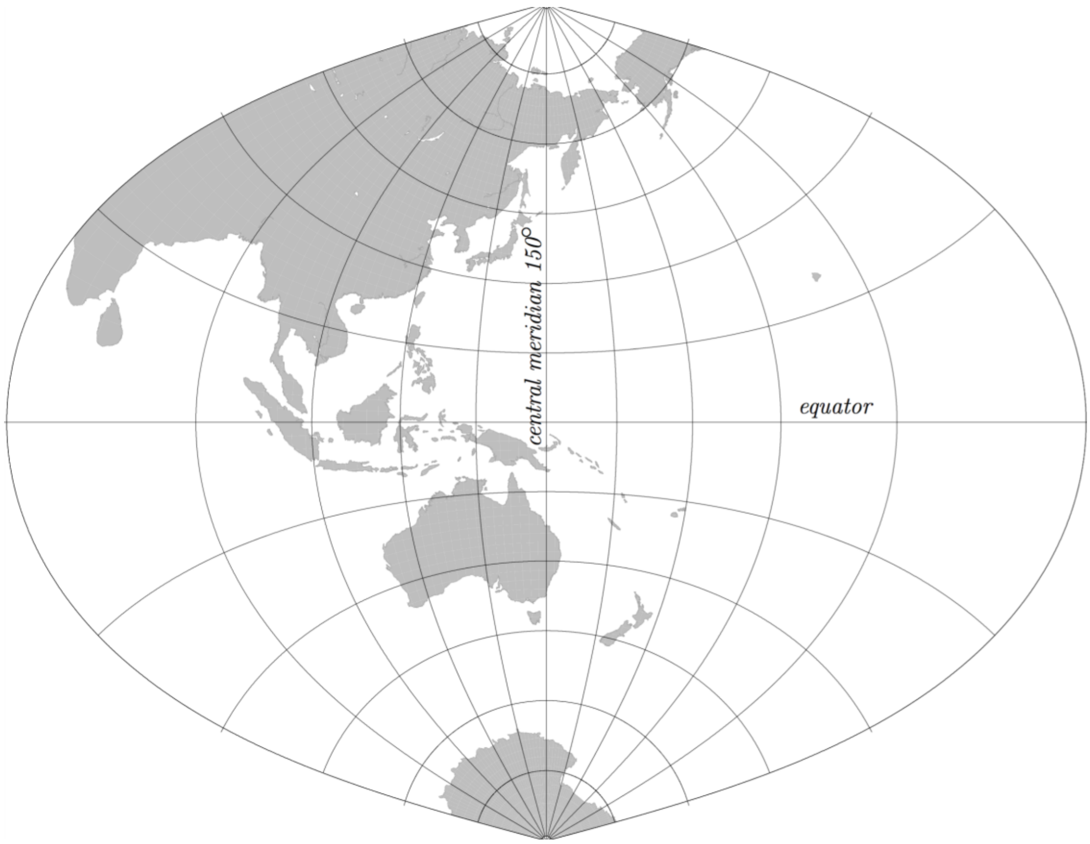

Figure 1.2: Transverse Mercator projection with central meridian of 150 degrees.

The TM projection is useful to map regions with large extents of latitude; however, distortions increase rapidly away from the central meridian.

The UTM system (Table 1.8) 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 1.3).

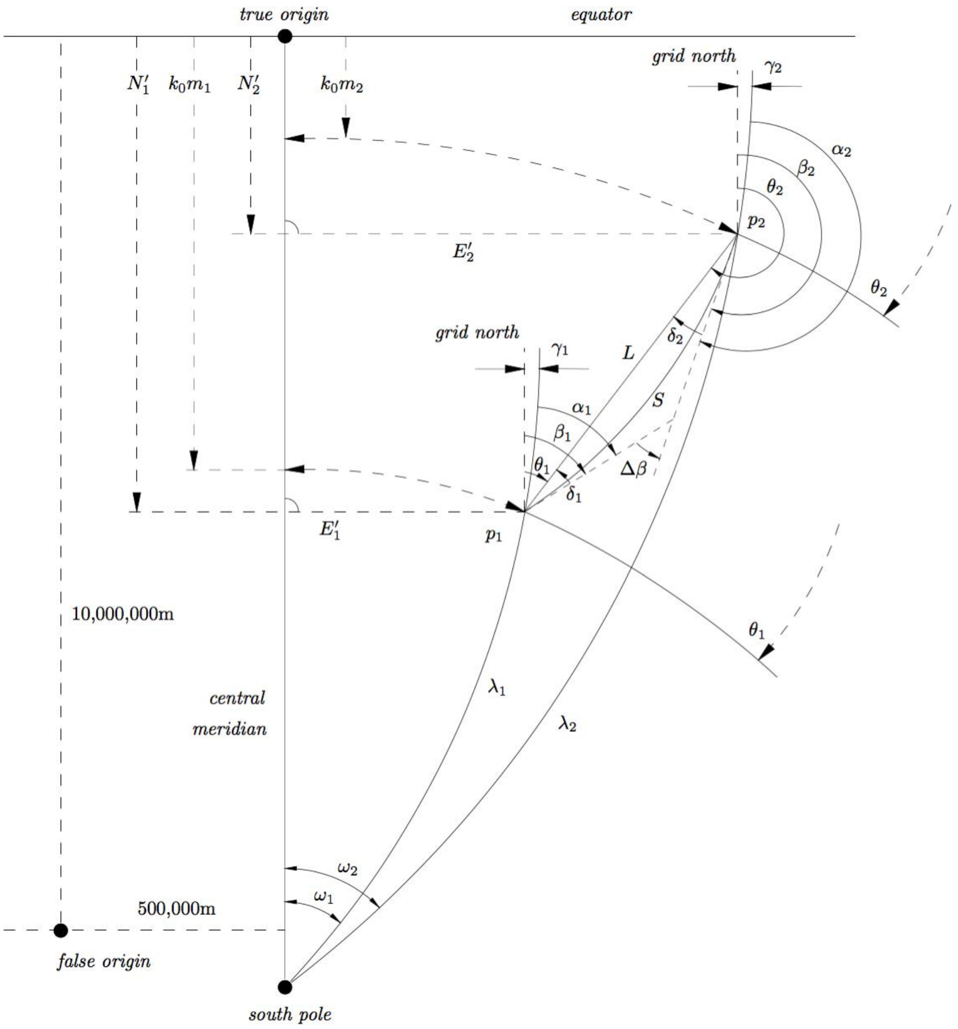

Figure 1.3: Relationship between geographic coordinates and projected coordinates.

Table 1.8: UTM 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 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 (Section 4.1).

2 Reference frame and coordinate system fundamentals

2.1 Coordinate systems

2.1.1 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 2.1). The Z-axis is in the direction of the rotational axis of the ellipsoid of revolution, the $X-Z$ plane is, by convention, the Greenwich meridian plane (the origin of longitudes) and the $X-Y$ plane is the equatorial plane of the ellipsoid (the origin of latitudes) (Gerdan and Deakin, 1999).

2.1.2 Geographic

The geographic coordinate system is a three-dimensional system with positions p referenced using latitude ϕ, longitude λ and ellipsoidal height h (Figure 2.1). Geodetic latitude and longitude are, by convention, measured relative to the equator and Greenwich meridian respectively.

Equations 1-3 can be used to convert from Cartesian coordinates to geographic coordinates.

$$\tan\lambda = \frac{Y}{X} \tag{1}$$

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

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

where

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

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

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

$$\varepsilon^2 = 2f - f^2 \tag{7}$$

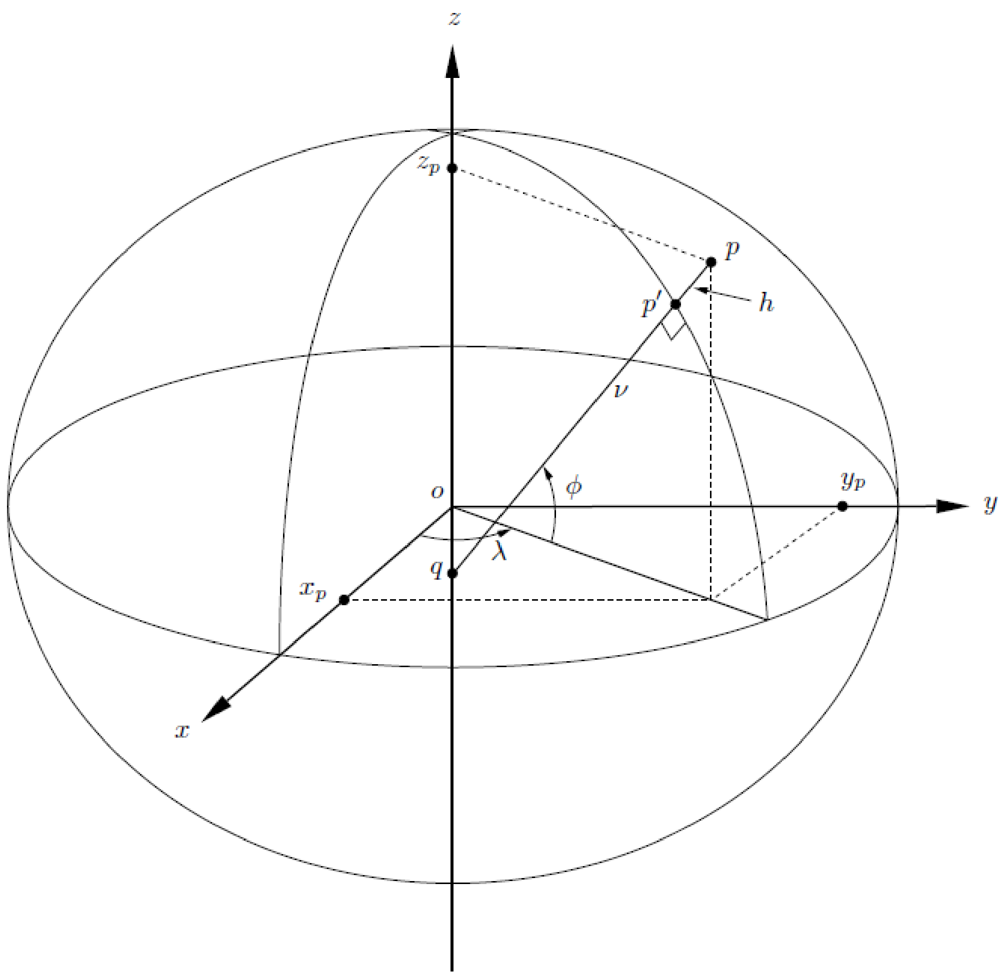

Figure 2.1: Relationship between Cartesian and geographic coordinate systems.

The following formulae can be used to convert from geographical coordinates to Cartesian coordinates.

$$X = (\nu + h)\cos\phi\cos\lambda \tag{8}$$

$$Y = (\nu + h)\cos\phi\sin\lambda \tag{9}$$

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

where

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

$$\varepsilon^2 = 2f - f^2 \tag{12}$$

$$h = N + H \tag{13}$$

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

2.1.3 Local

The local reference 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, Leahy and Collier, 2017; Figure 2.2).

