Title
Understanding coordinate systems, datums and transformations in Australia

Author
Janssen, V

Bibliographic citation
Janssen, V (2009). Understanding coordinate systems, datums and transformations in Australia. University Of Tasmania. Conference contribution.
https://figshare.utas.edu.au/articles/conference_contribution/Understanding_coordinate_systems_datums_and_

Is published in:

UNDERSTANDING COORDINATE SYSTEMS, DATUMS AND TRANSFORMATIONS IN AUSTRALIA

Volker Janssen
Survey Infrastructure and Geodesy, Land and Property Information
NSW Department of Lands
346 Panorama Avenue, Bathurst NSW 2795, Australia
Volker.Janssen@lands.nsw.gov.au

ABSTRACT

Spatial professionals are required to handle an increasingly wide range of positioning information obtained from various sources including terrestrial surveying, Global Navigation Satellite System (GNSS) observations and online GNSS processing services. These positions refer to a multitude of local, national and global datums. A clear understanding of the different coordinate systems and datums in use today and the appropriate transformations between these is therefore essential to ensure rigorous consideration of reference frame variations in order to produce high-quality positioning results. This paper provides a compendium for spatial practitioners, reviewing the concepts and definitions of coordinate systems and datums in the Australian context and outlining the practical procedures for coordinate transformations in Australia, in relation to both horizontal and vertical datums. The differences between Cartesian, curvilinear and projection coordinates are explained and practical solutions for the required coordinate conversions and transformations are presented. The computational procedure for the transformation between orthometric and ellipsoidal heights in the absence of geoid undulations referenced to a regional ellipsoid is outlined.

INTRODUCTION

The increasing use of Global Navigation Satellite System (GNSS) technology, online GNSS processing services and Geographic Information System (GIS) analysis tools requires spatial professionals to be familiar with a wide range of positioning information derived from various data sources and referenced to different coordinate datums. Often, several datasets need to be integrated for spatial analysis tasks, e.g. in order to investigate environmental change, manage national security and contribute to hazard and emergency management. High-quality coordinate transformations have become essential in practice to ensure that dynamic datum effects caused by tectonic plate motion and other geophysical phenomena are considered appropriately and the high precision and/or accuracy of the observations is not sacrificed during the transformation process.

This paper reviews the concepts and definitions of coordinate systems and datums in the Australian context. It is intended as a compendium for spatial practitioners, identifying and detailing the procedures necessary to perform coordinate transformations in Australia, in regards to both horizontal and vertical datums.

The following distinction is made between the terms conversion and transformation. A conversion describes a change of the coordinate system and does not include a change

Janssen, V. (2009). Understanding Coordinate Systems, Datums and Transformations in Australia. In: Ostendorf, B., Baldock, P., Bruce, D., Burdett, M. and P. Corcoran (eds.), Proceedings of the Surveying & Spatial Sciences Institute Biennial International Conference, Adelaide 2009, Surveying & Spatial Sciences Institute, pp. 697-715. ISBN: 978-0-9581366-8-6.

of the datum, e.g. a conversion between Cartesian and curvilinear coordinates relating to the same datum. A transformation describes a change of the datum and does not include a change of the coordinate system, e.g. a transformation of a set of coordinates given in a particular coordinate system between two datums. While a conversion can be interpreted as a direct calculation (i.e. a one-to-one relationship allowing for round-off errors), a transformation is a best estimate. In practice, both often have to be used in tandem since positions given in a certain coordinate system in Datum 1 are required to be transferred into positions given in a different coordinate system in Datum 2.

SHAPE OF THE EARTH

The shape of the earth is defined by its gravity field and not its topography. The gravity field is characterised by equipotential surfaces, i.e. surfaces of constant potential that are always perpendicular to the direction of gravity. The true shape of the earth is therefore known as the geoid, defined as a specific equipotential surface that best approximates mean sea level (MSL) on a global basis. It should be noted that MSL differs from an equipotential surface by up to about a metre due to effects such as atmospheric pressure, temperature, prevailing winds and currents, and salinity variations. The geoid is computationally very complex since density variations in the earth's interior cause it to be a very irregular surface.

It is therefore necessary to approximate the geoid by a surface that can efficiently be handled mathematically. For small scale mapping applications, a sphere is sufficient but generally an ellipsoid of revolution (sometimes also called spheroid) is adopted in order to consider the flattening of the poles caused by the earth's rotation. This ellipsoid is generated by rotating an ellipse around its minor axis and can be defined by the length of its semi-major axis (a) and its semi-minor axis (b) or, alternatively, the inverse flattening (f^{-1}). Over the years, many ellipsoids of various shapes and sizes have been defined in order to approximate the geoid, either locally or on a global basis (Fig. 1).

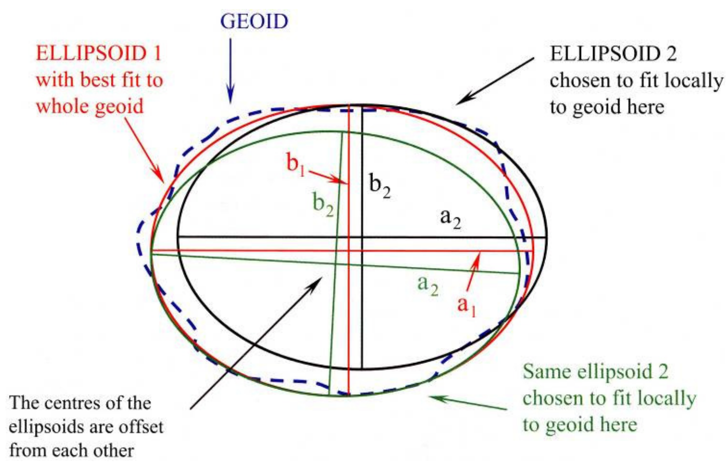

Fig. 1: Several ellipsoids approximating the geoid (adapted from Iliffe & Lott, 2008).

In Australia, spatial professionals will generally encounter three ellipsoids. The Geodetic Reference System 1980 (GRS80) and the World Geodetic System 1984 (WGS84) ellipsoids are both global earth models. The former has been widely accepted as international standard, while the latter is the nominal reference ellipsoid used by the Global Positioning System (GPS). These ellipsoids are geocentric, i.e. their origin coincides with the earth's centre of mass (including the earth's oceans and atmosphere), called the geocentre. Prior to the advent of space geodetic techniques such as GPS, it had not been possible to realise geocentric coordinate systems in practice. Consequently, the Australian National Spheroid (ANS) was designed as a locally best fit to the geoid in the Australian region. The ANS is non-geocentric, exhibiting an offset of approximately 200 metres from the geocentre. Table 1 lists the defining parameters of these three ellipsoids.

Tab. 1: Parameters of ellipsoids used in Australia.

Ellipsoid	Semi-major axis a (m)	Inverse flattening f^{-1}
ANS	6,378,160.0	298.25
GRS80	6,378,137.0	298.257222101
WGS84	6,378,137.0	298.257223563

The GRS80 and WGS84 ellipsoids only exhibit a very small difference in the flattening parameter, affecting 3-dimensional coordinates at the sub-millimetre level, and can therefore be assumed identical for most practical purposes (ICSM, 2002).

COORDINATE SYSTEMS

A coordinate system is a methodology to define the location of a feature in space. On the ellipsoid, positions are either expressed in Cartesian coordinates (X, Y, Z) or in curvilinear coordinates (ϕ, λ, h), i.e. geodetic latitude, longitude and ellipsoidal height (Fig. 2).

