Dynamic Datum Transformations in Australia and New Zealand

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Abstract

Dynamic datums, which account for crustal dynamics, are widely used in Australia and New Zealand, although in many cases users may not be aware that they are using such a datum. The most widely-used global dynamic datums in Australia and New Zealand are the International Terrestrial Reference Frame (ITRF) and the World Geodetic System 1984 (WGS84). The use of WGS84 presents particular challenges, as it cannot be directly accessed at the sub-metre level by most spatial professionals. The relationship between WGS84 and ITRF is explored in detail, leading to recommendations on how users should deal with WGS84 datasets. New Zealand and Australia have taken different approaches to modelling the relationship between global dynamic datums and their local geodetic datums. Australia has calculated a set of local transformation parameters, which incorporate tectonic movements. New Zealand has adopted a set of global parameters, and uses a deformation model to account for crustal dynamics. As both countries seek to modernise their geodetic datums, the availability of simple yet accurate transformations will be critical to the success of the modernisation process. This paper outlines the options for dynamic datum transformations within a modernised datum, discussing the strengths and weaknesses of each approach.

1 Introduction

Global positioning technologies have driven a profound change in the way in which geospatial data is collected and referenced. There is an ongoing shift away from relative measurements, made in local coordinate reference systems, to absolute positioning, made in terms of global coordinate reference systems. Global Navigation Satellite Systems (GNSS), of which the U.S. Global Positioning System (GPS) is the most widely used, provide positions in a global geocentric reference frame. Such positions may be regarded as three-dimensional position vectors originating at the centre of mass of the Earth, and terminating at the physical feature or point being measured with the GNSS device.

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The points being measured are attached to the surface of the Earth, which is continually moving due to crustal dynamics and other localised deformations. Thus if a point is regularly re-measured, its coordinates will change to reflect the reality that the point's relationship to the centre of the Earth has changed due to crustal dynamics. A reference frame or datum which enables this changing position to be tracked is referred to as 'dynamic'.

The two most widely used global dynamic reference frames in Australia and New Zealand (and much of the rest of the world) are the International Terrestrial Reference Frame (ITRF) and the World Geodetic System 1984 (WGS84). There are in fact a number of versions (or realisations) of each of these reference frames, and correct management of the various realisations is critical for high-precision positioning applications.

It is common practice for individual countries or geographic regions to define their own geodetic datums. These datums are often mandated for use in activities such as national mapping and cadastral surveying. Even where their use is not mandated, the national datum is usually the most appropriate reference frame to use for geospatial data, as that data is then easily integrated or compared with other datasets using the same datum. For Australia the national datum is the Geocentric Datum of Australia 1994 (GDA94) (ICSM, 2013a). This is a static datum aligned to ITRF92 at epoch 1994.0. For New Zealand, the national datum is New Zealand Geodetic Datum 2000 (NZGD2000) (Blick, 2003). NZGD2000 is referred to as a 'semi-dynamic' datum, as it incorporates a deformation model to refer measurements and coordinates to a common epoch. It is aligned with ITRF96 at epoch 2000.0.

GNSS measurements are often made in terms of a global reference frame, but presented as a derived final product in terms of the national geodetic datum. An important component of a nation's positioning infrastructure is the determination and maintenance of transformations from commonly used global reference frames to the national geodetic datum. A coordinate transformation is a mathematical operation that enables coordinates expressed in one reference frame (or datum) to be represented in terms of another (ISO, 2008). It is distinguished from coordinate propagation, which enables coordinates referenced to a particular epoch to be represented at another epoch, within the same reference frame. Official transformations in New Zealand and Australia focus on the relationship between the various ITRF realisations and the national datum. Conversely, despite the widespread use of WGS84, transformation parameters from WGS84 coordinates to the national datums are generally not widely known. This is due to factors such as the inaccessibility of WGS84 as a reference frame for sub-metre positioning (since there is a lack of accurate WGS84 ground control for relative positioning), and the consequent relatively high uncertainties associated with WGS84 datasets. Nevertheless, accurate transformations between WGS84 realisations and national datums can be determined via the relationship between ITRF and WGS84. For some datasets, knowing these transformations may be important.

The concept of 'uncertainty' is an important, but often overlooked, aspect of coordinate transformations. When considering positioning in terms of global reference frames, uncertainty of Cartesian coordinates is the relevant measure. This concept is referred to as 'positional uncertainty' in Australia (ICSM, 2013b), and 'network accuracy' in New Zealand (LINZ, 2009). There is usually little value in performing a transformation if the accuracy of a geospatial dataset is low, and consequently the uncertainty of the coordinates is substantially greater than the coordinate change determined from those transformation parameters. On the other hand, the uncertainty resulting from the process of the transformation itself is also rarely accounted for (Haasdyk & Janssen, 2011), and more attention will need to given to this process as measurements and datums improve in accuracy.