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

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

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

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

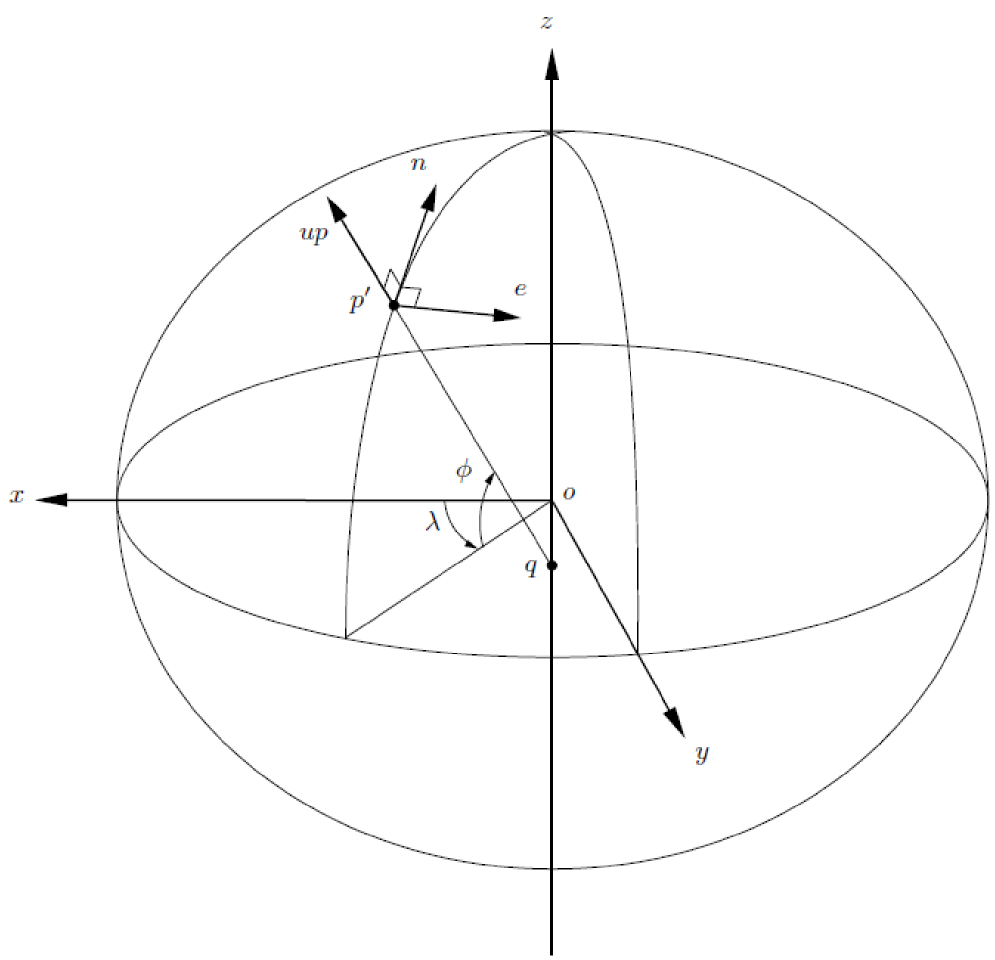

Figure 2.2: The local coordinate reference system.

2.2 Transformations between reference frames

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 translation $\dot{t}_x\ \dot{t}_y\ \dot{t}_z$, rotation $\dot{r}_x\ \dot{r}_y\ \dot{r}_z$ and scale $\dot{s}_c$ in time and eliminating the negligible terms (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.

$$\begin{pmatrix} X'_B \\ Y'_B \\ Z'_B \end{pmatrix} = \begin{pmatrix} t_x + \dot{t}_x(t - t_0) \\ t_y + \dot{t}_y(t - t_0) \\ t_z + \dot{t}_z(t - t_0) \end{pmatrix} + \left(1 + s_c + \dot{s}_c(t - t_0)\right)$$

$$\begin{pmatrix} 1 & r_z + \dot{r}_z(t - t_0) & -r_y - \dot{r}_y(t - t_0) \\ -r_z - \dot{r}_z(t - t_0) & 1 & r_x + \dot{r}_x(t - t_0) \\ r_y + \dot{r}_y(t - t_0) & -r_x - \dot{r}_x(t - t_0) & 1 \end{pmatrix} \begin{pmatrix} X_A \\ Y_A \\ Z_A \end{pmatrix} \qquad (17)$$

2.2.1 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, 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 the GDA2020 Technical Manual 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 Section 3 of this manual.

3 Coordinate transformation

Coordinate transformation is the process of changing coordinates from one reference frame to another. Options for the transformation of coordinates to, and from, GDA2020, are transformation parameters and transformation grids.

Table 3.1: Quick reference guide for assistance with transformations.

From	To	Section
GDA94	GDA2020	3.1, 3.2
ITRF2014	GDA2020	3.3
AGD66/84	GDA2020	3.4
ITRF (historic)	GDA2020	3.5
MGA94	MGA2020	3.6

3.1 GDA94 to GDA2020 transformation parameters

The 7-parameter similarity transformation (Equation (18)) is also known as a conformal transformation and accounts for the difference in scale, rotation and translation between two reference frames. In this section, the parameters are shown to transform between GDA94 and GDA2020. The official GDA94 to GDA2020 7 transformation parameters and associated uncertainties (Table 3.2) were computed using 18 GNSS CORS common to both the GDA94 RVS and the GDA2020 RVS. The GDA94 RVS (from 2011) 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 earthquake deformation.

$$\begin{pmatrix} X'_{GDA2020} \\ Y'_{GDA2020} \\ Z'_{GDA2020} \end{pmatrix} = \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix} + (1 + s_c) \begin{pmatrix} 1 & r_z & -r_y \\ -r_z & 1 & r_x \\ r_y & -r_x & 1 \end{pmatrix} \begin{pmatrix} X_{GDA94} \\ Y_{GDA94} \\ Z_{GDA94} \end{pmatrix} \qquad (18)$$

Table 3.2: 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
	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 from GDA2020 to GDA94 can be computed by multiplying the values in Table 3.2 by -1.

3.1.1 Example: GDA94 to GDA2020 (7–parameter transformation)

GDA94 coordinates of Alice Springs (ALIC)

Latitude (DMS)	Longitude (DMS)	Ellipsoidal Height (m)
-23° 40’ 12.44601876”	133° 53’ 07.847844”	603.3466

Latitude (DD)	Longitude (DD)	Ellipsoidal Height (m)
-23.67012389	133.88551329	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)
-23.67011014	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

3.2 Transformation Grids

3.2.1 Overview

Transformation grids provide users of spatial data with a simple and nationally consistent method to transform data between datums. The transformation grids are National Transformation version 2 (NTv2) files of binary grid shift (.gsb) format and are the preferred method for transforming between Australian datums. The transformation grids Table 3.5 and 3.6) are available from the ICSM GitHub repository (https://github.com/icsm-au/transformation_grids)

NOTE: The NTv2 format does not store ellipsoidal height information and therefore cannot be used to transform the heights of data from one datum to the other. To transform heights it is recommended that you convert your data from latitude, longitude, height LLH to earth-centred Cartesian coordinates XYZ using equations 8-10, apply the 7-parameter transformation from GDA94 to GDA2020 (Table 3.2) and then convert back to LLH using equations 1-3. This step is shown in the similarity transformation spreadsheet (Section 3.7.2).

3.2.2 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 GDA94 and GDA2020 coordinates is comprised of a conformal transformation component primarily due to plate tectonic motion (Figure 3.1), 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 differences in the datums. In the case of GDA94 to GDA2020, the distortion component is caused by the different strategies used by state and territories to propagate GDA94 coordinates onto ground survey control mark networks from the AFN and surface movement of parts of the Australian crust. The magnitude of the distortion varies between jurisdictions and can be in the order of decimetres.

The GDA94 - GDA2020 conformal only transformation grid delivers the same result as the 7-parameter similarity transformation (Section 3.1). 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. Please refer to Table 3.4 for recommendations.

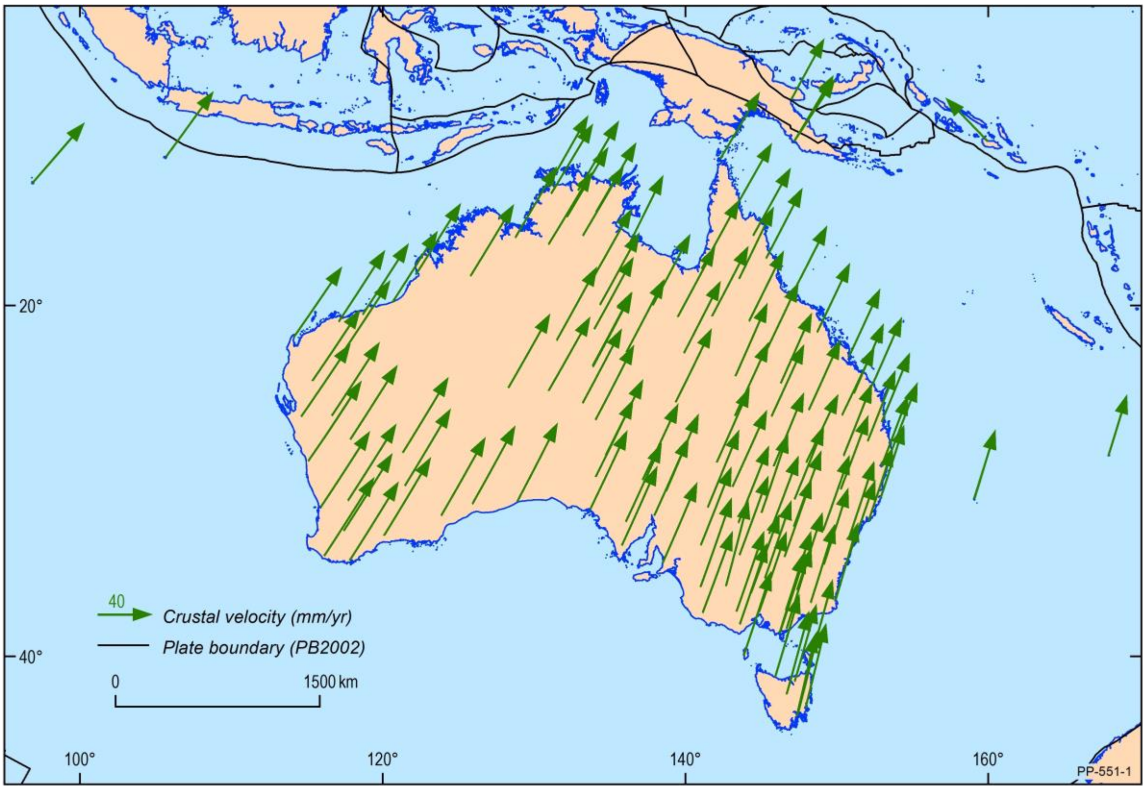

Figure 3.1: The difference between GDA94 and GDA2020 coordinates is primarily due to plate tectonic motion.

3.2.3 Development of transformation grids

The GDA94 – GDA2020 grids were developed using over 170,000 points at which both GDA94 and GDA2020 coordinates were available. The differences that remain after the conformal component is removed, is the distortion component. In some regions the distortion component is regular (Figure 3.2a) with a similar magnitude and direction, while in other cases it is irregular (Figure 3.2b) with a different magnitude and / or direction. In regions with an irregular distortion component, the transformation grid will be less reliable.

