# Options for Modernising the Geocentric Datum of Australia


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## Abstract

Instantaneous, reliable and fit-for-purpose positioning and time services across Australia are the aims of the National Positioning Infrastructure policy. Indeed, it is already possible to achieve centimetre-level positioning almost anywhere (outdoors) and anytime, following advances in positioning technologies over the last few decades. Not surprisingly, this capability has highlighted limitations and distortions in the current Geocentric Datum of Australia 1994 (GDA94) which was not designed to support positioning at this level of accuracy. A 'next-generation' datum or 'Australian Terrestrial Reference Frame' is currently being prepared which will remove the known distortions of the current datum realisation, create a homogenous 3-D datum across Australia based on permanent GNSS datum stations, be adaptable and flexible by incorporating new measurements and technologies as they become available, and assign realistic uncertainties to coordinates. Importantly, this datum will include a comprehensive deformation model to account for real-world dynamics which GDA94 currently ignores, such as the metre-level differences between our maps and mobile positioning devices due to tectonics, earthquakes, ground subsidence and localised deformation. This paper presents the technological progress towards this new datum, reports on recent user-needs assessments across Australia, discusses several options for the final realisation of the modernised datum, and discusses future research required to achieve a fully dynamic datum. While focused on the Australian datum, much of what is presented is also applicable to the modernisation of national and international datums across the globe.


## 1 Introduction

The purpose of this paper is to investigate the advantages and disadvantages of various options for the development of a modernised Australian datum or 'Australian Terrestrial Reference Frame' (ATRF). Such a modernised datum is required as a framework for the capture and comparison of modern survey, geodetic and other spatial data. These spatial data are collected at discrete epochs but represent an earth which is changing at rates which exceed current measurement precision. With significant improvements in positioning technology now enabling centimetre-level positioning capability via techniques such as Network Real Time Kinematic (NRTK) and Precise Point Positioning (PPP) (Janssen *et al*., 2011; Rizos *et al*., 2012), and decimetre-level accuracy or better soon available to the mass-market (Gakstatter, 2013a), the need to 'modernise' the geodetic datum is once again inevitable.



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The recent history of Australian datums demonstrates that, even on a relatively stable tectonic plate, improvements in positioning technology and changes in user accuracy requirements have driven datum updates on an approximately decadal time scale. The recent widespread establishment of Continuously Operating Reference Stations (CORS) which permanently gather range data to the satellites of Global Navigation Satellite Systems (GNSS) has highlighted distortions in the existing realisation of the Geocentric Datum of Australia 1994 (GDA94) and metre-level offsets from international datums such as the International Terrestrial Reference Frame (ITRF) and navigational systems such as the World Geodetic System (WGS84) (Haasdyk & Watson, 2013; Dawson & Woods, 2010, Altamimi *et al*., 2011, Donnelly *et al*., 2013).

Improvements in computing power and geodetic adjustment software mean that it is now possible to compute, on a daily basis, a rigorous national adjustment of all available measurements, incorporating new measurements and new positioning technologies immediately when they become available. As a result, survey control station coordinates (including those of CORS) which are used to realise the datum could conceivably change with a reasonably high frequency to reflect real-world dynamics including tectonic motion and episodic deformation (e.g. localised ground subsidence), as well as improvements in coordinate and uncertainty estimation.

The assumption that 'static' unchanging coordinates are sufficient for most spatial data users is being challenged, but users are understandably reticent to describe a locally 'stable' physical feature using 'dynamic' coordinates which change over time. However, it has been demonstrated that localised as well as large-scale deformation exists across Australia (e.g. Ng *et al*., 2010; Featherstone *et al*., 2012; Tregoning *et al*., 2013). Many users also create new spatial datasets in WGS84 (if using GPS broadcast satellite orbits), or in the latest ITRF, currently ITRF2008, (if using precise satellite orbits), in which coordinates of 'stable' physical features *do* change over time. Unfortunately, many users do not understand the implications of these datum differences and fail to apply the necessary transformations to their data, resulting in significant data inaccuracies (Gakstatter, 2013b; Donnelly *et al*., 2013).