This paper describes the dynamic global reference frames used in Australia and New Zealand, with a focus on WGS84, which is widely used but frequently misunderstood. It reviews the transformation parameters used in both countries between ITRF and the national datum, extending these for use with WGS84 datasets. Finally, as both Australia and New Zealand work towards modernisation of their national datums, options for dynamic datum transformations are considered in terms of future trends in positioning and geodetic datums.

2 The International Terrestrial Reference Frame (ITRF)

The International Earth Rotation and Reference Systems Service (IERS) is responsible for the maintenance and development of the International Terrestrial Reference Frame (ITRF), upon which all modern national geodetic datums are based. A reference frame is a realisation, according to a set of agreed conventions (Petit and Luzum, 2010), of the idealised International Terrestrial Reference System (ITRS).

A terrestrial reference system is one which is co-rotating with the Earth about a conventional pole (ibid, 2010). Various models are applied to remove the impact of phenomena such as ocean loading and earth tides, with the effect that the coordinates of a point on the Earth's surface do not change in response to these geophysical effects (ibid, 2010). The reference system needs to be very stable for monitoring long-term global phenomena such as sea-level change.

The latest realisation of the ITRF is ITRF2008 (Altamimi *et al*., 2011). A realisation of ITRF produces estimates of station coordinates and linear velocities for hundreds of stations worldwide. ITRF is now stable at the centimetre-level or better (ibid, 2011). Transformation parameters between the two most recent realisations of the ITRF (ITRF2008 and ITRF2005) are at the sub-centimetre level, a level of agreement which is likely to continue (or improve) for future realisations.

There is also a global tectonic plate model published in conjunction with ITRF2008 (Altamimi *et al*., 2012) which may be used to propagate coordinates between epochs using the defined Euler pole for 14 major tectonic plates. This model is a No-Net-Rotation (NNR) model derived from the station velocities published for ITRF2008, which aligns the orientation of all ITRFs to each other, and to the available geophysical models. Such a plate motion model works well for most of the Earth, where it is assumed that tectonic plates are non-deforming (that is, they are rigid plates that rotate about a point). This assumption is not valid near plate boundaries, which is the case for New Zealand, or where high accuracy over large distances is required, which is the case for all national geodetic datums. Both New Zealand and Australia have their own models for propagating coordinates, and do not directly use the ITRF2008 plate motion model.

The majority of users access the ITRF through GNSS technology, and associated products and services. The most precise products (such as satellite orbits) are produced by the International GNSS Service (IGS). The IGS produces its own ITRF-aligned reference frame, the current realisation being aligned to ITRF2008 and denoted IGb08 (IGS, 2010). The high degree of alignment between these frames means that they can be considered identical for all but the highest precision geodetic applications.

3 The World Geodetic System 1984 (WGS84)

The term 'WGS84' is one of the more ambiguous in global geodesy, which sometimes leads to confusion about the exact nature of this datum. Firstly, depending on context, WGS84 may refer to a reference system, a reference frame or a reference ellipsoid, which are each defined in more detail below. Secondly, even where it is clear from the context that it is the reference frame WGS84 which is the subject of discussion, the fact that there have been several different WGS84 reference frames is often not made clear. In general all are simply referred to as 'WGS84'.

WGS84 is managed by the National Geospatial Intelligence Agency (NGA), formerly the National Imagery and Mapping Agency (NIMA), which was itself the successor to the Defense Mapping Agency (DMA). The DMA was responsible for developing the WGS84 reference system and for the initial reference frame realisation.

3.1 WGS84: the reference system

The WGS84 reference system is designed to coincide as closely as possible with the ITRS (NIMA, 2000). The origin is the centre of mass of the Earth, scale is that of the local Earth frame (in the sense of the theory of general relativity) and initial orientation was consistent with that defined by the Bureau International de l'Heure (BIH) in 1984. The evolution of the orientation in time is such that there is no overall rotation of the system with respect to the Earth's surface (NIMA, 2000).

WGS84 is a right-handed, orthogonal reference system. Its X-axis is consistent with the IERS Reference Meridian (which is approximately equal to the Greenwich Meridian), the Z-axis is coincident with the IERS Reference Pole (which is approximately the geographical North Pole), and the Y-axis is oriented at ninety degrees with respect to the other two axes (NIMA, 2000).

It is the consistency of definition between the WGS84 and ITRS reference systems which results in the high levels of consistency between coordinates realised in the WGS84 and ITRF reference frames.

3.2 WGS84: the ellipsoid

The WGS84 ellipsoid is a reference surface approximating the size and shape of the Earth. Its origin is the centre of mass of the Earth, and it is formed by rotating an ellipse about the Z-axis. It is almost identical to the Geodetic Reference System 1980 (GRS80) ellipsoid associated with the ITRF. The slight difference in flattening is due to a truncation during the computation of the WGS84 flattening value, but is insignificant for all but the highest precision geodetic applications (NIMA, 2000). The difference in ellipsoidal heights calculated using the two ellipsoids is a maximum of just 0.1mm, at the poles. Table 1 lists the key parameters of the two ellipsoids.