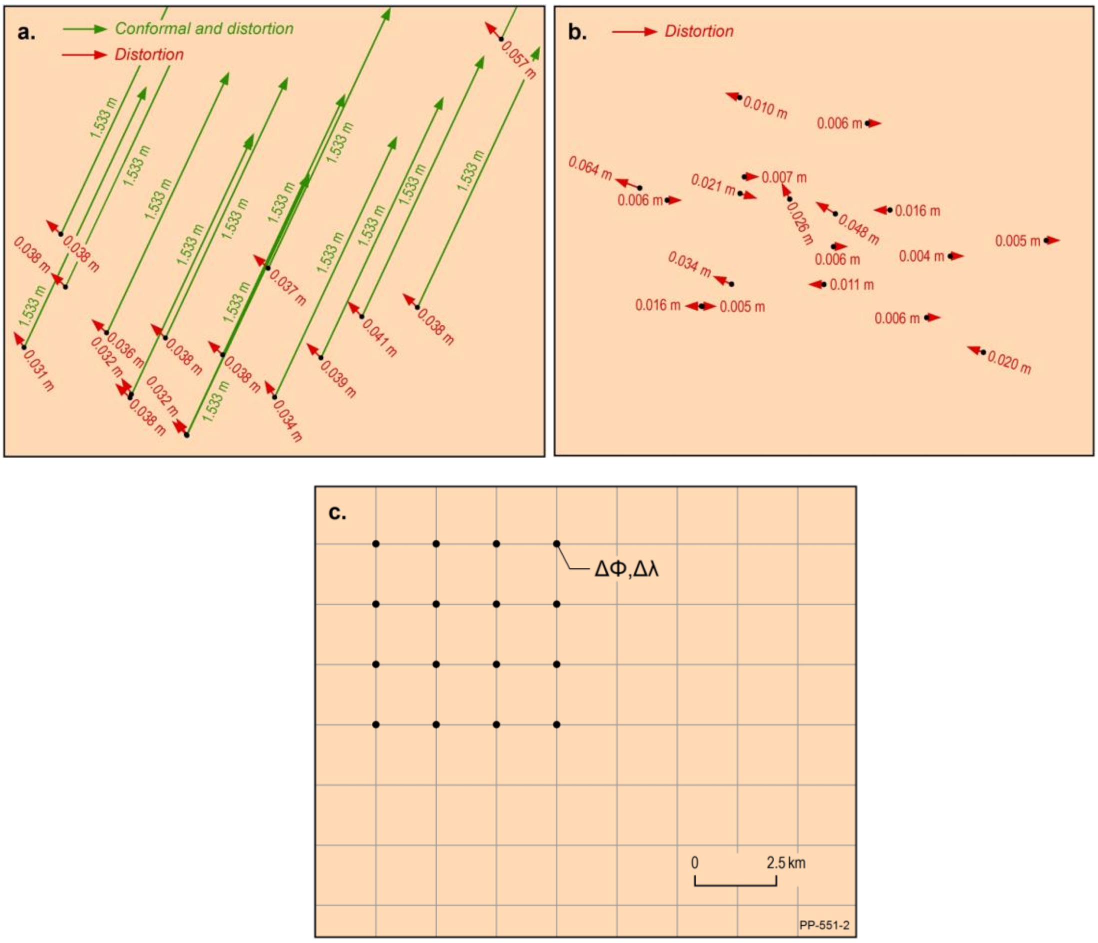

Figure 3.2: a) conformal (green) and distortion (red; high reliability) components of the transformation grids; b) low reliability; c) the grid has a latitude component and longitude component.

After removing the conformal component, a least squares prediction was used to compute the distortion in latitude (Δφ) and longitude (Δλ) on a regular 1’ grid (Figure 3.2c). The conformal component is then added back to each grid point to complete the conformal + distortion grid. For further information on the development of transformation grids, refer to Collier (2002).

3.3 Plate motion model (ITRF2014 to GDA2020)

The plate motion model enables the transformation of coordinates (or vectors) from ITRF2014 to GDA2020 and vice versa. The model was derived using 109 ARGN and AuScope GNSS CORS which were used to define the RVS.

The station coordinates and velocities were used to compute a conventional Euler plate model. This 3-parameter model can be expressed as a 14-parameter transformation with only rates of change rotation components (Table 3.3). Again, at the computational level this transformation is performed on the Cartesian $X\ Y\ Z$ coordinates.

Table 3.3: Transformation parameters for ITRF2014 to GDA2020 along with their one sigma uncertainties (1σ). Units are in meters (m) and m/yr for the translation 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.

	$t_x, \dot{t}_x$	$t_y, \dot{t}_y$	$t_z, \dot{t}_z$	$s_c, \dot{s}_c$	$r_x, \dot{r}_x$	$r_y, \dot{r}_y$	$r_z, \dot{r}_z$
	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

3.3.1 Example: ITRF2014 to GDA2020 (3–parameter transformation)

ITRF2014 at 2018.0 coordinates of Alice Springs (ALIC)

X (m)	Y (m)	Z (m)
-4052052.6588	4212835.9938	-2545104.6946

GDA2020 coordinates of Alice Springs (ALIC)

X (m)	Y (m)	Z (m)
-4052052.7373	4212835.9835	-2545104.5867

Difference (GDA2020 – ITRF2014 at 2018)

	X (m)	Y (m)	Z (m)
Alice Springs (ALIC)	-0.0785	-0.0103	0.1079

3.4 Transformation from / to AGD66 and AGD84

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 the grid transformation process using the appropriate ICSM transformation grids Appendix B is the most accurate and preferred transformation method.

3.5 Transformation from / to ITRF (historic)

Transformations between older ITRF realisations (i.e. ITRF2008 and older) and GDA2020 should be performed by first transforming to GDA94 as described in Dawson and Woods (2010) and then transforming to GDA2020 using the ICSM transformation grids (Section 3.2).

3.6 Transformation from / to MGA2020

To transform data in from one map grid (AMG66, AMG84, MGA94, MGA2020) to a different map grid, the projected coordinates need to first be converted into geographical coordinates. In the case of transforming coordinates 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)

Options for converting coordinates are presented in Section 4.

3.7 Transformation tools and services

3.7.1 Transformation grids

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 3.4, but if in doubt, contact your state / territory land survey authority.

Table 3.4: 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.
Tas	GDA94_GDA2020_conformal_and_distortion	Recommended for users transforming from GDA94 coordinates determined from the survey ground control network and where the origin of survey control is unknown or mixed (e.g. aggregated datasets available from LISTdata.)
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 when they become available.

The transformation grids cover the regions shown in Figure 3.3. Note that this does not yet include Christmas Island, Cocos Island which will be coming soon. In regions that are not covered by the grids, but are within the GDA2020 extent (Section 1.2.4), the 7-parameter similarity transformation is recommended to transform between GDA94 and GDA2020.

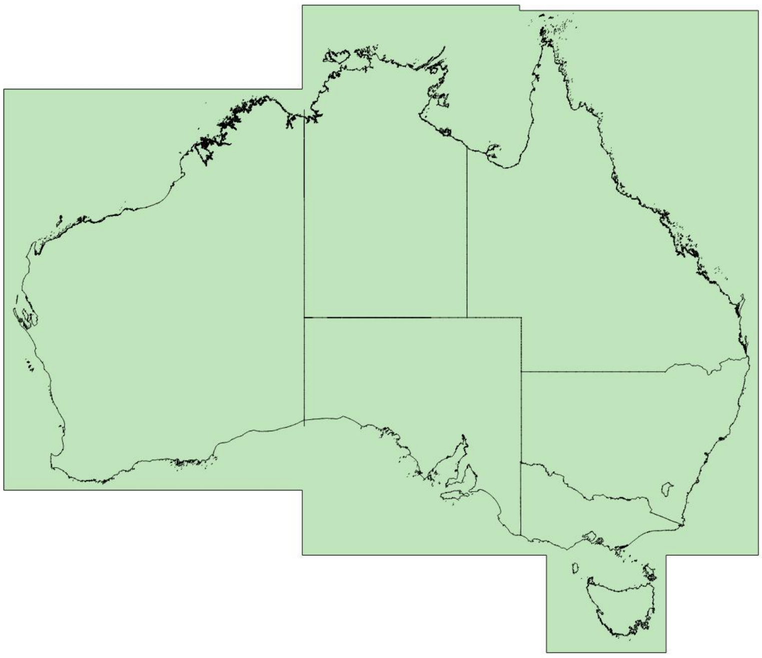

Figure 3.3: Extent of the GDA94-GDA2020 conformal, and conformal and distortion grids.

Table 3.5: NTv2 transformations grid files

Transformation	Grid File type	NTv2 Transformation file
AGD66 to GDA94	conformal and distortion	A66 National (13.09.01).gsb
AGD84 to GDA94	conformal and distortion	National 84(02.07.01).gsb
GDA94 to GDA2020	conformal	GDA94_GDA2020_conformal.gsb
GDA94 to GDA2020	conformal and distortion	GDA94_GDA2020_conformal_and_distortion.gsb
GDA94 to GDA2020 Christmas Island	conformal	GDA94_GDA2020_conformal_christmas_island.gsb
GDA94 to GDA2020 Cocos Island	conformal	GDA94_GDA2020_conformal_cocos_island.gsb

Table 3.6: EPSG codes for NTv2 transformation grid files

NTv2 Transformation file	EPSG Transformation Code	EPSG Transformation Name	Comments
A66 National (13.09.01).gsb	1803	AGD66 to GDA94 (11)	See Appendix A for coverage information
National 84(02.07.01).gsb	1804	AGD84 to GDA94 (5)	See Appendix A for coverage information
GDA94_GDA2020_conformal.gsb	*To be confirmed*	*To be confirmed*	
GDA94_GDA2020_conformal_and_distortion.gsb	*To be confirmed*	*To be confirmed*	
GDA94_GDA2020_conformal_christmas_island.gsb	*To be confirmed*	*To be confirmed*	
GDA94_GDA2020_conformal_cocos_island.gsb	*To be confirmed*	*To be confirmed*	

The transformation grids can be accessed under a BSD 3-Clause licence from the ICSM GitHub repository (https://github.com/icsm-au) and by direct download from the Amazon Simple Storage Service (S3):

GDA94-GDA2020 Conformal: https://s3-ap-southeast-2.amazonaws.com/transformation-grids/GDA94_GDA2020_conformal.gsb

GDA94-GDA2020 Conformal and Distortion: https://s3-ap-southeast-2.amazonaws.com/transformation-grids/GDA94_GDA2020_conformal_and_distortion.gsb

AGD66-GDA94: https://s3-ap-southeast-2.amazonaws.com/transformation-grids/A66_National_13_09_01.gsb

AGD84-GDA94: https://s3-ap-southeast-2.amazonaws.com/transformation-grids/National_84_02_07_01.gsb

3.7.2 Similarity transformation

An alternative to the transformation grid is the similarity transformation Spreadsheet available from https://github.com/icsm-au/DatumSpreadsheets. This process performs the 7-parameter transformation (Table 3.2), i.e. only the conformal transformation and does not include the distortion modelling.

3.7.3 Online transformation

ICSM has established a website (link available on http://positioning.fsdf.org.au) where you can upload a file to be transformed. This transformation will use the transformation grids and send you an email from where the transformed dataset can be downloaded.

3.7.4 QGIS Plug-ins

ICSM has arranged for an existing NTv2 transformation plugin for QGIS to be amended to incorporate the NTv2 grids for transforming between AGD66 ⁄ 84 - GDA94 and GDA94 - GDA2020. An ICSM branded plugin dealing only with the Australian datums has also been developed.

Details of these plugins are available at http://www.icsm.gov.au/gda/tools.html.

4 Coordinate conversion

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).