The goal of datum modernisation is to supply all users with the most complete yet most straightforward datum products which can define a locally consistent set of coordinates, such that their positioning device agrees with the physical world and associated spatial data to an acceptable level of accuracy. In this context, this paper explores options for datum modernisation which are nominally for application in Australia, but which are relevant for datum modernisation across the globe. Particular attention is given to minimising the risks and costs associated with frequent coordinate conversions, while exploring the benefits of maintaining a 'dynamic datum' in close alignment with the reference frame(s) used to define the GNSS satellite orbits, especially for the growing group of mass-market users who tend to be unaware of datum issues.

### 1.1 Defining a Dynamic Datum

Geodetic datums can be classified as either 'static', in which the coordinates of locally stable physical features do not change over time, as 'dynamic' (also 'fully-dynamic'), in which coordinates of physical features change continuously (i.e. in real-time) usually to reflect movement in a global context, or as 'semi-dynamic', in which coordinates are officially defined at a particular date or 'reference epoch' but dynamics are catered for via application of a deformation model. (e.g. Blick *et al*., 2009; Stanaway *et al*., 2011). The word 'kinematic' is also frequently used interchangeably with 'dynamic' in many texts.

In the case of both the 'dynamic' and 'semi-dynamic' datum, a deformation model is explicitly defined as part of the datum, providing for official and traceable propagation of coordinates (and measurements) between epochs. Deformation models generally consist of the velocity of rigid tectonic plates, and/or of discrete points representing site-specific motion in the region, and in some cases also define a series of episodic deformation events such as earthquakes or subsidence. The motion of any local station or feature can therefore be interpolated from this model.

In contrast, a 'static' datum is completely insensitive to any secular or deformation information, and defines only the coordinates of physical features as they were at a certain point in time. For example, GDA94 is a 'static' datum, with coordinates defined relative to the ITRF92 at epoch 1994.0. The fact that the Australian continent undergoes tectonic motion is simply disregarded in the definition of GDA94, and therefore GDA94 coordinates do not change over time.

To be explicit in this definition, it is noted that dynamic datums are actually constant in their definition: ITRF for example, is known as a dynamic datum, but the origin of the datum is defined as the centre of mass of the Earth, with the X, Y, and Z axis orientation strictly defined with respect to conventional international agreement (Altamimi *et al*., 2011; Petit & Luzum, 2010). These axes can be thought of as rotating with the Earth and do not change in response to surface deformations. On the surface of the Earth, however, tectonic plates move at rates which can be observed by modern positioning technologies; it is, in fact, the tectonic plates that are moving *within* the constant ITRF and therefore the coordinates expressed in ITRF change with time. The whole purpose of a dynamic datum is to define a stable reference frame against which one can monitor and describe long-term global phenomena such as sea-level change or global mass redistribution.

### 1.2 The Current Geocentric Datum of Australia

The current Geocentric Datum of Australia, GDA94, was defined by the Australia and New Zealand Intergovernmental Committee on Surveying and Mapping (ICSM) as Australia's first geocentric datum (ICSM, 2006; ICSM, 2013a). The purpose of defining GDA94 was to align Australia's datum and mapping with new satellite geodetic technologies and to correct distortions of up to 6 metres which had been detected by these technological advances (Featherstone, 2013). For all practical purposes, this static GDA94 datum was compatible with GPS and ITRF at the time of implementation.

To form the link to the global reference frames in which the satellite orbits are determined, the coordinates of eight permanent stations of the Australian Fiducial Network (AFN) were defined in three dimensions using GPS, in the most rigorous datum then available – the International Terrestrial Reference Frame 1992 (ITRF92) – at epoch 1994.0 (ICSM, 2006). Uncertainties at the AFN were determined to be approximately 30 mm (horizontal) and 50 mm (vertical) (95% confidence interval (CI) – Dawson & Woods, 2010). Additional ground control (horizontal only) were then adjusted in a hierarchy, in regional sections due to computational limitations, holding higher order control stations fixed, making it necessary to estimate rather than compute absolute positional uncertainty within the adjustment (ICSM, 2013b). The resulting coordinates were given uncertainty estimates (e.g. approximately 250 mm (95% CI) within NSW – Haasdyk & Watson, 2013), and further hierarchical densification is still undertaken today.