Table 1: GRS80 and WGS84 ellipsoid parameters

Ellipsoid	Semi-major axis (m)	Inverse flattening
GRS80	6 378 137 m	298.257 222 101
WGS84	6 378 137 m	298.257 223 563

3.3 WGS84: the reference frames

A WGS84 reference frame is a realisation of the WGS84 reference system through the defined coordinates (and more recently, velocities) for a set of reference stations (Wong *et al*., 2012). These reference stations and their coordinates are then used for applications such as calculating the orbits of GPS satellites. It is through orbital products such as the GPS broadcast ephemeris that the geospatial community is able to access the WGS84 reference frame. As at the start of 2014, the current realisation of the WGS84 system is the fifth such realisation.

The first realisation is the only one officially denoted as 'WGS84'. To avoid confusion, in the remainder of this paper, we denote this first WGS84 reference frame as 'WGS84(Doppler)', since it was based on the TRANSIT Doppler system, the predecessor positioning system to GPS. Each subsequent WGS84 realisation is distinguished by appending the GPS week in which the reference frame was implemented (NIMA, 2000). For example, the current realisation is denoted 'WGS84(G1674)', as it was implemented by the GPS Operational Control Segment (OCS) on 8 February 2012, which is GPS Week 1674 (Wong *et al*., 2012).

Wong *et al* (2012) provide full details of the current WGS84 realisation. This was aligned to ITRF2008 through direct adoption, where possible, of ITRF2008 coordinates published by the IERS for 11 WGS84 monitor stations distributed around the globe. Corrections were made to account for discontinuities due to activities such as equipment maintenance. For two stations, BHR2 in Bahrain and OSN1 in South Korea, the ITRF2008 coordinates could not be constrained without introducing large residuals, so these stations had new coordinates calculated. New coordinates were also calculated for the six United States Air Force sites which comprise the OCS. Velocities for the monitor stations were adopted from the ITRF2008 solution. For the OCS stations, velocities were adopted from a nearby International GNSS Service (IGS) station.

Table 2 summarises each of the five WGS84 reference frame realisations, indicating that since 2002 the positional uncertainty of the reference frame relative to the ITRF is about one centimetre, estimated based on the magnitude of similarity transformation parameters calculated between the ITRF and WGS84 precise orbits.

Table 2: WGS84 reference frames 1987-2013

Reference Frame	**Implementation Date (OCS)**	**Reference Epoch**	**Positional Uncertainty (m) (1-sigma) Relative to ITRF2008**	**Reference**
WGS84(Doppler)	1987, 1 January	NA	1.50	NIMA (2000)
WGS84(G730)	1994, 29 June	1994.0	0.10	NIMA (2000)
WGS84(G873)	1997, 29 January	1997.0	0.05	NIMA (2000)
WGS84(G1150)	2002, January	2001.0	0.01	Merrigan *et al*. (2002)
WGS84(G1674)	2012, 8 February	2005.0	0.01	Wong *et al*. (2012)

3.4 WGS84: An operational dynamic datum

WGS84 is probably the most widely used global reference frame. This popularity stems from its use as the reference frame for GPS orbits – the broadcast ephemeris used for GPS single point positioning. The reference frame of the GPS orbit determines the reference frame of the user position for this type of absolute positioning. On the 1 January each year, the coordinates of the GPS master control stations are propagated to an epoch in the middle of the year, and GPS satellite coordinates are determined relative to these master stations. Thus WGS84 coordinates determined by GPS single point positioning are related to the epoch of the middle of the calendar year in which the observations are made (ICG, 2012), not the reference epoch for the realisation. Thus a full reference for a dataset collected using GPS single point positioning during 2013 would be *WGS84(G1674) Epoch 2013.5*.

The dynamic nature of WGS84 is typically ignored by users who fail to account for the WGS84 reference frame realisation or the epoch of their derived coordinates in their metadata. Indeed it is practically impossible to rigorously reference WGS84 (and other dynamic datums) in most commonly used software packages. In the case of WGS84, ignoring the dynamic details does not usually compromise the data as the positional uncertainties associated with a WGS84 dataset collected via single point positioning are at the metre-level at best.

3.5 The myth of precise WGS84 coordinates

Outside the US military and other authorised users, direct access to sub-metre WGS84 coordinates is almost impossible. The NGA has published coordinates for only 11 tracking stations worldwide, with one in Australia and one in New Zealand (Wong *et al*., 2012). The GPS precise ephemeris data is published, which in theory enables the use of Precise Point Positioning (PPP) to generate centimetre-accurate WGS84 coordinates. In reality though, very few users have the capability to do the required processing.