4.1 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 and 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.

4.1.1 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).

The development of the Krueger n-series equations for the transverse Mercator projection involves three steps (Figure 4.1):

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.

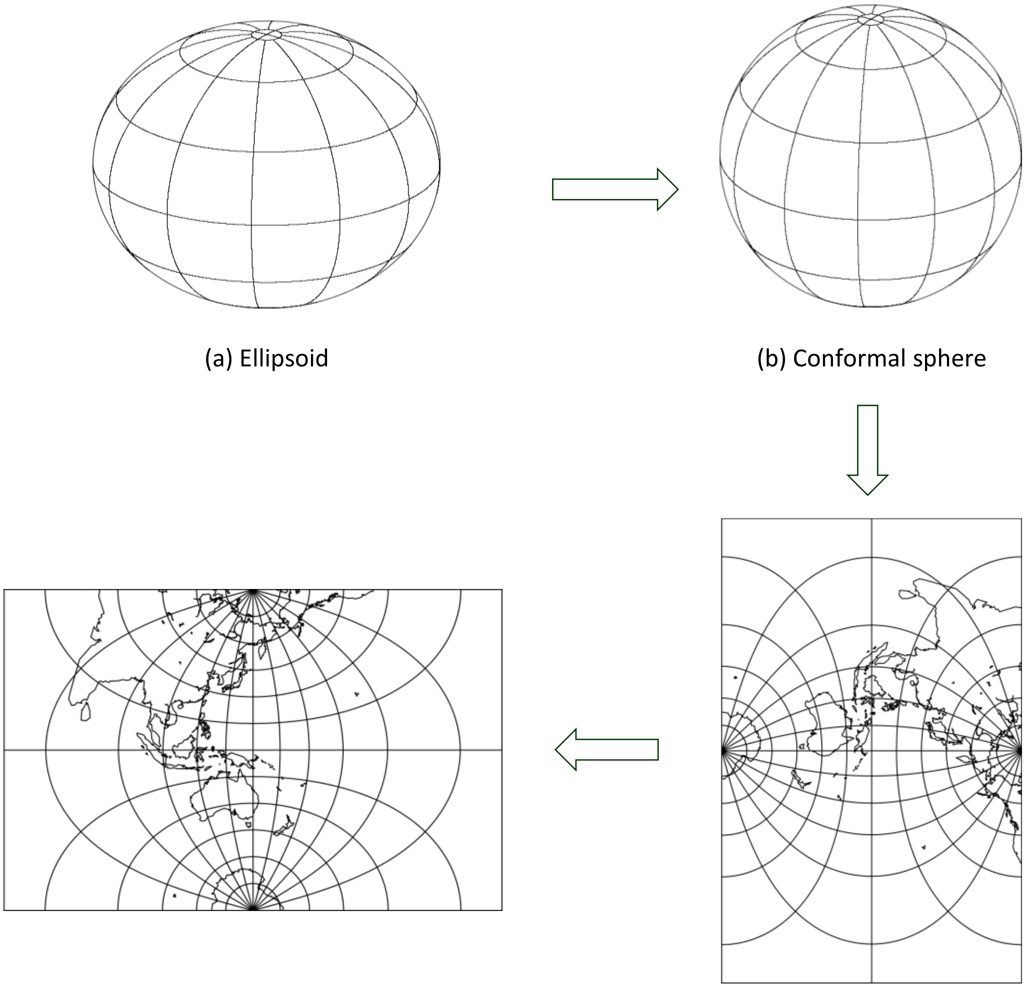

Figure 4.1: Sequence of conformal mapping used for geographic to grid conversion using Krueger n-series (adapted from Deakin, 2014).

4.1.1.1 Forward transformation (geographic to grid)

The forward transformation (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 transformation. 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)

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

$$n = \frac{a - b}{a + b} = \frac{f}{2 - f} \qquad (19)$$

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 $r = 1, 2, \ldots, 8$

$$\begin{aligned}
\alpha_2 &= \frac{1}{2}n - \frac{2}{3}n^2 + \frac{5}{16}n^3 + \frac{41}{180}n^4 - \frac{127}{288}n^5 + \frac{7891}{37800}n^6 + \frac{72161}{387072}n^7 - \frac{18975107}{50803200}n^8 \\
\alpha_4 &= \frac{13}{48}n^2 - \frac{3}{5}n^3 + \frac{557}{1440}n^4 + \frac{281}{630}n^5 - \frac{1983433}{1935360}n^6 + \frac{13769}{28800}n^7 + \frac{148003883}{174182400}n^8 \\
\alpha_6 &= \frac{61}{240}n^3 - \frac{103}{140}n^4 + \frac{15061}{26880}n^5 + \frac{167603}{181440}n^6 - \frac{67102379}{29030400}n^7 + \frac{79682431}{79833600}n^8 \\
\alpha_8 &= \frac{49561}{161280}n^4 - \frac{179}{168}n^5 + \frac{6601661}{7257600}n^6 + \frac{97445}{49896}n^7 - \frac{40176129013}{7664025600}n^8 \\
\alpha_{10} &= \frac{34729}{80640}n^5 - \frac{3418889}{1995840}n^6 + \frac{14644087}{9123840}n^7 + \frac{2605413599}{622702080}n^8 \\
\alpha_{12} &= \frac{212378941}{319334400}n^6 - \frac{30705481}{10378368}n^7 + \frac{175214326799}{58118860800}n^8 \\
\alpha_{14} &= \frac{1522256789}{1383782400}n^7 - \frac{16759934899}{3113510400}n^8 \\
\alpha_{16} &= \frac{1424729850961}{743921418240}n^8
\end{aligned} \tag{21}$$

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

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

4.1.1.2 Inverse transformation (grid to geographic)

The inverse transformation (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 traverse 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

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

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

$$\phi = \tan^{-1} t_{n+1} \tag{50}$$

10. Compute longitude difference ω and longitude λ from

$$\tan\omega = \frac{\sinh\eta'}{\cos\xi'} \tag{51}$$

$$\lambda = \lambda_0 \pm \omega \tag{52}$$

11. Compute q and p (to order n^8 and $= 8$. See Equations (33) and (34).

11. Compute the point scale factor k. See Equation (35).

12. Compute the grid convergence γ. See Equation (36).

4.1.2 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 (Section 4.1.1).

4.1.3 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 (Redfearn's formulae), 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.

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.

4.1.4 Tools / services

4.1.4.1 Krueger n-series

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).

4.1.4.2 Krueger λ-series (Redfearn's formulae)

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)

5 Coordinate computations

5.1 Ellipsoid computations

5.1.1 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.

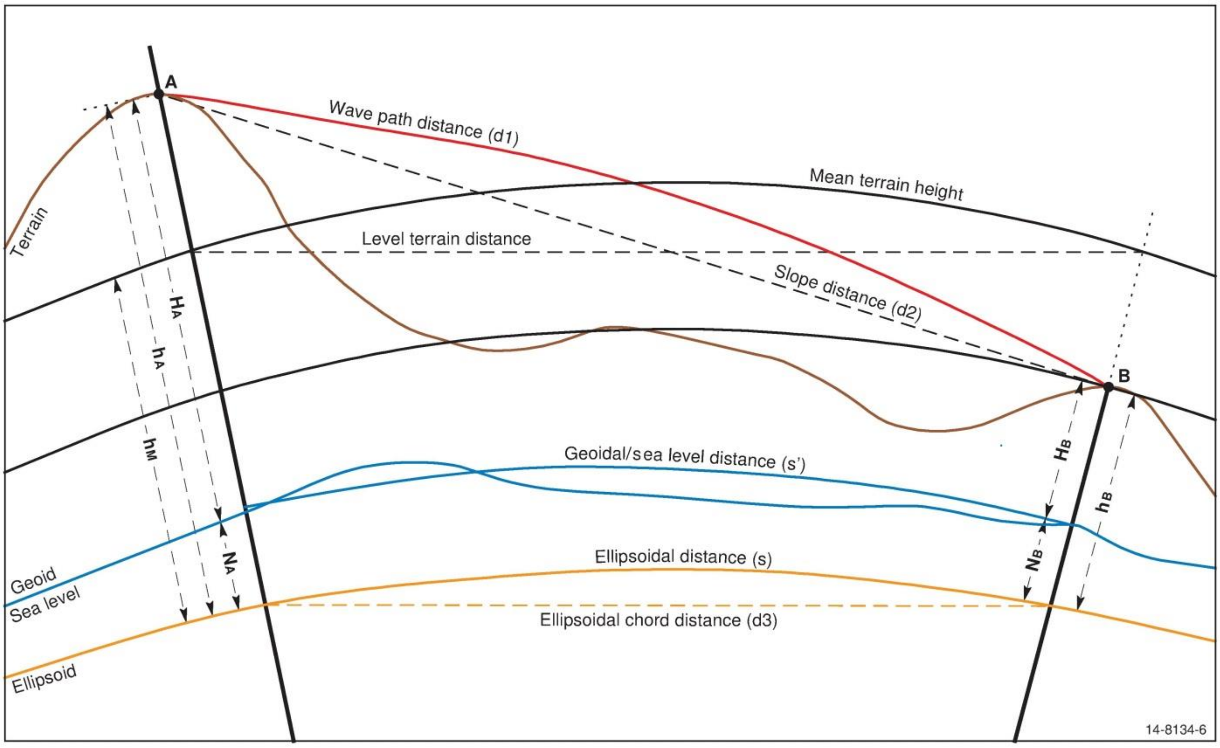

Figure 5.1 Reduction of distance to the ellipsoid.

The difference between the wave path length d_1 and the wave path chord (slope distance) 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. These physical corrections, which involve the application of certain velocity corrections to the measured wave path distance, are not discussed in this manual.

5.1.1.1 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)

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

The ellipsoidal chord distance d_3 is then easily reduced to the ellipsoidal arc distance s

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

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.

5.1.1.2 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 $+\,{d_3}^3/24{R_\alpha}^2\left\{+\,3{d_3}^5/640{R_\alpha}^4 + \ldots\right\}$ (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).

5.1.1.3 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.

5.1.1.4 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.

$$R_m = \sqrt{\rho\nu} \tag{62}$$

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

where:

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

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

5.1.2 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).

5.1.2.1 Formulae

Direction (reduced) = Direction (measured)

+ Deflection correction

+ Skew normal correction

+ Laplace correction (Laplace for azimuth only)

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

where ζ = $\xi\ sin\ \alpha - \eta\ cos\ \alpha$ (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)

5.1.3 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 centimeters 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).