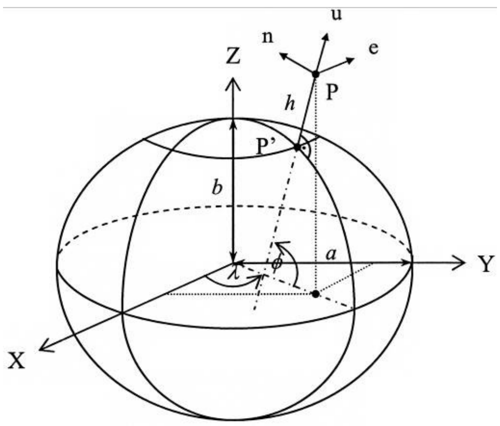

Fig. 2: Ellipsoidal coordinate systems.

In a geocentric, rectangular Cartesian coordinate system the Z-axis coincides with the mean position of the earth's rotation axis. The X-axis passes through the intersection of the Greenwich meridian and the equator, and the Y-axis completes a right-handed coordinate system by passing through the intersection of the 90°E meridian and the equator.

In regards to curvilinear coordinates, geodetic latitude is defined as the angle in the meridian plane between the equatorial plane and the ellipsoid normal through a point P. Geodetic longitude is measured in the equatorial plane as the angle between the Greenwich meridian (X-axis) and the meridian through a point P, while the ellipsoidal height is measured from the ellipsoid surface along the ellipsoid normal. It is important to note that a single ground point can have different geodetic coordinates depending on which ellipsoid the coordinate system refers to. Curvilinear coordinates can easily be converted into Cartesian coordinates by (e.g. Vaniček & Krakiwsky, 1986):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} (\nu + h)\cos\phi\cos\lambda \\ (\nu + h)\cos\phi\sin\lambda \\ (\nu(1-e^2)+h)\sin\phi \end{bmatrix} \tag{1}$$

where ν represents the radius of curvature in the prime vertical:

$$\nu = \frac{a}{\sqrt{1-e^2\sin^2\phi}} \tag{2}$$

The quantities a and $e^2 = 2f - f^2$ denote the length of the semi-major axis and the squared first eccentricity of the ellipsoid, respectively, defining its size and shape. The inverse conversion is not as straight forward and requires iteration (e.g. Torge, 2001):

$$\begin{aligned} \phi &= \tan^{-1}\left[\frac{Z}{\sqrt{X^2+Y^2}}\left(1-e^2\left(\frac{\nu}{\nu+h}\right)\right)^{-1}\right] \\ \lambda &= \tan^{-1}\left[Y/X\right] \\ h &= \sqrt{X^2+Y^2}\cdot\sec\phi-\nu \end{aligned} \tag{3}$$

However, since $\nu >> h$, the iteration converges quickly. Numerous alternative approaches have been developed, such as the non-iterative method by Bowring (1985) and the vector method by Pollard (2002), but will not be discussed here. For a comparison of various different methods and their computational efficiency, the reader is referred to, e.g., Seemkooei (2002) and Fok & Iz (2003).

Terrestrial geodetic measurements generally refer to the observation point located on the surface of the earth. Coordinates derived from these observations are therefore often expressed in a local (topocentric) reference coordinate system (n, e, u) that is tied to the direction of the ellipsoid normal at the observation point (Fig. 2). The origin of such a topocentric coordinate system is located at the observation point P. The u-axis (up) is aligned with the direction of the ellipsoid normal, while the n-axis (north) is perpendicular to the u-axis and directed towards ellipsoidal north (i.e. the geodetic meridian through P). The e-axis (east) completes a left-handed Cartesian system. Some countries utilise right-handed variations such as the east-north-up (e, n, u) or north-east-down (n, e, d) systems. The topocentric coordinate system is also helpful for applications where the area being mapped is sufficiently small to allow the curvature of the earth to be ignored, thereby rendering projections unnecessary.

Geodetic work is often concerned with relative positioning. It is therefore useful to transform between topocentric and global curvilinear coordinate differences (Soler, 1998):

$$\begin{bmatrix} \Delta n \\ \Delta e \\ \Delta u \end{bmatrix} = \begin{bmatrix} \rho + h & 0 & 0 \\ 0 & (\nu+h)\cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta\phi \\ \Delta\lambda \\ \Delta h \end{bmatrix} \tag{4}$$

where ϕ and h are the geodetic latitude and ellipsoidal height of the observation point P, respectively, and ρ represents the radius of curvature in the meridian plane:

$$\rho = \frac{a(1-e^2)}{(1-e^2\sin^2\phi)^{3/2}} \tag{5}$$

The transformation of coordinate difference vectors between the local topocentric (n, e, u) and the global Cartesian (X, Y, Z) system can be achieved by the matrix calculation (e.g. Hofmann-Wellenhof *et al.*, 2001):

$$\begin{aligned} \Delta\bar{\boldsymbol{X}}_{global} &= \boldsymbol{A}\,\Delta\bar{\boldsymbol{X}}_{local} \\ \Delta\bar{\boldsymbol{X}}_{local} &= \boldsymbol{A}^{-1}\Delta\bar{\boldsymbol{X}}_{global} = \boldsymbol{A}^{T}\Delta\bar{\boldsymbol{X}}_{global} \end{aligned} \tag{6}$$

where $\Delta\bar{\boldsymbol{X}}$ denotes the Cartesian coordinate difference vector between the observation point P and the target in each system, and

$$\boldsymbol{A} = \begin{bmatrix} -\sin\varphi\cos\lambda & -\sin\lambda & \cos\varphi\cos\lambda \\ -\sin\varphi\sin\lambda & \cos\lambda & \cos\varphi\sin\lambda \\ \cos\varphi & 0 & \sin\varphi \end{bmatrix}_{\text{evaluated at point P}} \tag{7}$$

These formulae allow the combination of results obtained from local terrestrial observations (e.g. theodolite and EDM measurements) and from satellite techniques (e.g. GPS baselines). However, it should be noted that results based on terrestrial observations will initially be referenced to the astronomical topocentric system, which is aligned with the local gravity vector (plumbline) through P and not the ellipsoid normal, and therefore need to be transformed into the ellipsoidal tropocentric system before computations on the ellipsoid can be performed. Alternatively, the initial astronomical observations can be transformed into ellipsoidal 'observations' before topocentric coordinates are obtained (e.g. Vaniček & Krakiwsky, 1986; Torge, 2001).

COORDINATE DATUMS

Since reference coordinate systems are idealised abstractions, they can only be accessed through their physical materialisation (or realisation) called reference frames or datums. The datum effectively defines the origin and orientation of the coordinate system at a certain instant in time (epoch), generally by adopting a set of station coordinates. Over time, different techniques with varying levels of sophistication have been applied to define the shape of the earth's surface, resulting in the adoption of many different datums. This section describes the datums used by spatial professionals in Australia today.

ITRF

The International Terrestrial Reference Frame (ITRF) is the most precise earth-centred, earth-fixed datum currently available and was first introduced in 1988. It is maintained by the International Earth Rotation and Reference Systems Service (IERS) and realised by an extensive global network of accurate coordinates derived from geodetic observations using GPS, Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) (Altamimi *et al.*, 2007). These coordinates are based on the GRS80, a geocentric ellipsoid designed to approximate the shape of the geoid on a global scale.