### 1.3 Drivers for Datum Update

Many of the same drivers for datum update which resulted in the development of GDA94 are again providing the need for datum modernisation, and are listed below (Dawson & Woods, 2010; Stanaway *et al*., 2011; Featherstone *et al*., 2012; Haasdyk & Watson, 2013; Stanaway & Roberts, 2013; Tregoning *et al*., 2013):

- Technological improvement and significantly more precise geodetic measurements gathered since 1994 can be used to compute improved coordinates and uncertainties.
- Systematic distortions in GDA94 of up to 300 mm (horizontal) have been detected by modern measurements such as from CORS, and 'site-transformations' are currently required to agree with local ground control coordinates.
- The Australian tectonic plate moves (and rotates) at ~7 cm/yr, but GDA94 is defined by coordinates locked to epoch 1994.0. GDA94 will therefore be offset with respect to ITRF and WGS84 coordinates by ~1.5 m in 2015. The rotation is significant for surveying and geodesy applications, affecting bearings of baselines by 7 mm per 30 km over a 20 year period.
- The 1.5 m offset is large enough to affect expected positioning accuracy of mass-market devices such as smartphones and tablets. These will likely determine coordinates in the latest ITRF − without direct reference to GDA94 − by directly accessing International GNSS Service (IGS) products in real time.
- Ground deformation is readily apparent in subsidence due to water, coal or gas extraction. Deformation due to seismic activity is more pronounced in other nearby countries, such as New Zealand, but is still observable within the Australian tectonic plate.
- A significant 9 cm vertical bias exists between ITRF92, upon which GDA94 is based, and ITRF2008.
- Improvements in computing hardware and software capabilities now make it possible to perform rigorous geodetic adjustments of a virtually unlimited number of station parameters and measurements.

## 2 Progress towards a new National Adjustment

In recent years, the Geodesy Technical Sub Committee (GTSC) – now the Permanent Committee on Geodesy (PCG) – of the ICSM has been preparing for datum modernisation. The following sections describe recent progress.

### 2.1 ATRF and APREF as a densification of the ITRF

While the ITRF provides the internationally accepted global reference frame for high-precision applications, the density of the network is low, with only 580 sites world-wide and 117 in the southern hemisphere (Altamimi *et al*., 2011). The Asia Pacific Reference Frame (APREF) has already been established to create and maintain a more densely realised geodetic framework of CORS in the Asia-Pacific region based on the continuous observation and analysis of GNSS data (Geoscience Australia, 2013). Recent APREF solutions report more than 300 stations across Australia and New Zealand, compared to fewer than 30 stations in the same region, in the ITRF solution.

An Australian Terrestrial Reference Frame (ATRF) would provide a further densification of ITRF and serve as the modernised dynamic datum in Australia by combining data from the Australian CORS of the APREF, a national homogenous adjustment of all available geodetic measurements, and a national deformation model (refer to section 2.4). ATRF would remain aligned to ITRF but provide the density of stations and/or deformation models required for the accurate maintenance of spatial data in Australia.

## 2.2 Collation of Jurisdictional Datasets

In Australia, each state or territorial jurisdiction is the custodian for its own geodetic measurements and legal source for ground control coordinates. Consequently, since GDA94 was defined, each jurisdiction has gathered and adjusted its survey control measurements using different methods, with some jurisdictions holding fixed the geodetic control coordinates originally adopted, and others re-coordinating all control stations as new measurements become available. This has caused discontinuities in coordinates at jurisdictional boundaries.

These measurements are currently being collated for an upcoming national adjustment (e.g. Haasdyk & Watson, 2013). Figure 1 shows some examples of jurisdictional adjustments, with Victoria and New South Wales, for example, providing tens of thousands of stations and up to 100,000 measurements each. The obvious differences between the state diagrams also reflect the different tools and processes being used to store, adjust and analyse the data at this time.