5.1.3.1 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 $(\alpha_{1-2}, \alpha_{2-1})$.

$$\tan U_1 = (1 - f)\tan \phi_1 \tag{71}$$

$$\tan U_2 = (1 - f)\tan \phi_2 \tag{72}$$

Starting with the approximation,

$$\lambda = \omega = \lambda_2 - \lambda_1 \tag{73}$$

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

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

$$\cos\sigma = \sin U_1 \sin U_2 + \cos U_1 \cos U_2 \cos\lambda \tag{75}$$

$$\tan\sigma = \sin\sigma / \cos\sigma \tag{76}$$

$$\sin\alpha = \cos U_1 \cos U_2 \sin\lambda / \sin\sigma \tag{77}$$

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

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

$$\lambda = \omega + (1 - C) f \sin\alpha \{\sigma + C \sin\sigma[\cos 2\sigma_m + C \cos\sigma\,(-1 + 2\cos^2 2\sigma_m)]\} \tag{80}$$

then:

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

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

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

$$\begin{aligned} \varDelta\sigma = B \sin\sigma\,\{\cos 2\sigma_m & \\ & + (B/4)\,[\cos\sigma(-1 + 2\cos^2 2\sigma_m) \\ & - (B/6)\cos 2\sigma_m(-3 + 4\sin^2\sigma)(-3 + 4\cos^2 2\sigma_m)]\} \end{aligned} \tag{84}$$

$$s = bA(\sigma - \varDelta\sigma) \tag{85}$$

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

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

5.1.3.2 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

$$\tan \Phi_2 = (\sin U_1 \cos \sigma + \cos U_1 \sin \sigma \cos \alpha_{1-2}) / \left\{(1-f)[\sin^2\alpha + (\sin U_1 \sin \sigma - \cos U_1 \cos \sigma \cos \alpha_{1-2})^2]^{\frac{1}{2}}\right\} \quad (98)$$

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

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

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

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

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

Note:

• "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 Manual, ω is used here.

Sample Data

Table 5.1 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"	

5.1.3.3 Ellipsoid computation tools

Tools available to perform ellipsoid computations are:

- Vincenty's inverse: (http://www.ga.gov.au/geodesy/datums/vincenty_inverse.jsp)
- Vincenty's direct: (http://www.ga.gov.au/geodesy/datums/vincenty_direct.jsp)
- Spreadsheet (https://github.com/icsm-au/DatumSpreadsheets)

6 Australian Height Datum and geoid models

6.1 Australian Height Datum 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 6.1).

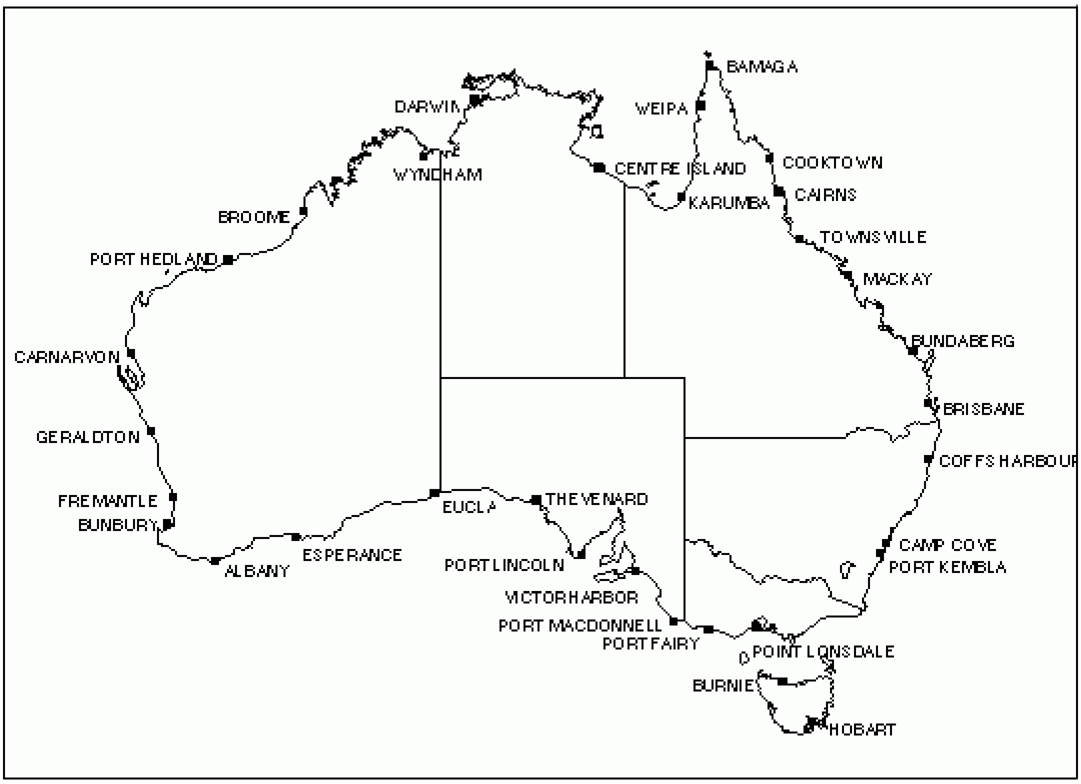

Figure 6.1: The locations of the tide gauges used to define AHD.

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.

6.1.1 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. 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)[1].

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.

6.2 Heighting fundamentals

Height determination in Australia requires a level of care due to the number and type of reference and working surfaces to which heights can be referred, including: AHD, MSL, Mean Sea Surface (MSS), ellipsoid and geoid (gravimetric or combined gravimetric and geometric). These surfaces are shown in Figure 6.2.

[1] 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”.

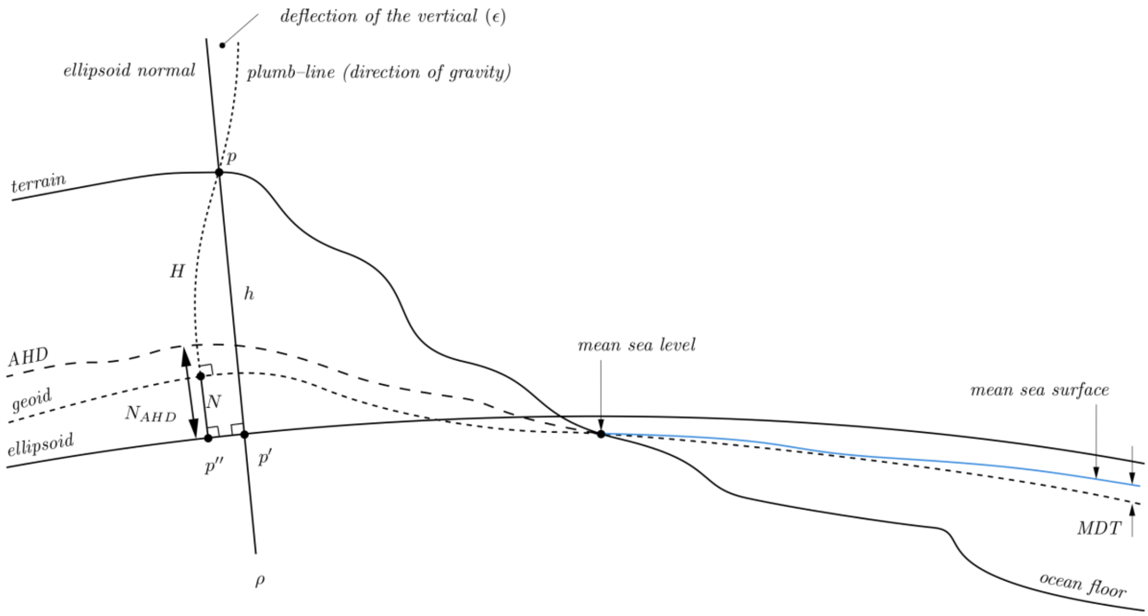

Figure 6.2: Reference and working surfaces for height in Australia.

Ellipsoid: Simplified mathematical representation of the Earth often used as a reference surface for positioning, navigation, map projections and geodetic calculations.

Ellipsoidal height: Distance between the ellipsoid and point of interest measured along a straight line perpendicular to the ellipsoid.

Geoid: Surface of equal gravitational potential (or equipotential) that closely approximates mean sea level.

Deflection of the vertical (ϵ): Deviation of actual gravity (i.e. gravity observed by gravimeter) from normal gravity (i.e. approximation of actual gravity using a model (e.g. ellipsoid)). It is made up of two components: north–south component (deflection in the prime meridian, ξ) and an east–west component (deflection in the prime vertical, η).

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 (Fraser, Leahy and Collier, 2017).

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.

Mean Dynamic Topography (MDT): Mean Dynamic Topography is the offset between the geoid and MSS.

For a thorough description of heighting fundamentals, refer to Heiskanen and Moritz (1967); Featherstone and Kuhn (2006); Filmer et al. (2010) and Fraser, Leahy and Collier (2017).

6.2.1 AHD: Normal-Orthometric height system

When the AHD was established, insufficient gravity observations were available to apply gravimetric height corrections. Instead, a truncated version of the normal-orthometric correction of Rapp (1961) was applied to the spirit levelling observations (Roelse et al., 1975; Featherstone and Kuhn 2006) which has no requirement for observed gravity in the correction. Instead it uses the normal gravity field only to derive all necessary gravity field related quantities. As such, the AHD is considered a normal-orthometric height system (Holloway 1988; Featherstone and Kuhn 2006; Filmer et al., 2010).

6.3 AUSGeoid2020

6.3.1 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 with uncertainty.

$$H_{AHD} = h - \zeta_{AHD} \tag{104}$$

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. For converting geometric heights to physical heights in areas not covered by AUSGeoid2020, you may consider using the Australian Gravimetric Quasigeoid 2017 (see Section 6.5).

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 an 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.

6.3.2 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 6.1) and the uncertainty in the ellipsoid to AHD separation (Table 6.2)

Table 6.1: 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 6.2: 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

6.3.3 Differences between AUSGeoid09 and AUSGeoid2020

6.3.3.1 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.

6.3.3.2 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.

6.4 AUSGeoid2020 tools and services

A web application is available on the Geoscience Australia website to perform AUSGeoid computations using AUSGeoid98, AUSGeoid09 and AUSGeoid2020 (http://www.ga.gov.au/ausgeoid/nvalcomp.jsp).

6.5 Australian Gravimetric Quasigeoid 2017

The Australian Gravimetric Quasigeoid 2017 (AGQG2017) is the gravimetric component of the AUSGeoid2020 model. It differs from AUSGeoid2020 (and AHD/MSL) by about 0.5 m in the north and south of Australia because of the influence of sea surface topography. Given that AGQG2017 is not biased by the influence of errors from GNSS heights or AHD, it is a smoother working surface, which is useful for large surveys or LiDAR datasets.

To avoid confusion with AUSGeoid2020, AGQG2017 has restricted distribution, however, if you are interested in using it, please contact geodesy@ga.gov.au.