The ITRF is a dynamic datum and changes according to temporal variations of its network coordinates and their velocities due to the effects of crustal motion, earth orientation, polar motion and other geophysical phenomena such as earthquakes and volcanic activity (Bock, 1998). It is updated regularly in order to account for the dynamics of the earth and now sufficiently refined to ensure that the change between successive ITRF versions is in the order of 1-2 cm. So far the following versions have been released: ITRF88, ITRF89, ITRF90, ITRF91, ITRF92, ITRF93, ITRF94, ITRF96, ITRF97, ITRF2000 and ITRF2005. Coordinates given in any of the ITRF realisations are referred to a specific epoch in order to enable appropriate consideration of tectonic plate motion. GNSS online processing services generally provide positioning results in the most recent ITRF and often also a national datum.

WGS84

The World Geodetic System 1984 (WGS84) was developed for the U.S. Defense Mapping Agency (DMA), later named NIMA (National Imagery and Mapping Agency) and now called NGA (National Geospatial-Intelligence Agency), and is the nominal datum used by GPS (NIMA, 2004). It is based on the WGS84 ellipsoid which can generally be assumed identical to the GRS80 (see Tab. 1). The WGS84 datum was first introduced in 1987 based on Doppler observations and has since been refined several times to be closely aligned with the ITRF in order to prevent degradation of the GPS broadcast ephemerides due to plate tectonics (True, 2004).

The first refinement was introduced in 1994 to align the WGS84 with ITRF91 and included a revised set of station coordinates for the tracking network, based entirely on GPS observations (Malys & Slater, 1994). It is known as WGS84 (G730) where G stands for ‘GPS’ and 730 denotes the GPS week number when NGA started expressing their derived GPS precise ephemerides in this frame, i.e. 2 January 1994. Swift (1994) estimated that the refined WGS84 agreed with the ITRF92 at the 10 cm level. The second refinement, WGS84 (G873), occurred on 29 September 1996 and resulted in coincidence with the ITRF94 at better than 10 cm (Malys *et al.*, 1997). It should be noted that the GPS Operational Control Segment did not implement the WGS84 (G730) and WGS84 (G873) coordinates until 29 June 1994 and 29 January 1997, respectively.

The latest refinement, WGS84 (G1150), was introduced and implemented on 20 January 2002 based on 15 days of GPS data collected during February 2001 at six U.S. Air Force monitoring stations, 11 NGA stations and several additional global tracking stations. After this alignment with the ITRF2000, it was shown that the WGS84 coincides with the ITRF within a few centimetres at the global level (Merrigan *et al.*, 2002). For all mapping and charting purposes the WGS84 and the most current ITRF can therefore be assumed identical (NIMA, 2004). However, it should be noted that the level of agreement worsens as the time gap between WGS84 (G1150) and the latest realisation of ITRF grows.

GDA94

The Australian geospatial infrastructure is currently referenced to the Geocentric Datum of Australia 1994 (GDA94), a static datum adopted by the Intergovernmental Committee on Surveying and Mapping (ICSM) that does not account for tectonic motion (ICSM, 2002). The GDA94 was introduced on 1 January 2000 to replace the AGD (described below) and is based on the GRS80 ellipsoid, thus making it compatible with GPS. The GDA94 is defined in the ITRF92 at epoch 1994.0 (i.e. coincident with ITRF92 on 1 January 1994), realised by the eight Australian Fiducial Network (AFN) sites whose coordinates were estimated to have an absolute accuracy of about 2 cm at 95% confidence (Morgan *et al.*, 1996), and has since been 'frozen' in a geodetic sense in order to avoid changing coordinate values. This definition is justified by the relatively uniform drift of the Australian continent at ~7 cm to the north-east per year. However, tectonic plate motion causes the difference between absolute ITRF/WGS84 coordinates and GDA94 coordinates to increase over time. For differential GPS applications within Australia this is not an issue, as both ends of a baseline move at the same rate. For most practical applications with an accuracy requirement of only a metre, it has previously been assumed that absolute ITRF/WGS84 coordinates can be considered the same as GDA94 (Steed & Luton, 2000). However, GPS users need to be aware that this assumption has ceased to be valid because the effect of tectonic motion since 1994.0 amounts to about 1 metre in 2008.

AGD66/84

Several different datums were used across Australia for surveying and mapping purposes until the introduction of the Australian Geodetic Datum (AGD) in 1966 provided the first datum uniformly adopted nationally. The AGD is based on the ANS, a non-geocentric ellipsoid providing a best fit over the Australian region, i.e. AGD coordinates are not directly compatible with GPS-derived positions. The ANS was oriented by aligning its minor axis parallel to the position of the earth's mean rotation axis at the start of 1962, and zero longitude was defined as 149°00'18.855" west of the Mount Stromlo observatory, i.e. at Greenwich (Bomford, 1967). The AGD66 was realised by fixing the coordinates of the Johnston Geodetic Station, located in the Northern Territory. The AGD84, an updated realisation based on a larger amount of data with higher quality and improved adjustment techniques, was only adopted by Western Australia, South Australia and Queensland. The difference between AGD66 and AGD84 coordinates of the same point can reach several metres, while positions referred to the GDA94 appear to be about 200 m north-east of those referenced to the AGD due to the origin shift between the respective ellipsoids (ICSM, 2002).

AHD71/83

In regards to vertical coordinates, most countries utilise an approximation of the orthometric height system referenced to the geoid. A vertical datum defines a reference for elevation comparisons and is essential for a wide range of applications such as floodplain management, waterway navigation management, roadway and drainage design, agricultural management and surveying in general. The Australian Height Datum (AHD) was realised in 1971 by setting the observed MSL to zero at 30 tide gauges situated around the coast of Australia and adjusting about 195,000 km of spirit levelling across the country (Roelse *et al.*, 1971). However, due to dynamic ocean effects (e.g. winds, currents, atmospheric pressure, temperature and salinity), tide gauge observations only spanning a period of 2-3 years and the omission of observed gravity, MSL was not coincident with the geoid at these tide locations. This introduced considerable distortions of up to ~1.5 m into the AHD, causing the AHD71 to be essentially a third-order datum (Morgan, 1992). The Tasmanian AHD (generally referred to as AHD83) was defined separately (in 1979) by setting MSL observations for 1972 at the tide gauges in Hobart and Burnie to zero and the Tasmanian levelling network was then readjusted in 1983 (ICSM, 2002). GPS observations together with the AUSGeoid98 (Featherstone *et al.*, 2001) have been used to establish a connection of the AHD between the mainland and Tasmania, showing differences of up to 0.26 ± 0.33 m (e.g. Featherstone, 2002). For a detailed treatment of height systems and vertical datums in the Australian context, the reader is referred to Featherstone & Kuhn (2006).

PROJECTION COORDINATES

In practice, it is often required to express positions on a flat surface in the form of grid coordinates, i.e. in a 2-dimensional Cartesian coordinate system such as Easting and Northing. This section briefly reviews map projections and introduces the principle of grid coordinates. A detailed treatment of this topic can be found in texts such as Maling (1993), Bugayevskiy & Snyder (1995) and Grafarend & Krumm (2006).

Map Projections

Map projections are used to represent a spatial 3-dimensional surface (e.g. the earth) on a plane, 2-dimensional surface (e.g. a paper map) according to a recognised set of mathematical rules, resulting in an ordered system of meridians and parallels. It is therefore necessary to project the spherical or ellipsoidal earth onto a developable surface that can be cut and flattened, i.e. a plane, cylinder or cone, thus resulting in an azimuthal, cylindrical or conic projection, respectively. This projection surface is generally located tangent or secant to the earth and its axis is either coincident with the earth's axis (polar or normal aspect), at right angles to the earth's axis (equatorial or transverse aspect) or at an arbitrary angle (oblique aspect). For instance, in a tangential azimuthal projection, the plane would be tangent to the earth either at one of the poles, at a point on the equator or at any other point central to the area that is to be mapped, respectively. Figure 3 illustrates examples of three commonly used projections. Note that the projection surface is tangent to the earth along a parallel of latitude, along a meridian and at a point, respectively. The projection parameters needed to convert curvilinear coordinates to grid coordinates are derived either geometrically or mathematically.