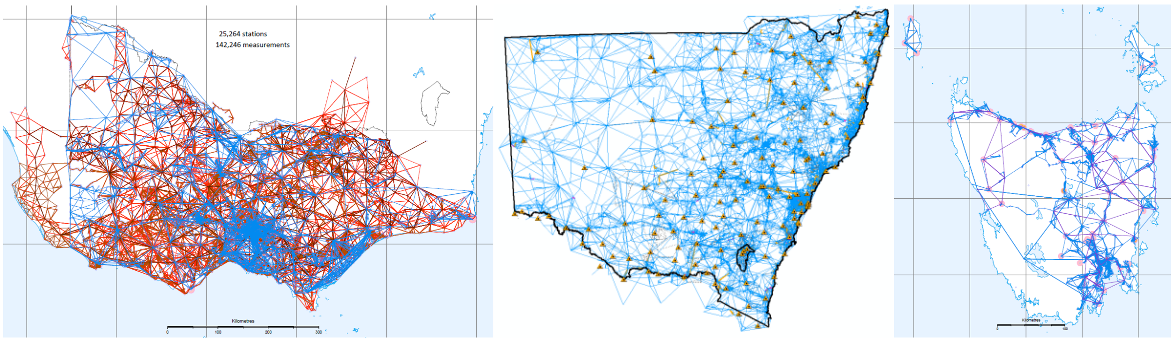


Figure 1: (Left to Right) Victoria, NSW and Tasmanian datasets. Scales vary. Colour schemes vary. (e.g. Victoria Data: Blue = GNSS, Red = Terrestrial)

## 2.3 New Geodetic Adjustment Software and Hardware

Historically, geodetic adjustments were limited in size due to computing memory and hardware available. More recently, Leahy and Collier (1998) described a 'dynamic phased-adjustment' which can perform a rigorous adjustment on a network of any size. This allows the computation of absolute Positional Uncertainty (PU) of all observed stations across the network, as well as relative uncertainty between any nominated stations, as described in the new Standards and Practices document (ICSM, 2013c).

DynaNet, a program that can perform such a dynamic network adjustment, has been developed at the former Department of Geomatics at the University of Melbourne (Fraser *et al*., 2014). This program has been modified to allow the adjustment to be computed in any datum and reference epoch, for example by rotating and translating all available GNSS baselines and position measurements to account for tectonic motion via published conformal transformations (e.g. Dawson & Woods, 2010). Further development is underway to incorporate the more complex deformation models described in section 2.4.

While DynaNet can be run on a desktop computer, the proposed national adjustment will be carried out on a new Australian supercomputer known as 'Raijin', currently the 27$^{th}$ fastest computer in the world (NCI, 2013). Primarily intended for climate modelling, Raijin is available for other computationally-intensive activities of national interest.

Testing of hypothetical large national adjustments has already been undertaken, with a 400,000 station network, comprising over 1.2 million GNSS measurements, adjusted within approximately 50 hours. Further improvements to the efficiency of the software are planned, which have the potential to substantially reduce the duration and memory requirements of the adjustment.

## 2.4 Deformation Models

Deformation of the land surface relative to the defined datum includes a complex combination of secular tectonic motion, and more localised, usually episodic deformation events such as those due to ground subsidence or earthquake events. Stanaway *et al*. (2012) provides a useful summary of deformation types and expected magnitudes. A deformation model is therefore required to enable coordinates (and measurements) to be propagated between epochs. For example, such a model would allow coordinates which are determined from contemporary measurements, as well as existing spatial datasets, to be propagated to a common epoch for direct comparison.

### 2.4.1 Secular Tectonic Motion

The internal deformation of the Australian continent (with the exception of isolated areas of intraplate earthquakes and subsidence) is less than 1.0 mm/yr over 4000 km or 0.25 ppb (Tregoning, 2003; Tregoning *et al*., 2013; Stanaway & Roberts, 2012). As a result, a rigid plate motion model is sufficient to account for most of the dynamics experienced by the Australian tectonic plate. Stanaway and Roberts (2013) indicate that a site velocity model based on the ITRF2008 plate model can account for tectonic motion in the stable parts of the Australian plate with an uncertainty of only 6 mm at 95% CI between 2013.0 and 1994.0. This model could be further improved by a higher density of observed site velocities at the APREF CORS.

The application of a deformation model based only on rigid tectonic plate motion would be in-line with current practice in North America and Europe, where the North American Datum 1983 (NAD83) and the European Terrestrial Reference System 1989 (ETRS89) are respectively fixed to the North American and Eurasian plates. In this way, NAD83 and ETRS89 are treated as plate-fixed static datums in the same way as GDA94, with the velocities of stable points minimized (Pearson and Snay, 2013; Ordnance Survey, 2013).