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Appendix A – Recognized-value standards of measurement in the Australian Fiducial Network

Global Cartesian coordinates of the Australian Fiducial Network can be expressed at any epoch t (years) through the application of the following linear model using the coordinates (X, Y, Z) and velocities (V_x, V_y, V_z)

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_t = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2020} + (t - 2020) \begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix} \tag{A-1}$$

This model is valid for 15 years either side of 2020:

$$|t - 2020| \leq 15.$$

	Coordinates (m) at 2020.0			Coordinate Uncertainty (m)			Velocity (m / year)			Velocity Uncertainty (m / year)		
Site	***X***	***Y***	***Z***	***95% CI***	***95% CI***	***95% CI***	V_X	V_Y	V_Z	***95% CI***	***95% CI***	***95% CI***
Ceduna (SA)	-3753473.1960	3912741.0310	-3347959.6998	0.0244	0.0249	0.0229	-0.0421	0.0024	0.0501	0.0002	0.0002	0.0002
Manton Dam (NT)	-4091359.6096	4684606.4258	-1408579.1371	0.0098	0.0105	0.0072	-0.0355	-0.0137	0.0576	0.0002	0.0001	0.0002
Mt Stromlo (ACT)	-4467103.2062	2683039.4818	-3666948.7613	0.0100	0.0080	0.0090	-0.0367	0.0006	0.0452	0.0002	0.0002	0.0002
Sydney (NSW)	-4648240.8666	2560636.4510	-3526317.7982	0.0107	0.0082	0.0093	-0.0352	-0.0015	0.0453	0.0002	0.0002	0.0002
Tidbinbilla (ACT)	-4460996.9609	2682557.0875	-3674442.6411	0.0104	0.0082	0.0093	-0.0368	0.0007	0.0452	0.0002	0.0002	0.0002
Hobart (TAS)	-3950072.2586	2522415.3710	-4311637.4095	0.0094	0.0079	0.0098	-0.0395	0.0083	0.0411	0.0002	0.0002	0.0002
Melbourne (VIC)	-4130636.7623	2894953.1442	-3890530.2534	0.0098	0.0083	0.0094	-0.0393	0.0042	0.0448	0.0002	0.0002	0.0002
Parkes (NSW)	-4554255.2088	2816652.4429	-3454059.6981	0.0107	0.0085	0.0093	-0.0363	-0.0015	0.0467	0.0002	0.0002	0.0002
Hillarys (WA)	-2355572.1203	4886093.2099	-3343993.6599	0.0081	0.0112	0.0091	-0.0478	0.0106	0.0491	0.0002	0.0001	0.0002
Bundaberg (QLD)	-5125977.5335	2688801.2479	-2669890.2146	0.0113	0.0082	0.0082	-0.0311	-0.0105	0.0490	0.0002	0.0002	0.0002

	Coordinates (m) at 2020.0			Coordinate Uncertainty (m)			Velocity (m / year)			Velocity Uncertainty (m / year)		
Site	***X***	***Y***	***Z***	**95% CI**	**95% CI**	**95% CI**	V_X	V_Y	V_Z	**95% CI**	**95% CI**	**95% CI**
Kalgoorlie (WA)	-2862346.1852	4678388.0851	-3245553.1345	0.0091	0.0120	0.0096	-0.0460	0.0069	0.0505	0.0002	0.0001	0.0002
Norfolk Island (NSW)	-5457454.4185	1166108.4501	-3078178.9928	0.0120	0.0071	0.0088	-0.0245	-0.0095	0.0398	0.0001	0.0002	0.0002
Albany (WA)	-2441715.0069	4629128.6333	-3633362.7930	0.0091	0.0125	0.0105	-0.0479	0.0122	0.0478	0.0002	0.0002	0.0002
Burnie (TAS)	-3989420.9187	2699532.9340	-4166619.7796	0.0100	0.0083	0.0101	-0.0397	0.0070	0.0426	0.0002	0.0002	0.0002
Liawenee (TAS)	-3973071.4774	2612492.7923	-4238233.8906	0.0099	0.0083	0.0103	-0.0396	0.0076	0.0418	0.0002	0.0002	0.0002
Burakin (WA)	-2511499.0840	4892172.2095	-3220858.0287	0.0088	0.0124	0.0096	-0.0471	0.0088	0.0501	0.0002	0.0001	0.0002
Kellerberrin (WA)	-2527265.3639	4813192.3590	-3324975.7001	0.0087	0.0124	0.0097	-0.0472	0.0095	0.0496	0.0002	0.0001	0.0002
Norseman (WA)	-2844072.6212	4589300.5857	-3385094.4352	0.0091	0.0117	0.0097	-0.0463	0.0080	0.0498	0.0002	0.0001	0.0002
Hyden (WA)	-2603131.0876	4717143.4739	-3402748.0718	0.0088	0.0122	0.0098	-0.0471	0.0096	0.0493	0.0002	0.0001	0.0002
Warakurna (WA)	-3583757.5864	4538446.7043	-2683056.6943	0.0090	0.0101	0.0081	-0.0420	-0.0014	0.0537	0.0002	0.0001	0.0002
Buckleboo (SA)	-3863896.2323	3723681.6406	-3436456.0075	0.0105	0.0102	0.0097	-0.0415	0.0024	0.0493	0.0002	0.0002	0.0002
Beechworth (VIC)	-4297030.4444	2827160.2393	-3759485.1907	0.0112	0.0091	0.0102	-0.0381	0.0023	0.0453	0.0002	0.0002	0.0002
Yeelana (SA)	-3787467.5311	3685160.4447	-3559786.1635	0.0093	0.0091	0.0090	-0.0420	0.0038	0.0486	0.0002	0.0002	0.0002
Saltia (SA)	-3998750.5658	3608798.4710	-3404651.9508	0.0098	0.0093	0.0090	-0.0407	0.0014	0.0493	0.0002	0.0002	0.0002
West Wylong (NSW)	-4471091.7769	2868001.2873	-3519326.3705	0.0103	0.0083	0.0091	-0.0370	-0.0005	0.0466	0.0002	0.0002	0.0002
Bairnsdale (VIC)	-4265638.5627	2701208.9154	-3884372.5851	0.0118	0.0094	0.0109	-0.0381	0.0034	0.0442	0.0002	0.0002	0.0002
Port Kembla (NSW)	-4599806.4397	2558778.9950	-3590075.1156	0.0116	0.0087	0.0100	-0.0356	-0.0007	0.0450	0.0002	0.0002	0.0002
Douglas Daly (NT)	-4079102.7002	4661682.9452	-1515238.0262	0.0113	0.0122	0.0079	-0.0360	-0.0128	0.0574	0.0002	0.0001	0.0002
Toowoomba (QLD)	-4994482.4972	2663618.0089	-2931171.1575	0.0121	0.0088	0.0091	-0.0324	-0.0079	0.0481	0.0002	0.0002	0.0002
Andamooka (SA)	-4035145.8277	3741808.3918	-3213842.4359	0.0098	0.0094	0.0088	-0.0403	-0.0002	0.0504	0.0002	0.0002	0.0002
Gabo Island (VIC)	-4379911.9542	2537393.8597	-3867574.2197	0.0112	0.0087	0.0103	-0.0370	0.0026	0.0436	0.0002	0.0002	0.0002
Coober Pedy (SA)	-3927330.9419	3965547.9511	-3077376.8165	0.0093	0.0093	0.0083	-0.0409	-0.0005	0.0514	0.0002	0.0002	0.0002

	Coordinates (m) at 2020.0			Coordinate Uncertainty (m)			Velocity (m / year)			Velocity Uncertainty (m / year)		
Site	***X***	***Y***	***Z***	**95% CI**	**95% CI**	**95% CI**	V_X	V_Y	V_Z	**95% CI**	**95% CI**	**95% CI**
Katherine (NT)	-4147413.8177	4581462.5900	-1573359.0837	0.0098	0.0103	0.0072	-0.0358	-0.0128	0.0572	0.0002	0.0001	0.0002
Wagin (WA)	-2455774.3624	4735625.3849	-3485038.1973	0.0083	0.0112	0.0094	-0.0477	0.0110	0.0486	0.0002	0.0001	0.0002
Ravensthorpe (WA)	-2664852.2528	4602498.8360	-3509390.6909	0.0088	0.0116	0.0097	-0.0471	0.0100	0.0488	0.0002	0.0001	0.0002
Mt Cavanagh (NT)	-3929412.1216	4183417.4556	-2773890.6215	0.0096	0.0099	0.0083	-0.0404	-0.0028	0.0530	0.0002	0.0002	0.0002
Wiluna (WA)	-2871830.1215	4930661.0498	-2841419.6642	0.0083	0.0109	0.0083	-0.0452	0.0039	0.0524	0.0002	0.0001	0.0002
Tibooburra (NSW)	-4383698.9008	3417850.9363	-3117538.7823	0.0110	0.0096	0.0093	-0.0379	-0.0029	0.0501	0.0002	0.0002	0.0002
Ivanhoe (NSW)	-4310476.3634	3190508.6627	-3441393.5542	0.0098	0.0085	0.0088	-0.0384	-0.0001	0.0480	0.0002	0.0002	0.0002
Broome (WA)	-3234208.1569	5134028.8375	-1958815.1914	0.0088	0.0113	0.0075	-0.0413	-0.0046	0.0560	0.0002	0.0001	0.0002
Nhill (VIC)	-4035390.1167	3193137.6972	-3755906.1988	0.0100	0.0089	0.0095	-0.0402	0.0038	0.0464	0.0002	0.0002	0.0002
Warramunga (NT)	-4193700.6368	4289270.2773	-2160904.9454	0.0100	0.0102	0.0077	-0.0375	-0.0088	0.0553	0.0002	0.0002	0.0002
Mt Magnet (WA)	-2629526.8926	4978260.9506	-2987965.8480	0.0082	0.0112	0.0086	-0.0463	0.0064	0.0514	0.0002	0.0001	0.0002
Larrimah (NT)	-4208011.6662	4479077.7734	-1701337.7347	0.0111	0.0114	0.0078	-0.0360	-0.0122	0.0568	0.0002	0.0001	0.0002
Leonora (WA)	-2905528.2178	4775175.2276	-3062280.3715	0.0085	0.0109	0.0087	-0.0455	0.0053	0.0515	0.0002	0.0001	0.0002
Tuross Head (NSW)	-4477434.2788	2572331.0877	-3731376.5980	0.0101	0.0079	0.0092	-0.0365	0.0010	0.0444	0.0002	0.0002	0.0002
Bald Rock (VIC)	-4188591.0788	3020461.0294	-3731086.9242	0.0097	0.0083	0.0092	-0.0391	0.0027	0.0461	0.0002	0.0002	0.0002
Horn Island (QLD)	-4960946.6284	3834778.7885	-1164513.3408	0.0110	0.0094	0.0069	-0.0291	-0.0205	0.0564	0.0002	0.0002	0.0002
Mt Emu (VIC)	-4065544.7571	3013958.9753	-3869590.3370	0.0106	0.0090	0.0101	-0.0398	0.0044	0.0453	0.0002	0.0002	0.0002
Stony Point (VIC)	-4111952.8138	2856387.6375	-3938194.1385	0.0097	0.0082	0.0095	-0.0393	0.0046	0.0444	0.0002	0.0002	0.0002
Alice Springs (NT)	-4052052.7360	4212835.9841	-2545104.5883	0.0095	0.0098	0.0079	-0.0393	-0.0052	0.0540	0.0002	0.0002	0.0002
Roslyn Bay (QLD)	-5121089.4297	2863243.2415	-2493143.3274	0.0164	0.0118	0.0100	-0.0311	-0.0118	0.0503	0.0002	0.0002	0.0002
Larrakeyah (NT)	-4072230.1682	4713609.1735	-1366659.3497	0.0113	0.0122	0.0077	-0.0354	-0.0139	0.0577	0.0002	0.0001	0.0002
Broken Hill (NSW)	-4235701.4667	3372839.2104	-3360245.2676	0.0104	0.0092	0.0092	-0.0390	-0.0003	0.0489	0.0002	0.0002	0.0002