Within the geospatial community, therefore, one would expect precise datasets that are referenced to WGS84 to be exceedingly rare. This is not the case, largely due to misunderstandings about WGS84 and its role in GPS positioning. Accurate positioning using GPS almost always involves relative pseudorange or carrier phase positioning to achieve accuracies ranging from centimetres to a metre. In these techniques, some of the stations occupied have known coordinates, and it is the datum of these coordinates which determines the datum for the subsequent geospatial dataset. In Australia the datum would typically be GDA94, in New Zealand, NZGD2000. While many of these techniques do use the broadcast ephemeris during processing, it is not used as a source of coordinates, so does not determine the datum of the coordinates being generated.

The mislabelling of precise geospatial datasets as WGS84, when they are not WGS84, can cause problems if the data epoch is incorrectly assumed. For example, consider the case where a relative positioning dataset is generated in 2013 from a base station with GDA94 coordinates, but is referenced as WGS84. A future user of the dataset, knowing it was generated in 2013, might reasonably assume that the reference frame is WGS84(G1674) with an epoch of 2005.0 (which is the reference epoch for this particular WGS84 frame) or an epoch of 2013.5 (which is the epoch at which WGS84 coordinates are realised for that year). In fact the epoch for the data is 1994.0, which is derived from the GDA94 coordinates of the base-station, so a coordinate error of up to 0.8 m (due to the 7 cm/year tectonic motion of Australia) is immediately introduced.

A smaller systematic error is caused by the incorrect specification of the reference frame. Using the same example, the difference between WGS84(G1674) and GDA94 is nearly 0.1m in height. These problems are often time-consuming and difficult to identify with confidence. Users should be wary if a dataset is purported to be referenced to WGS84, and positional uncertainties are less than a metre.

Even the definition of WGS84 as a dynamic datum, while technically correct, is misleading in terms of the way users access the datum. From the user perspective, it is a series of epoch reference frames, each of which is at the mid-year epoch as discussed in section 3.4. Thus the 'dynamic' WGS84 coordinates derived from point positioning have up to half a year's worth of error due to tectonic movement in them. While this is not noticeable to users accessing WGS84 via single point positioning, it is further reason not to use WGS84 where precise coordinates are required.

4 Transformations Between ITRF, WGS84 and National Datums

The first WGS84 realisation preceded the first ITRF realisation. All subsequent realisations have been aligned to the ITRF through the use of stations with ITRF coordinates in the realisation of the WGS84 reference frame. The alignment between WGS84 and ITRF in each instance is sufficiently close that the two are considered identical, within the uncertainty of the WGS84 reference frame. Table 3 lists the ITRF reference frames to which successive WGS84 reference frames are aligned.

Table 3: Alignment of WGS84 and ITRF realisations

WGS84 realisation	ITRF realisation
WGS84(Doppler)	Not applicable
WGS84(G730)	ITRF91
WGS84(G873)	ITRF94
WGS84(G1150)	ITRF2000
WGS84(G1674)	ITRF2008

WGS84, by definition, tracks a particular realisation of the ITRF, therefore the official transformation parameters between the national datum and ITRF in each country can be used as a proxy for WGS84 parameters with careful attention being paid to the epoch of the WGS84 coordinates as previously discussed.

4.1 ITRF/WGS84 transformation parameters for New Zealand

The parameters in Table 4 should be used to transform from a particular ITRF or WGS84 reference frame to NZGD2000, which is aligned with ITRF96. To transform between reference frames, the transformation parameters must first be determined at the epoch of transformation, which in many cases will be the epoch of the coordinates being transformed. The parameter T_x at time t (in years) is calculated using:

$$\delta t = t - 2000 \quad (1)$$

$$T_{x,t} = T_x + \delta t.\dot{T}_x \quad (2)$$

The transformation is then carried out using:

XYZNZGD2000=XYZITRF/WGS84+cTTx,tcTTy,tcTTz,t+cSSt−cRRz,tcRRy,tcRRz,tcSSt−cRRx,t−cRRy,tc RRx,tcSStXYZITRF/WGS84(3)

where

c_T = 0.001 (millimetres to metres, applies to T_x, T_y and T_z)
c_S = 1.0×10^{-9} (part-per-billion to ratio, applies to S)
c_R = $\pi/(180\times60\times60\times1000) = 4.84814\times10^{-9}$ (milli-arcseconds to radians, applies to R_x, R_y and R_z)

With one exception, these parameters are derived from those published by the IERS (IERS, 2013). The transformation parameters between ITRF96 and ITRF97 as calculated by the IGS (Soler and Snay, 2004) were used in preference to those specified by the IERS. The IERS had determined that no significant transformation existed between ITRF96 and ITRF97. The calculations by the IGS determined a non-zero transformation, which New Zealand has adopted since NZGD2000 is based principally on GNSS observations. However, at the time of writing, New Zealand is reviewing its use of the IGS values, which could lead to a change in the transformation parameters in Table 4.