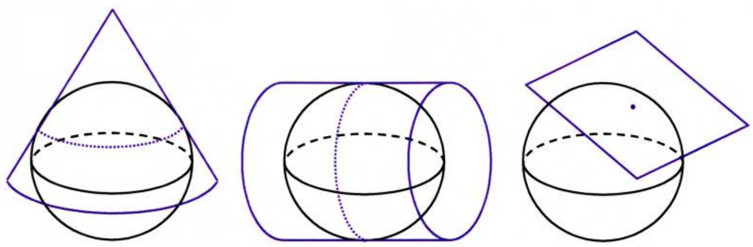

Fig. 3: The normal conic, transverse cylindrical and oblique azimuthal projections.

It should be apparent that it will be impossible to convert a 3D surface into a 2D surface without any distortions. A multitude of projections has been developed in order to satisfy certain cartographic properties, i.e. the preservation of shape locally (conformal projection), scale (equidistant projection) or area (equal-area projection). Thus it is possible to eliminate certain distortions at the expense of others or to minimise all types of distortions. However, some distortion will always remain. The type of projection chosen is therefore dependent on the extent, scale and intended purpose of the map, e.g. in order to investigate the global or regional distribution of wheat growing areas, an equal-area map is required to consistently represent the size of each area while considerable distortions in the shape and position of these areas may be tolerated.

UTM Projection

On a conformal map, meridians and parallels intersect at right angles, and the scale at any point on the map is the same in any direction, although it will vary from point to point. Conformal maps therefore allow the analysis, control or recording of motion and angular relationships. Hence they are essential for the generation of navigational charts, meteorological charts and topographic maps. An example of a conformal projection is the Transverse Mercator projection, which is used extensively around the world as a basis for grid coordinates and is therefore treated in more detail here. This projection is mathematically derived and utilises a cylinder that is tangent to a chosen meridian, called the central meridian (CM) (see Fig. 3). The scale is therefore true (i.e. unity) along the central meridian but increases with increasing distance from it, thereby causing a growing distortion in scale. The Transverse Mercator projection is most appropriate for regions exhibiting a large north-south extent but small east-west extent. However, by splitting up the area to be mapped into longitudinal zones of limited extent and merging the resulting plane maps, the entire world can be mapped with minimal distortion.

The Universal Transverse Mercator (UTM) projection utilises a zone width of 6° and ensures that the scale is very close to unity across the entire zone by defining a central scale factor of 0.9996 for the CM which results in a scale of 1.0010 at the zone boundary located 3° away from the CM. The UTM projection divides the world into 60 zones, zone 1 having a CM at longitude 177°W, while the latitudinal extent of each zone is 80°S to 84°N, indicated by 20 bands labelled C to X with the exclusion of I and O for obvious reasons. All latitude bands are 8° wide, except the most northerly (X) which is 12° wide to allow Greenland to be mapped in its entirety (Fig. 4). The increasing distortion in scale evident at high latitudes is caused by the north-south gridlines not converging at the poles, i.e. the poles would be projected as lines rather than points. The island of Tasmania, e.g., is located in zone 55G. Note that while the latitude extent is generally part of the coordinate display in most GPS receivers, in a GIS environment it is often replaced by N or S to indicate the hemisphere when a global UTM system is used.

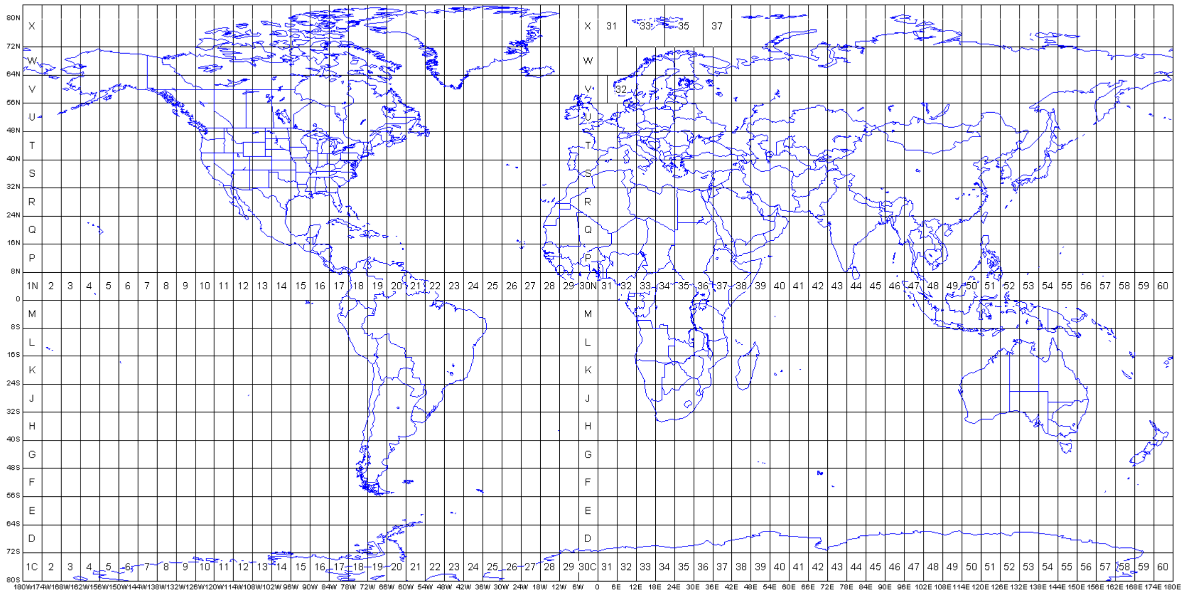

Fig. 4: UTM grid zones of the world (http://www.dmap.co.uk/utmworld.htm).

Grid Coordinates

In each UTM zone, the projected grid coordinates, i.e. Easting and Northing, are initially referenced to the origin defined by the intersection of the CM and the equator, resulting in negative Easting coordinates west of the CM and negative Northing coordinates in the southern hemisphere. In order to ensure positive coordinate values across the entire zone, the UTM system applies false coordinates to the origin by adding 500,000 m to the true Easting and, in the southern hemisphere, 10,000,000 m to the true Northing. It should be noted that variations of this global UTM convention are used in numerous national mapping datums, applying different zone widths, false coordinates and central scale factors.

In Australia, the global convention presented above applies to both the AGD66/84 and GDA94 datums. Grid coordinates derived from a UTM projection of the AGD66 geodetic coordinates are known as the Australian Map Grid 1966 (AMG66) coordinate set. If the AGD84 is used, the resulting grid coordinates are denoted as AMG84. The same UTM projection applied to geodetic GDA94 coordinates results in the Map Grid of Australia 1994 (MGA94) coordinate set. It is important to note that while all three coordinate grids are obtained using the same projection, the resulting grids differ significantly since AGD and GDA are based on different ellipsoids. In practice, the MGA coordinates appear to be approximately 200 m north-east of the AMG coordinates for the same feature.