	Coordinates (m) at 2020.0			**Coordinate Uncertainty (m)**			**Velocity (m / year)**			**Velocity Uncertainty (m / year)**		
Site	***X***	***Y***	***Z***	**95% CI**	**95% CI**	**95% CI**	V_X	V_Y	V_Z	**95% CI**	**95% CI**	**95% CI**
Cape Ferguson (QLD)	-5054583.3968	3275504.1131	-2091538.4726	0.0108	0.0086	0.0075	-0.0312	-0.0143	0.0529	0.0002	0.0002	0.0002
Wallal (WA)	-3060306.4338	5165740.4734	-2144656.6187	0.0086	0.0113	0.0077	-0.0425	-0.0023	0.0552	0.0002	0.0001	0.0002
Spring Bay (TAS)	-3988046.7045	2498705.5367	-4290516.8742	0.0113	0.0090	0.0113	-0.0392	0.0079	0.0411	0.0002	0.0002	0.0002
Eucla (WA)	-3410392.1827	4229088.8868	-3330284.3849	0.0093	0.0103	0.0091	-0.0439	0.0043	0.0504	0.0002	0.0002	0.0002
Coonabarabran (NSW)	-4687675.6162	2786705.8985	-3297865.3737	0.0110	0.0085	0.0092	-0.0352	-0.0034	0.0472	0.0002	0.0002	0.0002
Arubiddy (WA)	-3183133.6965	4393393.4410	-3342516.9213	0.0086	0.0100	0.0088	-0.0449	0.0057	0.0503	0.0002	0.0002	0.0002
Baladonia (WA)	-3002034.1354	4472882.6994	-3403723.4851	0.0087	0.0106	0.0091	-0.0457	0.0072	0.0498	0.0002	0.0002	0.0002
Mainoru (NT)	-4306320.1817	4444883.0498	-1537980.0653	0.0115	0.0116	0.0078	-0.0348	-0.0140	0.0571	0.0002	0.0002	0.0002
Bingleburra (NSW)	-4743762.8083	2559346.3040	-3399327.9127	0.0115	0.0085	0.0096	-0.0345	-0.0030	0.0459	0.0002	0.0002	0.0002
Portland (VIC)	-3926098.9113	3110284.5779	-3935497.1170	0.0110	0.0096	0.0108	-0.0408	0.0057	0.0452	0.0002	0.0002	0.0002
Rocklands (NT)	-4445289.3356	4025824.8715	-2164421.6420	0.0108	0.0103	0.0079	-0.0360	-0.0102	0.0549	0.0002	0.0002	0.0002
Thevanard (SA)	-3735034.6262	3908923.6990	-3372521.9630	0.0100	0.0102	0.0094	-0.0422	0.0027	0.0499	0.0002	0.0002	0.0002
Exmouth (WA)	-2417814.5397	5401707.5260	-2370380.3097	0.0080	0.0117	0.0079	-0.0452	0.0031	0.0533	0.0002	0.0001	0.0002
Fitzroy Crossing (WA)	-3547066.8913	4918047.3803	-1971686.4311	0.0095	0.0115	0.0077	-0.0401	-0.0064	0.0562	0.0002	0.0001	0.0002
Gnangara (WA)	-2368688.0424	4881316.7075	-3341794.9823	0.0081	0.0114	0.0092	-0.0477	0.0105	0.0492	0.0002	0.0001	0.0002
Flinders Island (TAS)	-4147112.4604	2567153.7563	-4096196.5874	0.0109	0.0087	0.0106	-0.0385	0.0056	0.0425	0.0002	0.0002	0.0002
New Norcia (WA)	-2414152.3781	4907778.6372	-3270644.2049	0.0088	0.0125	0.0096	-0.0475	0.0097	0.0496	0.0002	0.0001	0.0002
Tom Price (WA)	-2706524.4877	5221344.9511	-2461226.3825	0.0087	0.0124	0.0084	-0.0447	0.0021	0.0536	0.0002	0.0001	0.0002
North Star (NSW)	-4854589.1186	2752849.4480	-3078537.4439	0.0117	0.0088	0.0091	-0.0338	-0.0060	0.0479	0.0002	0.0002	0.0002
Cooladdi (QLD)	-4707740.5468	3213770.3725	-2852875.4128	0.0122	0.0098	0.0091	-0.0352	-0.0068	0.0504	0.0002	0.0002	0.0002
Birdsville (QLD)	-4355739.6469	3740194.4994	-2769171.5091	0.0113	0.0105	0.0090	-0.0378	-0.0053	0.0523	0.0002	0.0002	0.0002
Boulia (QLD)	-4496431.9209	3785936.3941	-2467980.3960	0.0111	0.0101	0.0083	-0.0363	-0.0083	0.0534	0.0002	0.0002	0.0002

	Coordinates (m) at 2020.0			Coordinate Uncertainty (m)			Velocity (m / year)			Velocity Uncertainty (m / year)		
Site	***X***	***Y***	***Z***	**95% CI**	**95% CI**	**95% CI**	V_X	V_Y	V_Z	**95% CI**	**95% CI**	**95% CI**
Hughenden (QLD)	-4833918.6817	3485758.7318	-2266147.6174	0.0125	0.0101	0.0084	-0.0334	-0.0118	0.0531	0.0002	0.0002	0.0002
Julia Creek (QLD)	-4687826.4385	3697044.2812	-2237232.1656	0.0118	0.0103	0.0083	-0.0345	-0.0111	0.0539	0.0002	0.0002	0.0002
Neutral Junction (NT)	-4123557.7648	4274539.2155	-2318810.9705	0.0122	0.0124	0.0089	-0.0383	-0.0072	0.0548	0.0002	0.0002	0.0002
Lambina (SA)	-3957272.6859	4088878.0706	-2872293.9157	0.0097	0.0098	0.0084	-0.0404	-0.0022	0.0525	0.0002	0.0002	0.0002
Mt Doreen (NT)	-3916571.9695	4428011.7783	-2388294.0779	0.0119	0.0126	0.0089	-0.0396	-0.0055	0.0548	0.0002	0.0001	0.0002
Jervois (NT)	-4237233.1317	4077484.9793	-2462642.0014	0.0117	0.0116	0.0087	-0.0380	-0.0068	0.0540	0.0002	0.0002	0.0002
Coen (QLD)	-4956013.1005	3710714.3539	-1528615.7435	0.0150	0.0117	0.0081	-0.0305	-0.0179	0.0555	0.0002	0.0002	0.0002
Laura (QLD)	-5000453.3825	3572456.4740	-1701780.3240	0.0132	0.0107	0.0079	-0.0307	-0.0169	0.0547	0.0002	0.0002	0.0002
Northcliffe (WA)	-2311144.1346	4712785.4091	-3611358.5979	0.0084	0.0119	0.0100	-0.0483	0.0128	0.0476	0.0002	0.0001	0.0002
Kilkivan (QLD)	-5073245.0941	2668929.5700	-2787555.0317	0.0127	0.0091	0.0090	-0.0316	-0.0094	0.0486	0.0002	0.0002	0.0002
Meadow (WA)	-2373305.7835	5181466.1948	-2854287.0682	0.0084	0.0126	0.0089	-0.0467	0.0069	0.0514	0.0002	0.0001	0.0002
Yarragadee (WA)	-2389026.6159	5043317.0600	-3078529.5586	0.0080	0.0114	0.0087	-0.0472	0.0085	0.0505	0.0002	0.0001	0.0002
North Bourke (NSW)	-4587935.3985	3116314.3026	-3139419.8358	0.0113	0.0092	0.0093	-0.0363	-0.0040	0.0490	0.0002	0.0002	0.0002
Harding River Dam (WA)	-2713833.2684	5303935.1133	-2269513.7542	0.0081	0.0113	0.0077	-0.0441	0.0007	0.0542	0.0002	0.0001	0.0002
Port Headland (WA)	-2867484.8313	5242158.9057	-2223764.3419	0.0085	0.0118	0.0079	-0.0434	-0.0006	0.0547	0.0002	0.0001	0.0002
Murchison (WA)	-2556630.0412	5097138.2863	-2848384.7843	0.0083	0.0117	0.0085	-0.0462	0.0058	0.0518	0.0002	0.0001	0.0002
Gascoyne (WA)	-2482748.2739	5243145.5489	-2642213.9892	0.0093	0.0143	0.0094	-0.0458	0.0047	0.0525	0.0002	0.0001	0.0002
Normanton (QLD)	-4728960.2818	3819993.0037	-1923811.0896	0.0140	0.0122	0.0085	-0.0334	-0.0137	0.0550	0.0002	0.0002	0.0002
King Island (TAS)	-3953946.8747	2888865.8595	-4073040.9386	0.0096	0.0083	0.0097	-0.0403	0.0066	0.0437	0.0002	0.0002	0.0002
Hernani (NSW)	-4887853.3609	2545879.9420	-3202305.1047	0.0124	0.0088	0.0097	-0.0333	-0.0053	0.0466	0.0002	0.0002	0.0002
Christmas Island (WA)	-1696344.7537	6039590.0096	-1149275.0866	0.0075	0.0132	0.0072	-0.0419	-0.0015	0.0538	0.0002	0.0001	0.0002
Lord Howe Island (NSW)	-5082756.5673	1944860.6793	-3315203.5926	0.0116	0.0076	0.0092	-0.0304	-0.0056	0.0433	0.0002	0.0002	0.0002

	Coordinates (m) at 2020.0			Coordinate Uncertainty (m)			Velocity (m / year)			Velocity Uncertainty (m / year)		
Site	***X***	***Y***	***Z***	**95% CI**	**95% CI**	**95% CI**	V_X	V_Y	V_Z	**95% CI**	**95% CI**	**95% CI**
Eidsvold (QLD)	-5049378.8605	2785132.1517	-2716869.1227	0.0147	0.0102	0.0100	-0.0319	-0.0097	0.0493	0.0002	0.0002	0.0002
Nebo (QLD)	-5068236.7291	3081711.6353	-2337561.3869	0.0163	0.0122	0.0101	-0.0314	-0.0126	0.0515	0.0002	0.0002	0.0002
Aramac (QLD)	-4827919.3114	3349814.0161	-2472422.8950	0.0114	0.0093	0.0082	-0.0338	-0.0102	0.0521	0.0002	0.0002	0.0002
Tambo (QLD)	-4820440.5593	3216767.7633	-2656380.4455	0.0154	0.0116	0.0104	-0.0341	-0.0088	0.0511	0.0002	0.0002	0.0002
Mulgathing (SA)	-3833528.0707	3961621.4057	-3197513.8708	0.0102	0.0103	0.0092	-0.0415	0.0009	0.0509	0.0002	0.0002	0.0002
Kidman Springs (NT)	-4017486.2068	4628837.9322	-1759281.7840	0.0171	0.0183	0.0106	-0.0372	-0.0107	0.0568	0.0002	0.0001	0.0002
Renner Springs (NT)	-4192073.9978	4368928.5517	-1999279.4623	0.0109	0.0112	0.0080	-0.0370	-0.0100	0.0559	0.0002	0.0002	0.0002
Esperance (WA)	-2800842.3479	4500734.2962	-3534898.1927	0.0171	0.0260	0.0185	-0.0466	0.0094	0.0489	0.0002	0.0002	0.0002
Jabiru (NT)	-4236472.9665	4559859.3702	-1388764.0422	0.0170	0.0175	0.0095	-0.0347	-0.0147	0.0576	0.0002	0.0001	0.0002
Yellowdine (WA)	-2698549.7646	4741476.9407	-3293657.2537	0.0147	0.0232	0.0163	-0.0466	0.0082	0.0501	0.0002	0.0001	0.0002
Walhallow (NT)	-4344184.0427	4247715.9745	-1934909.3899	0.0182	0.0186	0.0110	-0.0360	-0.0113	0.0559	0.0002	0.0002	0.0002

Appendix B

B1. AGD66 / AGD84 to GDA94 transformations

B1.1 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 B-1 and B-2 for details of various transformation files related to respective EPSG transformation codes and names.

Table B-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 B-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

B1.2 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.