Once the transformation has been carried out, the NZGD2000 deformation model would normally be used to propagate the coordinates to the reference epoch (2000.0).

Table 4: Transformations to NZGD2000

	T_x (mm) $\dot{T}_x$ (mm/yr)	**T_y (mm) $\dot{T}_y$ (mm/yr)**	**T_z (mm) $\dot{T}_z$ (mm/yr)**	**S (ppb) $\dot{S}$ (ppb/yr)**	**R_x (mas) $\dot{R}_x$ (mas/yr)**	**R_y (mas) $\dot{R}_y$ (mas/yr)**	**R_z (mas) $\dot{R}_z$ (mas/yr)**	**Reference Epoch**
ITRF2008/ WGS84(G1674)	4.8	2.09	-17.67	1.40901	-0.16508	0.26897	0.11984	2000
rates	0.79	-0.6	-1.34	-0.10201	-0.01347	0.01514	0.01973	
ITRF2005	6.8	2.99	-12.97	0.46901	-0.16508	0.26897	0.11984	2000
rates	0.49	-0.6	-1.34	-0.10201	-0.01347	0.01514	0.01973	
ITRF2000/ WGS84(G1150)	6.7	3.79	-7.17	0.06901	-0.16508	0.26897	0.11984	2000
rates	0.69	-0.7	0.46	-0.18201	-0.01347	0.01514	0.01973	
ITRF97	0	-0.51	15.53	-1.51099	-0.16508	0.26897	0.05984	2000
rates	0.69	-0.1	1.86	-0.19201	-0.01347	0.01514	-0.00027	
ITRF96	0	0	0	0	0	0	0	2000
rates	0	0	0	0	0	0	0	
ITRF94/ WGS84(G873)	0	0	0	0	0	0	0	2000
rates	0	0	0	0	0	0	0	
ITRF93	28.8	0.2	5.4	-0.49	1.71	1.48	0.36	2000
rates	2.9	-0.4	-0.8	0	0.11	0.19	-0.05	
ITRF92	-8	-2	8	0.71	0	0	0	2000
rates	0	0	0	0	0	0	0	
ITRF91/ WGS84(G730)	-20	-16	14	-0.69	0	0	0	2000
rates	0	0	0	0	0	0	0	
ITRF90	-18	-12	30	-0.99	0	0	0	2000

	T_x (mm) $\dot{T}_x$ (mm/yr)	T_y (mm) $\dot{T}_y$ (mm/yr)	T_z (mm) $\dot{T}_z$ (mm/yr)	S (ppb) $\dot{S}$ (ppb/yr)	R_x (mas) $\dot{R}_x$ (mas/yr)	R_y (mas) $\dot{R}_y$ (mas/yr)	R_z (mas) $\dot{R}_z$ (mas/yr)	Reference Epoch
rates	0	0	0	0	0	0	0	
ITRF89	-23	-36	68	-4.39	0	0	0	2000
rates	0	0	0	0	0	0	0	
ITRF88	-18	0	92	-7.49	-0.1	0	0	2000
rates	0	0	0	0	0	0	0	
WGS84(Doppler)	-78	505	253	10.01	-18.3	0.3	-7	2000
rates	0	0	0	0	0	0	0	

4.2 ITRF/WGS84 transformation parameters for Australia

The transformation parameters for Australia have been published in Dawson and Woods (2010). Note that the signs of the rotations in Table 5 have been reversed from those published in Dawson and Woods (2010), so that the values are consistent with Equation (3).

Table 5: Transformations to GDA94

	T_x (mm) $\dot{T}_x$ (mm/yr)	T_y (mm) $\dot{T}_y$ (mm/yr)	T_z (mm) $\dot{T}_z$ (mm/yr)	S (ppb) $\dot{S}$ (ppb/yr)	R_x (mas) $\dot{R}_x$ (mas/yr)	R_y (mas) $\dot{R}_y$ (mas/yr)	R_z (mas) $\dot{R}_z$ (mas/yr)	Reference Epoch
ITRF2008/ WGS84(G1674)	-84.68	-19.42	32.01	9.710	0.4254	-2.2578	-2.4015	1994
rates	1.42	1.34	0.90	0.109	-1.5461	-1.182	-1.1551	
ITRF2005	-79.73	-6.86	38.03	6.636	0.0351	-2.1211	-2.1411	1994
rates	2.25	-0.62	-0.56	0.294	-1.4707	-1.1443	-1.1701	
ITRF2000/ WGS84(G1150)	-45.91	-29.85	-20.37	7.070	1.6705	-0.4594	-1.9356	1994
rates	-4.66	3.55	11.24	0.249	-1.7454	-1.4868	-1.2240	
ITRF97	-14.63	-27.62	-25.32	6.695	1.7893	0.6047	-0.9962	1994
rates	-8.60	0.36	11.25	0.007	-1.6394	-1.5198	-1.3801	
ITRF96	24.54	-36.43	-68.12	6.901	2.7359	2.0431	-0.3731	1994
rates	-21.80	4.71	26.27	0.388	-2.0203	-2.1735	-1.6290	

4.3 International Case Studies

By way of comparison, two international case studies are presented below. The focus is on transformations from ITRF to the national datum, although using Table 3, transformations to and from the various WGS84 realisations could be inferred.