The conversion between curvilinear and grid coordinates is performed using Redfearn's (1948) formulae and computational tools are readily available. In the Australian context, these formulae are accurate to better than 1 mm in any AMG or MGA zone and can therefore be regarded as exact (ICSM, 2002). GPS receivers routinely allow the user to display positions in a selected coordinate system, datum and/or projection, while new datums can be defined.

DATUM TRANSFORMATIONS

The coordinates of a point will differ depending on which datum these coordinates refer to. Several coordinate transformations exist and their accuracy depends on the method chosen as well as the number, distribution and accuracy of the common points used to determine the transformation parameters. It is generally recommended to use the most accurate method available, although it is recognised that less accurate options may be sufficient for certain applications.

Grid Transformation

The most accurate method is the grid-based approach which supplies users with transformation parameters and, being a particularly useful benefit of this technique, transformation accuracy (not to be confused with the accuracy of the transformed coordinates) on a regularly spaced grid. The transformation components of any point within the grid are generally determined based on bi-linear interpolation using the known components of the four surrounding grid nodes. In Australia, a complex model is employed which combines a datum shift based on a 7-parameter similarity transformation (discussed in the next section) with the modelling of distortions caused by the surveying techniques employed in the datum realisations of the AGD. This is achieved by utilising grids that have been developed using the method of least squares collocation, which allows the contribution of the distortion at surrounding data points to be weighted according to their distance from the interpolation point (Collier, 2002).

The advantage of these grids is that a complex transformation model with a high accuracy can be implemented in a relatively routine fashion. The user only has to perform a simple interpolation to obtain coordinate shifts, followed by a simple addition to perform the transformation. The user friendliness of these grids has led to their adoption in several countries such as the U.S., Canada and Australia. An analysis of the errors introduced by the use of such transformation grids is provided by Nievinski & Santos (2007).

In Australia, it was found that distortions for the transformation between AGD66/84 and GDA94 reach several metres, especially in the more remote regions of the country (Collier, 2002). If the distortion pattern across an area is regular, high transformation accuracy can be achieved, while an irregular distortion pattern will cause the transformation accuracy to deteriorate. Generally, the transformation accuracy of the AGD66/84-GDA94 grids is better than ±0.1 m, although it increases to ±0.5 m or more in some cases (Collier, 2002).

National transformation grids for the transformation between the two realisations of the AGD and GDA94 are provided by ICSM (2002) and supersede previous state-wide grids. These grids utilise the National Transformation Version 2 (NTv2) format developed by the Geodetic Survey Division of Geomatics Canada which is now being used in many GIS software packages. The NTv2 format was chosen because it enables accuracy estimates of the transformation parameters to be included and allows sub-grids of different density which is very useful when dealing with variable distortion patterns (Collier, 2002). Australian state jurisdictions have developed readily available transformation software, e.g. GDAit (Victoria), GDAy (Queensland), GEOD and DatumTran (both NSW). The latter has been specifically designed to transform GIS data in various formats (NSW Department of Lands, 2008a). Alternatively, these grid transformations can be performed within the GIS environment.

Similarity Transformation

A 7-parameter similarity transformation, also known as Helmert transformation, accounts for the difference between two 3-dimensional datums by applying three translations along the coordinate axes, three rotations about the axes and one scale factor change (e.g. Harvey, 1986):

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} + (1+\delta s) \begin{bmatrix} 1 & \gamma & -\beta \\ -\gamma & 1 & \alpha \\ \beta & -\alpha & 1 \end{bmatrix} \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} \tag{8}$$

where (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) are the coordinates of a point in Datum 1 and Datum 2 respectively, ΔX, ΔY, ΔZ are the coordinates of the origin of Datum 2 in Datum 1 (i.e. the origin shift), α, β, γ are small differential rotations (i.e. up to a few seconds) around the X, Y, Z axes of Datum 1 respectively to establish parallelism with the axes of Datum 2, and δs is a differential scale change between the two datums. If the rotations exceed a few seconds, the use of a rigorous rotation matrix is required (cf. Hofmann-Wellenhof *et al.*, 2001).

If a transformation in the opposite direction is desired, the same equation can be used but the signs of all parameters need to be reversed. By convention, a positive rotation is an anti-clockwise rotation when viewed along the positive axis towards the origin. It should be noted that in Australia the rotations are assumed to be of the coordinate axes, while the IERS assumes the rotations to be of the position around the coordinate axes. If the IERS convention is to be used in the Australian context, the sign of the rotation parameters needs to be reversed (ICSM, 2002).

Since this transformation is based on Cartesian coordinates, geodetic coordinates first need to be converted using equation (1). The transformed Cartesian coordinates can then be converted back to curvilinear coordinates using equation (3), effectively allowing curvilinear coordinates to be transformed between two datums. The similarity transformation is also known as a conformal transformation because it maintains the shape (but not the orientation and size) of the transformed objects. A 7-parameter similarity transformation can achieve transformation accuracies of about 1 m for AGD66/84-GDA94 transformations, using the parameters given in Table 2. Online tools and spreadsheets to perform these calculations are available from various sources (e.g. NSW Department of Lands, 2008b; GA, 2009).

Tab. 2: Transformation parameters from AGD to GDA94 (ICSM, 2002).

Parameter	national		regional AGD66			
	AGD84	AGD66	ACT	TAS	VIC & NSW	NT
ΔX (m)	-117.763	-117.808	-129.193	-120.271	-119.353	-124.133
ΔY (m)	-51.510	-51.536	-41.212	-64.543	-48.301	-42.003
ΔZ (m)	139.061	137.784	130.730	161.632	139.484	137.400
α (")	-0.292	-0.303	-0.246	-0.217	-0.415	0.008
β (")	-0.443	-0.446	-0.374	0.067	-0.260	-0.557
γ (")	-0.277	-0.234	-0.329	0.129	-0.437	-0.178
δs (ppm)	-0.191	-0.290	-2.955	2.499	-0.613	-1.854

If a dynamic datum is involved in the transformation, e.g. between different realisations of the ITRF or between the GDA94 and a particular ITRF, the velocities of the seven parameters need to be taken into account in order to refer the parameters to the desired epoch. This 14-parameter similarity transformation can be performed according to Dawson & Steed (2004). Alternatively, equation (8) can be used after the parameters have been updated according to (IERS, 2008):

$$P(t) = P(t_0) + \dot{P} \cdot (t - t_0) \tag{9}$$

where $P(t)$ is the parameter at the desired epoch t (i.e. observation epoch), $P(t_0)$ is the parameter at the epoch t_0 of its initial definition, and $\dot{P}$ is the rate (velocity) of this parameter. The epoch is given in decimal years. Parameters and their rates to transform from ITRF2000 to the other ITRF realisations are listed in Table 3. Note that these parameters are valid at the indicated epoch only.

Tab. 3: Transformation parameters and their rates from ITRF2000 to other frames (IERS, 2008).