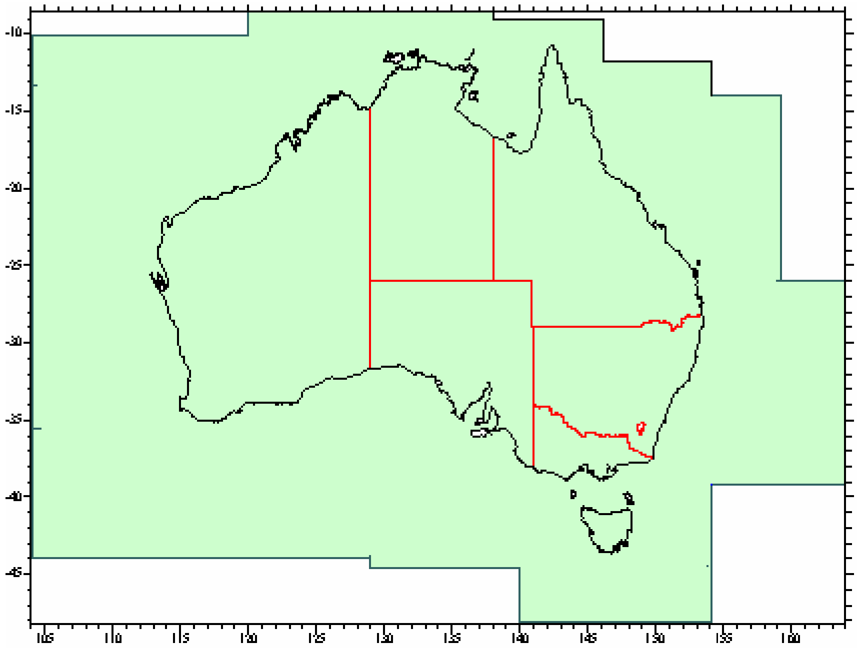

Figure B-1 AGD66 to GDA94 Transformation Grid Coverage

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.

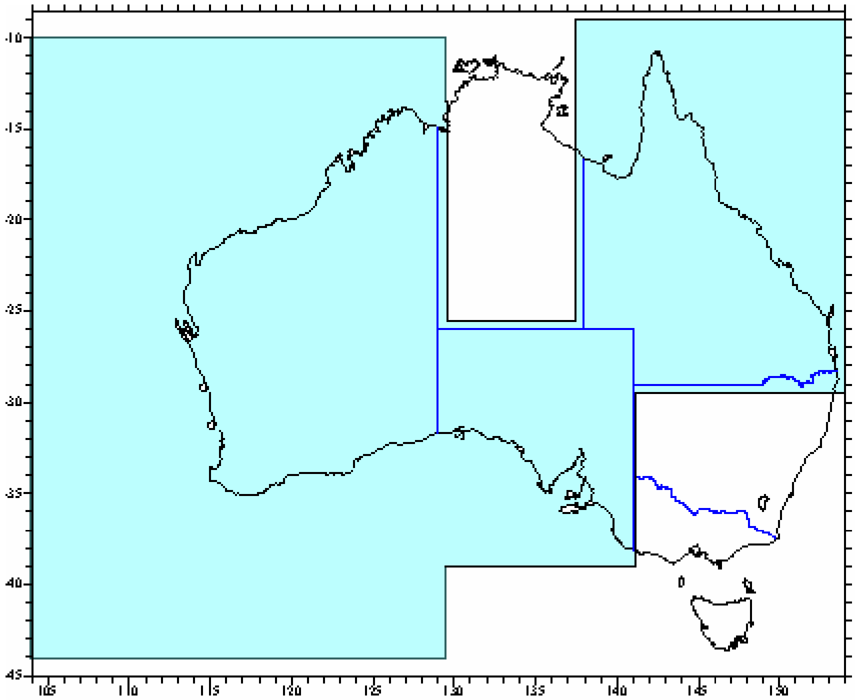

Figure B-2 AGD84 to GDA94 Transformation Grid Coverage

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.

B2. National 7 parameter similarity transformations

National similarity transformation parameters to convert between AGD66 / AGD84 and GDA94 were developed (Table B-3 and B-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 B-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 Section 2.2.1 Rotation Matrix Sign Convention for important information about the rotation signs.

Table B-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.

B3. 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 B-4 are only valid for transformation between AGD66 and GDA94 for the jurisdiction indicated.

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

EPSG Transformation Code	EPSG transformation name	Comments
5827	AGD66 to GDA94 (19)	Coverage – ACT. Replaced code 1458 in 2012????
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 C

C1. Grid bearings and ellipsoidal distance

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

$$\tan\theta_1 = (E_2' - E_1')/(N_2 - N_1) = \cot\theta_1 = (N_2 - N_1)/(E_2' - E_1') \qquad \text{(C-1)}$$

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

$$L = (E_2' - E_1')/\sin\theta_1 = (N_2 - N_1)/\cos\theta_1 \qquad \text{(C-1)}$$

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

$$s = L/K \qquad \text{(C-3)}$$

$$\delta_1{}'' = -(N_2 - N_1)(E_2' + 2E_1')[1 - (E_2' + 2E_1')^2/27{r_m}^2]/6{r_m}^2 \text{ (radians)} \qquad \text{(C-4)}$$

$$\delta_1{}'' = 206264.8062\ \delta_1 \text{ (seconds)} \qquad \text{(C-5)}$$

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

$$\delta_2{}'' = 206264.8062\ \delta_2 \text{ (seconds)} \qquad \text{(C-7)}$$

$$\beta_1 = \theta_1 - \delta_1 \qquad \text{(C-8)}$$

$$\beta_2 = \theta_1 \pm 180° - \delta_2 \qquad \text{(C-9)}$$

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.

$$N' = N - False\ Northing \qquad \text{(C-10)}$$

$$N_m' = (N_1' + N_2')/2 \qquad \text{(C-11)}$$

$$\phi_m'(1st\ approx) = (N_m'/k_0)/111132.952 \qquad \text{(C-12)}$$

$$\phi_m'(2nd\ approx) = \left((N_m'/k_0) + 16038.508\ \sin 2\phi_m'\right)/111132.952 \qquad \text{(C-13)}$$

$$\rho_m = a(1 - e^2)/(1 - e^2\sin^2\phi_m')^{3/2} \qquad \text{(C-14)}$$

$$\nu_m = a/(1 - e^2\sin^2\phi_m')^{1/2} \qquad \text{(C-15)}$$

$${r_m}^2 = \rho_m \nu_m {k_o}^2 \qquad \text{(C-16)}$$

C1.1 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:

- $E_1' = E_1 - 500\ 000$ (C-17)
- $E_2' \approx E'_1 + k_1 s \sin\beta_1$ (C-18)
- $N_2 - N_1 \approx k_1 s \cos\beta_1$ (C-19)

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

$$k_1 \approx 0.9996 + 1.23E'^2 10^{-14} \quad \text{(C-20)}$$

$$K = k_0\left\{1 + \left[\left(E_1'^2 + E_1'E_2' + E_2'^2\right)/6r_m^2\right]\underline{\left[1 + \left(E_1'^2 + E_1'E_2' + E_2'^2\right)/36r_m^2\right]}\right\} \quad \text{(C-21)}$$

$$L = sK \quad \text{(C-22)}$$

$$\sin\delta_1 = -(N_2 - N_1)(E_2' + 2E_1')\left[\underline{1 - (E_2' + 2E_1')^2/27r_m^2}\right]/6r_m^2 \quad \text{(C-23)}$$

$$\theta = \beta_1 + \delta_1 \quad \text{(C-24)}$$

$$\sin\delta_2 = (N_2 - N_1)(2E_2' + E_1')\left[\underline{1 - (2E_2' + E_1')^2/27r_m^2}\right]/6r_m^2 \quad \text{(C-25)}$$

$$\beta_2 = \theta \pm 180° - \delta_2 \quad \text{(C-26)}$$

$$\Delta E = L\sin\theta \quad \text{(C-27)}$$

$$\Delta N = L\cos\theta \quad \text{(C-28)}$$

$$E_2 = E_1 + \Delta E \quad \text{(C-29)}$$

$$N_2 = N_1 + \Delta N \quad \text{(C-30)}$$

The mean radius of curvature can be calculated as shown below, using an approximate value for the mean latitude $\left(\phi_m'\right)$. 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.

$$N' = N - False\ Northing \tag{C-31}$$

$$N'_m = (N'_1 + N'_2)/2 \tag{C-32}$$

$$\phi'_m(1st\ approx) = \left(N'_m/k_0\right)/111132.952 \tag{C-33}$$

$$\phi'_m(2nd\ approx) = \left(\left(N'_m/k_0\right) + 16038.508 \sin 2\phi'_m\right)/111132.952 \tag{C-34}$$

$$\rho_m = a(1 - e^2)/\left(1 - e^2 \sin^2 \phi'_m\right)^{3/2} \tag{C-35}$$

$$\nu_m = a/\left(1 - e^2 \sin^2 \phi'_m\right)^{1/2} \tag{C-36}$$

$$r_m{}^2 = \rho_m \nu_m k_0{}^2 \tag{C-37}$$

C1.2 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 Section 5. 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.

C1.2.1 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.

C1.2.2 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

$$P_2 = O_2 + \delta_{23} - \delta_{21} \tag{C-38}$$

where angles are measured clockwise only.

C1.2.3 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 B.1 should be referred to with the above text.

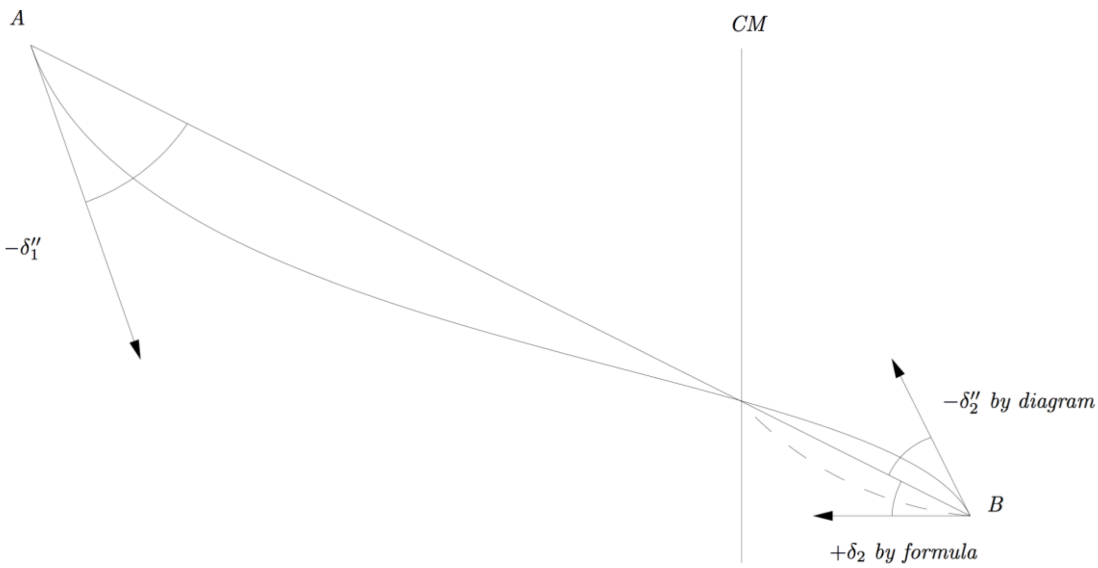

Figure C.1 Arc-to-chord correction

Sample Data

Table C.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	

Traverse Diagram