4.3.1 United States

The national datum in the United States is the North American Datum 1983 (NAD83). Like WGS84, this datum was originally based on TRANSIT Doppler observations and consequently is not strictly geocentric, being offset by approximately 2 metres (Soler and Marshall, 2003). NAD83 has been periodically re-realised to enable the incorporation of modern observation techniques such as GNSS, with the most recent realisation being NAD83(2011), which has an epoch of 2010.0 (Pearson and Snay, 2013).

NAD83(2011) is fixed to the North American plate, so that the velocities of stable points are minimised across the country. For most users, such as those working in central and eastern United States, station velocities in this plate-fixed frame are negligible. This allows those users to treat NAD83 as a static datum. For regions such as the western United States and parts of Alaska, the proximity to the plate boundary means that a simple plate motion model cannot accurately account for the more complex motions present. For these areas, more complex displacement models, including models which account for earthquakes, are required (Pearson and Snay, 2013).

Transformation parameters from ITRF96 to NAD83 were defined jointly by Canada and the United States using 12 Very Long Baseline Interferometry (VLBI) stations with coordinates in each datum. The NUVEL-1A plate motion model (De Mets et al, 1994) was used to determine the rotations for the North American plate (Soler and Snay, 2004). The IGS transformation is used from ITRF96 to ITRF97, but for all subsequent realisations of ITRF, the transformation parameter values published by the IERS are used. The total transformation from ITRF2008 to NAD83 is obtained by addition of these individual sets of transformation parameters (Pearson and Snay, 2013). This is identical to the approach currently taken in New Zealand, except that NZGD2000 is by definition aligned to ITRF96.

4.3.2 Great Britain

The national mapping datum for Great Britain is Ordnance Survey Great Britain 1936 (OSGB36). This is a local datum, with its ellipsoid positioned to best fit the Earth's surface over the landmass of Great Britain. Consequently, the fit to the Earth as a whole is relatively poor with the origin of OSGB36 being offset from the geocentre by over 700 metres. For high precision positioning applications, the official datum is the European Terrestrial Reference Frame 1989 (ETRF89), which is a realisation of the European Terrestrial Reference System 1989 (ETRS89). ETRF89, along with all subsequent ETRF realisations is fixed to the stable part of the Eurasian plate, in much the same way as NAD83 is fixed to the North American plate. This enables users to ignore the effects of tectonic plate motion (Ordnance Survey, 2013).

To transform from ITRF to OSGB36 requires that the coordinates first be transformed to ETRF89. This is achieved using the procedure recommended by the IAG Subcommission for the European Reference Frame (EUREF), as outlined in Boucher and Altamimi (2011). It involves a two-step procedure. Firstly, IERS-published published parameters are used to transform from the ITRF realisation of the coordinates to ITRF89. Secondly, three rotation rates (which account for plate motion) are applied to transform from ITRF89 to ETRF89.

Because OSGB36 is based on triangulation, distortions in the network mean it is not possible to transform coordinates from ETRF89 using a 7-parameter transformation to any better than 5 metres. Therefore, a gridded displacement model is used for this transformation (Ordnance Survey, 2013).

4.4 Differing approaches to dynamic datum transformations

Inspection of Tables 4 and 5 reveals substantial disparities in the numerical values used in Australia and New Zealand, which cannot be solely attributed to the different versions of ITRF and epochs to which each national datum aligns. These disparities are mainly due to the different approaches taken by New Zealand and Australia to define their official transformation parameters.

The New Zealand parameters keep the process of reference frame transformation quite separate from the process of coordinate propagation. Propagation of coordinates to or from the reference epoch of 2000.0 is achieved using the NZGD2000 deformation model.

In contrast, Australia has calculated a localised set of transformation parameters between ITRF and GDA94 which are only applicable on the Australian tectonic plate (Dawson and Woods, 2010). Transformation and propagation are carried out in a single process enabling ITRF/WGS84 data at any epoch to be transformed to GDA94 using a 14-parameter transformation. Note that a standard 14-parameter transformation assumes the same data epoch for both the input and output coordinates, but the Australian transformation is quite unique in that the GDA94 coordinates always refer to 1994.0. A user may validly choose to propagate their ITRF coordinates to epoch 1994.0 (e.g. using the ITRF2008 plate motion model) before or after the ITRF to GDA94 transformation, but will notice coordinate differences of up to 20 mm compared to a direct transformation at the current epoch (Haasdyk & Janssen, 2011).