Frame	ΔX (m)	ΔY (m)	ΔZ (m)	δs (ppm)	α (")	β (")	γ (")	Epoch (t_0)
ITRF2005	-0.0001	0.0008	0.0058	-0.00040	0.00000	0.00000	0.00000	2000.0
Rate (yr^{-1})	0.0002	-0.0001	0.0018	-0.00008	0.00000	0.00000	0.00000	
ITRF97	0.0067	0.0061	-0.0185	0.00155	0.00000	0.00000	0.00000	1997.0
Rate (yr^{-1})	0.0000	-0.0006	-0.0014	0.00001	0.00000	0.00000	0.00002	
ITRF96	0.0067	0.0061	-0.0185	0.00155	0.00000	0.00000	0.00000	1997.0
Rate (yr^{-1})	0.0000	-0.0006	-0.0014	0.00001	0.00000	0.00000	0.00002	
ITRF94	0.0067	0.0061	-0.0185	0.00155	0.00000	0.00000	0.00000	1997.0
Rate (yr^{-1})	0.0000	-0.0006	-0.0014	0.00001	0.00000	0.00000	0.00002	
ITRF93	0.0127	0.0065	-0.0209	0.00195	-0.00039	0.00080	-0.00114	1988.0
Rate (yr^{-1})	-0.0029	-0.0002	-0.0006	0.00001	-0.00011	-0.00019	0.00007	
ITRF92	0.0147	0.0135	-0.0139	0.00075	0.00000	0.00000	-0.00018	1988.0
Rate (yr^{-1})	0.0000	-0.0006	-0.0014	0.00001	0.00000	0.00000	0.00002	
ITRF91	0.0267	0.0275	-0.0199	0.00215	0.00000	0.00000	-0.00018	1988.0
Rate (yr^{-1})	0.0000	-0.0006	-0.0014	0.00001	0.00000	0.00000	0.00002	
ITRF90	0.0247	0.0235	-0.0359	0.00245	0.00000	0.00000	-0.00018	1988.0
Rate (yr^{-1})	0.0000	-0.0006	-0.0014	0.00001	0.00000	0.00000	0.00002	
ITRF89	0.0297	0.0475	-0.0739	0.00585	0.00000	0.00000	-0.00018	1988.0
Rate (yr^{-1})	0.0000	-0.0006	-0.0014	0.00001	0.00000	0.00000	0.00002	
ITRF88	0.0247	0.0115	-0.0979	0.00895	0.00010	0.00000	-0.00018	1988.0
Rate (yr^{-1})	0.0000	-0.0006	-0.0014	0.00001	0.00000	0.00000	0.00002	

In order to obtain GDA94 coordinates, users have to perform the appropriate transformation from a given ITRF to ITRF92 at epoch 1994.0. Alternatively, Dawson & Steed (2004) produced parameters to be used to transform directly from several ITRF frames to GDA94 (Tab. 4). Users transforming coordinates derived from International GNSS Service (IGS) products after 2 December 2001 are provided with additional high-quality transformation parameters that are referred to as ITRF2000(IGS).

To date, direct ITRF2005-GDA94 transformation parameters have not been published. Users are therefore required to first transform ITRF2005 coordinates to ITRF2000 at the required epoch and then apply the appropriate parameters from ITRF2000 to GDA94. Note that in order to transform the coordinates of a point in a given ITRF realisation to a different epoch, knowledge is required of the coordinate velocities referred to this particular realisation. The similarity transformation can model the differences between various ITRF realisations at the cm level, provided that the rates are applied to account for tectonic plate motion (Dawson & Steed, 2004).

Tab. 4: Transformation parameters and their rates from various ITRF frames to GDA94 (Dawson & Steed, 2004).

Frame	ΔX (m)	ΔY (m)	ΔZ (m)	δs (ppm)	α (")	β (")	γ (")	Epoch (t_0)
ITRF2000	-0.0761	-0.0101	0.0444	0.007935	0.008765	0.009361	0.009325	2000.0
Rate (yr^{-1})	0.0110	-0.0045	-0.0174	-0.000538	0.001034	0.000671	0.001039	
ITRF2000(IGS)	-0.0663	-0.0050	0.0426	0.007936	0.008814	0.009127	0.009042	2000.0
Rate (yr^{-1})	0.0049	0.0039	0.0049	0.000096	0.001616	0.001200	0.001013	
ITRF97	-0.2088	0.0119	0.1855	0.004559	0.012059	0.013639	0.011825	2000.0
Rate (yr^{-1})	-0.0220	0.0049	0.0169	-0.001090	0.002040	0.001782	0.001697	
ITRF96	-0.0140	0.0431	0.2010	0.024607	0.012464	0.012013	0.006434	2000.0
Rate (yr^{-1})	0.0411	0.0218	0.0383	0.005897	0.002542	0.001431	-0.000234	

Lower Accuracy Transformations

Lower accuracy methods, such as the Molodensky and abridged Molodensky formulae or a simple block shift, provide transformation accuracies at the 5-10 m level (e.g. ICSM, 2002). However, these will not be discussed here since the more accurate methods are generally preferred in practice. An extensive evaluation of different models using published parameters to transform from AGD to GDA94 was presented by Kinneen & Featherstone (2004) and can be consulted for more details on these methods.

TRANSFORMATION OF HEIGHTS

Positions obtained by a GNSS such as GPS, Glonass or Galileo include heights referred to a reference ellipsoid. These heights are based purely on the geometry of the ellipsoid and therefore have no physical meaning. In practice, however, heights are generally required that correctly reflect the flow of water, e.g. for drainage and pipeline design. National height datums such as the AHD are therefore based on orthometric heights, referenced to the geoid or an approximation thereof.

Geoid Undulation

Ellipsoidal heights (h) can be converted into orthometric heights (H) by applying the geoid undulation (N), also known as geoid-ellipsoid separation, geoid height or N value:

$$H = h - N \tag{10}$$

Strictly speaking, this equation is an approximation since h and N are measured along the ellipsoid normal, while H is measured along the curved plumbline, i.e. the direction of the gravity vector (Fig. 5). The angle between the direction of the gravity vector and the ellipsoid normal at a surface point is known as the deflection of the vertical. Since this angle amounts to only several seconds of arc, its effect on equation (10) can generally be ignored in practice (Featherstone, 2007).

It is essential that the N value refers to the correct reference ellipsoid, i.e. in order to convert an ellipsoidal height in the GDA94 to an AHD height, the N value relative to the GRS80 ellipsoid must be known. Across Australia, the AUSGeoid98 (Featherstone *et al.*, 2001) provides geoid undulations relative to the GRS80 ellipsoid on a 2’ by 2’ (approx. 3.6 km by 3.6 km) grid, which can also be used in conjunction with heights referenced to the WGS84 ellipsoid since both ellipsoids are practically identical. Using a simple interpolation, N values can then be obtained for any location in Australia, e.g.

through Geoscience Australia's freely available WINTER software (GA, 2007). In a GIS context, this transformation needs to be performed before the data are imported into the GIS if it is desired to create from GPS-derived positions a digital elevation model (DEM) that has a physical meaning and therefore must be based on orthometric heights. A new geoid-type model for Australia is currently being produced to replace AUSGeoid98 (Featherstone *et al.*, 2007; 2009).

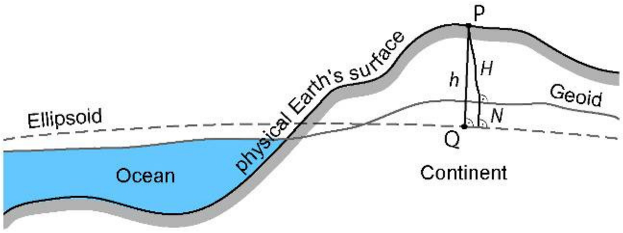

Fig. 5: Relationship between ellipsoidal height (*h*), orthometric height (*H*) and geoid undulation (*N*), courtesy of M. Kuhn, Curtin University of Technology.

In practice, geoid undulation information therefore plays two crucial roles (Rizos, 1997): On the one hand, N values are needed to convert (non-GPS) geodetic control information (i.e. orthometric heights) into a mathematically equivalent reference system to which GPS results refer (i.e. ellipsoidal heights). On the other hand, we require N values to obtain orthometric heights (i.e. physical meaning) from GPS-derived ellipsoidal heights (i.e. geometrical meaning), which is referred to as GPS levelling or GPS heighting.