For example, ETRF89 (the European Terrestrial Reference Frame realisation of ETRS89 used in Great Britain) was equivalent to ITRF89 at epoch 1989.0. To propagate from current ETRF89 coordinates to the ITRF89 on which it is based requires only the application of the rigid tectonic plate model. Conveniently, the motion of a rigid plate can be described simply by three parameters, namely rotation about the X, Y, and Z axis of the defined datum (Stanaway & Roberts, 2009). These parameters can be easily applied in the form of a 7-parameter conformal transformation, which is commonly accepted in many software packages, with translation and scale parameters set to zero. Propagation from GDA94 to ITRF92 could be accomplished in the same manner. Of course for regions in deforming zones such as the western United States, the proximity to the plate boundary means that a rigid plate motion model cannot accurately account for the more complex motions observed.

Any remaining transformation between datums, e.g. between current ITRF2008 coordinates and ITRF89 on which ETRF89 is based, requires a second step in which a 14-parameter transformation is applied. It is possible to accomplish both transformation between datums and propagation between epochs in one step, by combining the parameters from the two steps above, as in ITRF2008 to ETRF89, or ITRF2008 to GDA94 transformations (Boucher & Altamimi, 2011; Dawson & Woods, 2010).

### 2.4.2 Gridded Deformation Model

While most of Australia experiences little relative deformation, in some areas such the Perth Basin, Newcastle and the Latrobe Valley, significant deformation has been observed relative to the surrounding stable plate. For example, Featherstone *et al*. (2012) demonstrate subsidence of greater than 5 mm/yr in Perth due to ground-water extraction.

Stanaway and Roberts (2013) have proposed a gridded deformation model for the Australian continent which can be used to propagate ITRF coordinates at any epoch, to GDA94. This Australian continental deformation model consists of a 1 degree grid of site velocities to account for tectonic plate motion and other site-specific velocities, plus a 1 degree grid of coordinate 'patch' corrections at defined epochs to account for distortion between the reference frames as well as episodic deformation events. The gridded deformation model has advantages over the current 14-parameter model (Dawson & Woods, 2010) in that localised deformation can be defined within the model and denser nested grids can be used in areas where greater precision is required, or where more significant deformation is occurring.

The proposed site velocity model is derived from the ITRF2008 plate model (Altamimi *et al*., 2011) with corrections applied based on observed versus modelled site velocities at a number of APREF CORS stations with time series longer than eight years. The national patch model is derived from differences between the gazetted coordinates of these APREF stations and the site velocity model regressed to epoch 1994. Evaluation of the model indicates agreement within several millimetres compared to the current 14-parameter transformation at these sites.

### 2.4.3 Deformation Model of the New Zealand Geodetic Datum 2000 (NZGD2000)

An example of a deformation model in practice is the NZGD2000 Deformation Model, published by Land Information New Zealand (Crook and Donnelly, 2013; Winefield *et al*., 2010). This model, recently updated, includes a simple linear velocity model at a regular grid of roughly 10 km spacing, and as of February 2014 also includes sub-models or 'patches' for 10 significant earthquakes to have affected New Zealand since 1 January 2000, including the 2010 and 2011 Canterbury earthquakes.

These 'patches' represent any distortion which is measured (e.g. from a network of CORS or geodetic control stations) or inferred (e.g. from large scale geophysical models) and also provide associated uncertainty values. Patches provide variable resolution information of complex motions (e.g. linear, ramp, step or exponential decay) which describe any known deformation events to the maximum ability of the existing measurements and models.

### 2.4.4 Deformation determined by DInSAR and Other Non-traditional Geodetic Techniques

Ground surface deformation, for example due to natural events such as earthquakes or anthropogenic activities such as water extraction, can be highly variable over a small area, and is often non-linear. These complex deformations cannot be adequately monitored using technologies such as GNSS because of the sparse distribution of ground control stations and the high cost of field operations to occupy and observe these control stations before, during and after the deformation event(s).

Research is currently being undertaken via the Cooperative Research Centre for Spatial Information (CRCSI) to determine how best to take advantage of large-scale quick-repeat remote sensing techniques such as Lidar and Differential Interferometric Synthetic Aperture Radar (DInSAR) to complement traditional geodetic point-based techniques, and how best to model and quickly disseminate deformation information to allow the spatial community to easily create and maintain products which are precise and accurate at the centimetre-level.