The Australian continent is extremely stable, with very little relative deformation across its landmass. Thus the fourteen-parameter transformation is able to accurately incorporate the national-scale plate motion. From the user perspective, there is no need to utilise a deformation model and some geospatial software packages can handle fourteen-parameter transformations. Those that cannot perform a 14 parameter transformation usually at least have the capacity to carry out seven-parameter transformations, giving the user the opportunity to enter the appropriate seven-parameter values for the epoch at which the transformation is required.

This approach would not work well in New Zealand. Even at a national scale there is significant relative deformation that would not be modeled adequately using a simple fourteen-parameter transformation for coordinate transformation and propagation. Thus it is necessary to separate the processes of coordinate transformation and propagation. Currently, the lack of support for the deformation model in commercial software makes its use impractical for many users, who continue to rely on a dense network of passive marks which they can use to calculate local transformations to account for deformation.

The case studies of the United States and Great Britain further highlight the variation in transformation approaches, to reflect local circumstances. While crustal dynamics can be simply handled in Great Britain (as in Australia), the continued use of a local geodetic datum based on terrestrial measurements means that accurate transformations to geocentric datums requires the use of a gridded model. The United States has taken the approach of satisfying the current desire of most users for a static datum by fixing NAD83 to the North American Plate, while still providing the necessary means for users in areas of significant deformation to accurately transform coordinates.

5 Transformation Options for Modernised National Dynamic Datums

Both New Zealand and Australia are investigating how best to modernise their datums so that they continue to support high accuracy positioning in each country. In Australia's case a new dynamic datum is proposed, to be released in approximately 2020. For New Zealand, modernisation may occur within the framework of the existing datum which already accounts for dynamics, or a new datum may be developed. For both countries, accurately representing the dynamics of the Earth's surface will be a key challenge, as will maintaining compatibility with international systems.

The development of modernised datums will follow established international conventions and utilise accepted global models, such as those specified in the IERS conventions (Petit and Luzum, 2010). This will ensure maximum consistency with preferred positioning methodologies such as GNSS, which also follow these conventions. As well as providing consistency, the use of established conventions and models provides a level of traceability to a datum, which flows to the positions derived.

5.1 Option 1: Local 14 parameter transformation, including national-scale tectonics, plus residual deformation model

This is an enhancement of the approach already implemented for GDA94. Currently GDA94 assumes that the Australian continent is stable and that coordinates do not change over time.

This option assumes that any future dynamic datum retains a single reference epoch. In this option, a 14-parameter transformation continues to be provided that includes both the reference frame transformation and propagation between ITRF and GDA, and between the epoch of the dataset and the reference epoch. A gridded deformation model can then be used to account for the residual deformation, which is not included in the 14-parameter transformation. Most users will only need to use the simpler and more widely supported 14-parameter transformation.

For New Zealand, such an approach is unlikely to provide a practical solution. Even national-scale deformation is so complex that the size of the residual deformation would be significant for most geospatial applications. Thus both the 14-parameters and the deformation model would need to be applied in the majority of cases.

In Australia, by contrast, the stable tectonic setting means that the residual deformation field will be insignificant for many applications, although it is noted that in the future, the accuracy demands of many applications is likely to increase as centimetre-level absolute positioning becomes mainstream. Applications that only require decimetre-level accuracy could continue to use the 14-parameter transformation, as they do currently. This option may present the simplest approach for a large proportion of Australian spatial users.

Disadvantages of this approach for Australia is that it may not be favoured internationally, as a number of countries are at least partially straddling plate boundaries (although 94% of the Earth's surface lies within the stable portion of a tectonic plate). In practical terms this may not matter, given that software needs to handle 14-parameter transformations for global reference frame transformations.

5.2 Option 2: Global 14 parameter transformation, excluding national-scale tectonics, plus deformation model

This is the approach currently used for NZGD2000.

The use of global transformation parameters provides the maximum level of consistency with, and traceability to, global standards and conventions, an important consideration for a national datum, particularly one which aims to support the use of global positioning technologies.

A future dynamic datum may use all available global ITRF stations in its processing, following the approach taken by regional reference frames such as the Asia-Pacific Reference Frame (APREF) (Haasdyk *et al.*, 2014). At the very least it will include a substantial subset of global stations distributed over a significant proportion of the globe. If this is the case, then the future national datum is explicitly aligned to a global network of stations. Logically therefore, a globally determined set of transformation parameters is appropriate.

With this approach, coordinate propagation is handled in totality by a deformation model, maintaining complete separation between transformation and propagation. The current disadvantage of this approach is that most software does not have the capacity to incorporate deformation models. This situation is likely to change in the coming years as the necessity for incorporating deformation models to fully utilise accurate geospatial data is better understood.