Geoid Determination

If N values are not available for a particular ellipsoid or are not accurate enough, there are several options to calculate geoid undulations in order to determine a local geoid model for an area (e.g. Steed, 1990; Rizos, 1997):

1) Astro-geodetic method: Profiles of N values are calculated by comparison of positions determined geodetically (referred to local ellipsoid, e.g. ANS) and astronomically (referred to geoid) through computation of the deflection of the vertical at each point. A relative accuracy of a few metres is achievable but the method is difficult and expensive to undertake, hence it is no longer used in practice.
2) Geopotential models: These models are derived from a combination of satellite and terrestrial data, using high degree spherical harmonic series expansions to evaluate N values relative to a geocentric ellipsoid. The achievable accuracy is generally a few m (absolute) and ~5 ppm (relative). This method is very convenient to use and therefore often included in GNSS software.
3) Geometric method: A local representation of the geoid is obtained according to equation (10) at points which have both levelled (orthometric) and ellipsoidal (GNSS-derived) heights. N values at other points are then linearly interpolated. The achievable accuracy is very much dependent on the number and quality of the common points and the smoothness of the geoid, but the method is very easy to implement and therefore commonly applied in practice.
4) Gravimetric method: This method utilises Stokes' integral and requires terrestrial gravity data in the vicinity of the points at which the geoid is to be evaluated – a severe restriction in some parts of the world. Where good gravity data coverage is

available, a relative accuracy of a few cm can be achieved, making this potentially the most accurate geoid determination method. However, it is inconvenient to use since it must be pre-computed.

Datum Transformation using Geoid Undulations

In Australia, spatial professionals continue to face the task of transforming coordinates from projected grid coordinates, based on a regional ellipsoid, and gravity-related heights (i.e. E, N, H in the AMG66/84) to curvilinear coordinates based on a geocentric ellipsoid (i.e. ϕ, λ, h in the GDA94), e.g. in order to combine older terrestrial survey control information with recent GPS observations. The orthometric height H is independent of the reference ellipsoid. However, this transformation requires knowledge of the appropriate N value referring to the regional ellipsoid (i.e. N_{ANS}). AMG coordinates can then be transformed into GDA94 as follows:

1) Convert $(E, N)_{\mathrm{AMG}}$ to $(\phi, \lambda)_{\mathrm{AGD}}$ on the ANS ellipsoid using Redfearn's (1948) formulae.
2) Convert H to h_{ANS} using equation (10) and N_{ANS} (if known).
3) Convert the curvilinear coordinates $(\phi, \lambda, h)_{\mathrm{AGD}}$ in the regional datum to Cartesian coordinates $(X, Y, Z)_{\mathrm{AGD}}$ using equation (1) and the ANS ellipsoid parameters.
4) Perform a similarity transformation between the regional datum $(X, Y, Z)_{\mathrm{AGD}}$ and the geocentric datum $(X, Y, Z)_{\mathrm{GDA94}}$ according to equation (8) and the parameters given in Table 2.
5) Convert the Cartesian coordinates $(X, Y, Z)_{\mathrm{GDA94}}$ in the geocentric datum to curvilinear coordinates $(\phi, \lambda, h)_{\mathrm{GDA94}}$, e.g. using equation (3).

However, we may not have access to the required N values that refer to the regional datum. The readily available AUSGeoid98 only supplies geoid undulations related to the geocentric GRS80 ellipsoid (i.e. N_{GRS80}). This problem can be overcome by making use of the fact that the difference in ellipsoidal height is equivalent to the change in geoid undulation between the datums (ignoring rotations and scale change):

$$h_{\mathrm{ANS}} = H + N_{\mathrm{ANS}} \quad \text{and} \quad h_{\mathrm{GRS80}} = H + N_{\mathrm{GRS80}} \tag{11}$$

Since H is independent of the reference ellipsoid and therefore constant, differencing yields:

$$\Delta h_{\mathrm{GRS80\text{-}ANS}} = \Delta N_{\mathrm{GRS80\text{-}ANS}} \tag{12}$$

If, in the procedure outlined above, step 2 is skipped and an initial ellipsoidal height of $h_{\mathrm{ANS}} = 0$ is used in step 3, the result after step 5 represents the difference in ellipsoidal height $\Delta h_{\mathrm{GRS80\text{-}ANS}}$ between the two ellipsoids. The AUSGeoid98 can then be used to obtain N_{GRS80} and thus N_{ANS} is determined based on equation (12). The final coordinates in the GDA94 are obtained by performing step 2 and repeating steps 3-5 with the correct h_{ANS} value. It should be noted that a more rigorous treatment of the problem is required if the scale change between the datums cannot be ignored, cf. Kotsakis (2008).

CONCLUDING REMARKS

This paper has provided a compendium of the theory and the tools required for spatial professionals to handle transformations between the various coordinate systems and datums currently used in Australia. The differences between Cartesian, curvilinear and projection coordinates referring to different geodetic datums have been reviewed, and practical solutions for the required coordinate conversions and transformations have been outlined. Transformation parameters to be used in the Australian context have been compiled in order to provide this information in one place and in a consistent manner, referring the interested reader to the literature for a more in-depth treatment where appropriate. The computational procedure for the transformation between orthometric and ellipsoidal heights in the absence of geoid undulations referenced to a regional ellipsoid has been presented. It is hoped that this paper has eliminated any confusion in regards to geodetic transformations applicable to the Australian spatial science community.

REFERENCES

Altamimi, Z., Collilieux, X., Legrand, J., Garayt, B. and Boucher, C. (2007) ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and earth orientation parameters, *Journal of Geophysical Research*, 112, B09401, doi:10.1029/2007JB004949.

Altamimi, Z., Sillard, P. and Boucher, C. (2002) ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications, *Journal of Geophysical Research*, 107(B10), 2214, doi:10.1029/2001JB000561.

Bock, Y. (1998) Reference systems, in: Teunissen, P.J.G. and Kleusberg, A. (Eds.) *GPS for geodesy*, Springer, Berlin, 1-42.

Bomford, A.G. (1967) The geodetic adjustment of Australia 1963-1966, *Survey Review*, 19(144), 52-71.

Bowring, B.R. (1985) The accuracy of geodetic latitude and height equations, *Survey Review*, 28(218), 202-206.

Bugayevskiy, L.M. and Snyder, J.P. (1995) *Map projections: A reference manual*, Taylor & Francis, London.

Collier, P. (2002) Development of Australia's national GDA94 transformation grids, Consultant's Report to the Intergovernmental Committee on Surveying and Mapping, University of Melbourne, Australia.

Dawson, J. and Steed, J. (2004) International Terrestrial Reference Frame (ITRF) to GDA94 coordinate transformations, http://www.ga.gov.au/image_cache/GA3795.pdf (viewed 30 Apr 2009).

Featherstone, W.E. (2002) Attempts to unify the Australian Height Datum between the mainland and Tasmania, in: Drewes, P., Dodson, A., Fortes, L.P., Sanchez, L. and Sandoval, P. (Eds.) *Vertical reference systems*, Springer, Berlin, 328-333.

Featherstone, W.E. (2007) Absolute and relative testing of gravimetric geoid models using Global Positioning System and orthometric height data, *Computers & Geosciences*, 27, 807-814.

Featherstone, W.E., Kirby, J.F., Claessens, S.J., Filmer, M., Kuhn, M., Johnston, G.M. and Brown, N. (2009) AUSGeoid2009, Proc. SSC2009, Adelaide, 28 Sep - 2 Oct.

Featherstone, W.E., Kirby, J.F., Kearsley, A.H.W., Gilliland, J.R., Johnston, G.M., Steed, J., Forsberg, R. and Sideris, M.G. (2001) The AUSGeoid98 geoid model for Australia: Data treatment, computations and comparisons with GPS-levelling data, *Journal of Geodesy*, 75, 313-330.

Featherstone, W.E. and Kuhn, M. (2006) Height systems and vertical datums: A review in the Australian context, *Journal of Spatial Science*, 51(1), 21-42.

Featherstone, W.E., Kuhn, M., Kirby, J.F., Sproule, D.M., Darbeheshti, N. and Awange, J.L. (2007) Progress towards the new Australian geoid-type model as a replacement for AUSGeoid98, Proc. SSC2007, Hobart, Tasmania, 14-18 May, 243-261.

Fok, H.S. and Iz, H.B. (2003) A comparative analysis of the performance of iterative and non-iterative solutions to the Cartesian to geodetic coordinate transformation, *Journal of Geospatial Engineering*, 5(2), 61-74.

GA (2007) AUSGeoid98, http://www.ga.gov.au/geodesy/ausgeoid/ (viewed 30 Apr 2009).

GA (2009) Geodetic calculation methods, http://www.ga.gov.au/geodesy/datums/calcs.jsp (viewed 30 Apr 2009).

Grafarend, E.W. and Krumm, F.W. (2006) *Map projections: Cartographic information systems*, Springer, Berlin.

Harvey, B.R. (1986) Transformation of 3D co-ordinates, *The Australian Surveyor*, 33(2), 105-125.

Hofmann-Wellenhof, B., Lichtenegger, H. and Collins, J. (2001) *GPS: Theory and practice*, 5th ed., Springer, Wien.

ICSM (2002) Geocentric Datum of Australia technical manual, Version 2.2, http://www.icsm.gov.au/icsm/gda/gdatm/index.html (viewed 30 Apr 2009).

IERS (2008) ITRF transformation parameters, http://itrf.ensg.ign.fr/trans_para.php (viewed 29 Apr 2009).

Iliffe, J. and Lott, R. (2008) *Datums and map projections for remote sensing, GIS and surveying*, 2nd ed., Whittles Publishing, Dunbeath.

Kinneen, R.W. and Featherstone, W.E. (2004) Empirical evaluation of published transformation parameters from the Australian Geodetic Datums (AGD66 and AGD84) to the Geocentric Datum of Australia (GDA94), *Journal of Spatial Science*, 49(2), 1-31.

Kotsakis, C. (2008) Transforming ellipsoidal heights and geoid undulations between different geodetic reference frames, *Journal of Geodesy*, 82, 249-260.

Maling, D.H. (1993) *Coordinate systems and map projections*, 2nd ed., Pergamon Press, Oxford.

Malys, S. and Slater, J. (1994) Maintenance and enhancement of the World Geodetic System 1984, Proc. ION GPS-94, Salt Lake City, UT, 20-23 September, 17-24.

Malys, S., Slater, J.A., Smith, R.W., Kunz, L.E. and Kenyon, S.C. (1997) Refinements to the World Geodetic System 1984, Proc. ION GPS-97, Kansas City, MO, 16-19 September, 841-850.

Merrigan, M.J., Swift, E.R., Wong, R.F. and Saffel, J.T. (2002) A refinement to the World Geodetic System 1984 reference frame, Proc. ION GPS 2002, Portland, OR, 24-27 September, 1519-1529.

Morgan, P.J. (1992) An analysis of the Australian Height Datum: 1971, *The Australian Surveyor*, 37(1), 46-63.

Morgan, P., Bock, Y., Coleman, R., Feng, P., Garrard, D., Johnston, G., Luton, G., McDowall, B., Pearse, M., Rizos, C. and Tiesler, R. (1996) A zero order GPS network for the Australian region, Unisurv Report S-46, The University of New South Wales, Sydney, Australia.

NIMA (2004) Department of Defense World Geodetic System 1984: Its definition and relationships with local geodetic systems, Technical Report TR8350.2, http://earth-info.nga.mil/GandG/publications/tr8350.2/tr8350_2.html (viewed 30 Apr 2009).
Nievinski, F.G. and Santos, M.C. (2007) An analysis of errors introduced by the use of transformation grids, in: Tregoning, P. and Rizos, C. (Eds.) *Dynamic planet*, IAG Symp. Vol. 130, Springer, Berlin, 677-684.
NSW Department of Lands (2008a) DatumTran software, http://www.lands.nsw.gov.au/survey_maps/geodesy/gda/datumtran_software (viewed 30 Apr 2009).
NSW Department of Lands (2008b) GDA – Seven parameter method transformation, http://scims.lands.nsw.gov.au/transform.html (viewed 30 Apr 2009).
Pollard, J. (2002) Iterative vector methods for computing geodetic latitude and height from rectangular coordinates, *Journal of Geodesy*, 76, 36-40.
Redfearn, J.C.B. (1948) Transverse Mercator formulae, *Empire Survey Review*, 69, 318-322.
Rizos, C. (1997) *Principles and practice of GPS surveying*, Monograph 17, School of Geomatic Engineering, The University of New South Wales, Sydney, Australia.
Roelse, A., Granger, H.W. and Graham, J.W. (1971) The adjustment of the Australian levelling survey 1970-1971, Technical Report 12, Division of National Mapping, Canberra, Australia.
Seemkooei, A.A. (2002) Comparison of different algorithms to transform geocentric to geodetic coordinates, *Survey Review*, 36(286), 627-633.
Soler, T. (1998) A compendium of transformation formulas useful in GPS work, *Journal of Geodesy*, 72, 482-490.
Steed, J. (1990) A practical approach to transformation between commonly used reference systems, *The Australian Surveyor*, 35(3), 248-264 and 35(4), 384.
Steed, J. and Luton, G. (2000) WGS84 and the Geocentric Datum of Australia 1994, Proc. ION GPS 2000, Salt Lake City, UT, 19-22 September, 432-437.
Swift, E. (1994) Improved WGS84 coordinates for the DMA and Air Force GPS tracking sites, Proc. ION GPS-94, Salt Lake City, UT, 20-23 September 1994, 285-292.
Torge, W. (2001) *Geodesy*, 3rd ed., de Gruyter, Berlin.
True, S.A. (2004) Planning the future of the World Geodetic System 1984, Proc. IEEE PLANS 2004, Monterey, CA, 26-29 April, 639-648.
Vaniček, P. and Krakiwsky, E.J. (1986) *Geodesy: The concepts*, 2nd ed., North Holland, Amsterdam.

BRIEF BIOGRAPHY OF PRESENTER

Volker Janssen is a GNSS Surveyor (CORS Network) in the Survey Infrastructure and Geodesy branch at the NSW Department of Lands in Bathurst, Australia. He holds a Dipl.-Ing. (MSc) in Surveying from the University of Bonn, Germany, and a PhD in the field of GPS Surveying from the University of New South Wales (UNSW). He has worked as an assistant lecturer at UNSW and a graduate surveyor in Sydney before being employed as a Lecturer in Surveying and Spatial Sciences at the University of Tasmania between 2004 and 2009. Volker's research interests lie in the fields of geodesy and geodynamics, with an emphasis on GPS/GNSS studies and CORS networks.