5.3 Option 3: Local 14 parameter transformation, excluding national-scale tectonics, plus deformation model

This is similar to Option 2, the difference being that rather than using a published set of parameters from the IERS, a local set is calculated using the ITRF stations in each country. The difference from Option 1 is that the 14 parameters are only accounting for the reference frame transformation – tectonic motion is accounted for by the deformation model. The advantage of this approach is that it enables any regional biases in ITRF to be accounted for in the transformation, increasing the alignment of the coordinates generated by the transformation with the ITRF stations in the region. However, the improving precision of successive realisations of the ITRF should make the calculation of local parameters unnecessary. Any local discrepancies are likely to be due to deformation not fully accounted for in the ITRF, which is more properly included within a deformation model. An example of such a local discrepancy is the 4 mm per year average residual rotation rate identified in Australia when comparing the ITRF plate motion model with the recently released NNR-MORVEL56 model (Altamimi *et al*, 2012).

It would still be worth calculating a local set of transformation parameters before making a decision against this option, to prove that they are not significantly different from the global parameters.

5.4 Option 4: Deformation model only

This option combines propagation and transformation in a variable resolution grid of site velocities and offsets. Stanaway and Roberts (2013) discuss this option in detail. A key advantage of this option is that coordinate transformation and propagation are combined, yet the full range of non-secular deformation can be included. Consequently, loss of precision when propagating uncertainty is minimised. If Australia were to define a refined GDA94, such a model would enable the propagation of these refined GDA94 coordinates with an uncertainty of 6 mm at the 95% confidence level (Stanaway and Roberts, 2013).

For New Zealand, this option has similar advantages, albeit that the more complex nature of the country's deformation compared with Australia means that sub-centimetre propagation uncertainties are not realistic. Given that New Zealand already utilises a deformation model, it would not be a major change to amend this model to incorporate components for reference frame transformation.

As for the other options involving deformation grids, the biggest disadvantage to this approach at the current time is the inability of software to support these models.

5.5 Option 5: Reduced parameter sets

Other options could involve variations in the number of parameters used in a transformation/propagation model. For example, a three-parameter transformation of three rotations and the reference epoch could be used to propagate coordinates to the geodetic datum. In this scenario, scale and translations are assumed to be null. With options such as this, increased simplicity is being traded off against decreased precision. For applications that only require limited precision, the accuracy provided by simpler options is likely to be perfectly adequate. Once again, this is particularly relevant for Australia, given its stable tectonic setting.

One issue with this approach is that it will not provide the precision required for more demanding applications, such as engineering or geodetic surveying. Therefore, this option would need to be combined with one of the options discussed above. Having multiple transformation options requires more care from users to record appropriate metadata, so that any transformation applied can be confidently reversed.

6 Concluding Remarks

As it becomes easier to acquire centimetre-accurate geospatial datasets in terms of global reference frames, it is important that reference frame transformations are handled correctly. For dynamic datums this means that the propagation of coordinates between epochs must also be carried out in addition to the transformation itself. While the concept of a dynamic datum may appear new, they are in fact widely used in Australia and New Zealand already, through the global reference frames WGS84 and ITRF. For WGS84 in particular, reference frame transformations are not carried out in a rigorous manner. In many cases this does not matter, due to the relatively high levels of uncertainty present in most WGS84 positions. However, transformation parameters have been recommended in this paper to enable rigorous transformations where they are required. These transformation parameters assume the close alignment of WGS84 with the ITRF. With the increasing prominence of multi-GNSS positioning, users are encouraged to use ITRF as their reference frame in preference to WGS84. ITRF is more accessible, with all global positioning technologies being aligned to it. In addition, the application of epoch is much more transparent and easier to understand for ITRF. The differences in the ITRF/WGS84 transformation parameters between Australia and New Zealand reflect the different approaches taken by each country to transformations between ITRF and their national datum. These differences are primarily due to the highly stable tectonic setting in Australia, contrasted to the relatively unstable plate tectonics in New Zealand.

Both countries are actively investigating datum modernisation through implementation of a dynamic datum (Australia) or improvements to the current semi-dynamic datum (New Zealand). Options for dynamic datum transformations have been considered. There may be advantages to separating transformation from propagation, and utilising globally-determined transformation parameters. There may also be advantages to using a gridded model to handle both transformation and propagation of coordinates. However, a solution that might be preferable from a geodetic perspective may not be the simplest approach for users of the datum. For this reason, Australia will probably continue to advocate the use of 14-parameter transformations, at least as a transitional measure until commonly used software can utilise deformation models. The final determination of a preferred method for dynamic datum transformations will need to be made considering the current state of ITRF and available user tools at the time a new datum is promulgated.

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