For example, DInSAR can measure land movements to a precision of a few millimetres (Simons and Rosen, 2007). This technique uses airborne or spaceborne radar to create deformation maps or grids, from measurements made with a density down to 10 metres. Thus areas of anomalous deformation can be readily identified for additional monitoring with GNSS, Lidar or further DInSAR measurements.

Additional work will need to be undertaken to resolve potential discontinuities in deformation that could result from making measurements at unstable monuments. For example, geodetic monuments, historically placed on reservoirs or silos to assist with long-distance sighting, may be subject to large deformations which are station-specific and do not agree with land deformation in the near vicinity (Haasdyk & Roberts, 2013).

### 2.5 User Discussion Forums

A number of education and discussion forums have been convened by state, territory or national geodetic authorities across the country in the last two years. These forums aim to introduce the plans for a next generation datum to a diverse group of spatial data users, and to understand the perceived and real costs, benefits and opportunities associated with datum modernisation from the users who will be most affected by these changes.

The first forum, internally run at NSW LPI in late 2012, highlighted the diverse groups (councils, engineering, mining, construction, research, etc.) currently utilising legacy datasets in GDA94. The first open forum was held in March 2013 with predominantly surveyors (around 250) interested in centimetre-level positioning. The second, in April at the SSSI conference, was targeted at geospatial professionals and the audience contained a diverse range of users. Since then, additional forums have been held in NSW, VIC, ACT, NT, TAS and webinars describing datum modernisation issues have been made available (Donnelly & Haasdyk, 2013)

Most importantly, as a result of these forums, it is recognised that the decision of spatial data holders to modernise their existing datasets should be dependent on readiness of their systems. The modernised datum should provide opportunities for geospatial professionals to create innovative high-accuracy products and applications, but not to force all users into upgrades for which they are not yet prepared. Users are understandably concerned about the cost and risk of transforming or propagating existing datasets, the dearth of existing tools to handle deformation, and the methods by which data from various epochs will be combined for comparisons. The prevalence of value-adding to existing datasets for provision to third parties has been discussed, along with implications of frequent datum updates on data management.

A common theme at all forums is the need for metadata management, and in particular information about when data was captured, and the methodology and estimated precision of the data capture. Many users were surprised to realise that WGS84 was, in practice, a collection of lower-precision datums and that time-stamp metadata was an integral component of expressing coordinates in WGS84 (Donnelly *et al*., 2013).

The provision of an 'authoritative epoch' to which data can be referred was desirable, but the feedback from several forums indicated that users would rather avoid a short-term interim solution of another static, albeit higher accuracy, realisation of the datum. Rather, the general response appears to be that if and when the tools to handle deformation are available, most users would prefer to make a single step directly to a dynamic datum and adopt a new (if necessary) reference epoch.

## 3 Options for Realisation of the New Datum

A number of optional 'features' are under consideration which would affect the final realisation of a 'next-generation' geodetic datum. These include corrections of known distortions, adoption of the modern ITRF/ATRF, adoption of a deformation model (simple or complex) and therefore a dynamic datum, and choice of reference epoch. It is not the purpose of this paper to select or promote the features of the final realisation, as that authority rests with the ICSM. Instead, this paper presents a discussion of the potential advantages and disadvantages associated with each option, and summarises a few of the likely realisations in Table 1. The following discussion assumes that some form of modernisation *will* be undertaken, the alternative being to accept the status quo and ignore the current issues highlighted in section 1.3.

### 3.1 Correction between GDA94 and an Homogenous and Rigorous National Adjustment

The most basic form of datum modernisation involves the adoption of modern measurements and adjustment methods to correct any known distortions in the existing GDA94 datum which have been highlighted by modern high precision GNSS baseline measurements and continuous CORS observations (Haasdyk & Watson, 2013). The advantage of a new simultaneous national adjustment of all available measurements is the provision of improved, rigorous and homogenous coordinates and positional uncertainty across Australia.

These updated coordinates can be compared to existing GDA94 coordinates to characterise and quantify these distortions at a reasonably high density. Figure 2 demonstrates that within NSW for example, the distortions between current GDA94 coordinates and a new national adjustment expressed in GDA94 are quite systematic, with expected coordinate changes of up to 300 mm for this GNSS-only dataset. Of course control stations which are remote or currently have only terrestrial measurements such as directions and distances are likely to have even greater coordinate improvements when re-observed in future with GNSS measurements, with an associated improvement in their positional uncertainty.

Any control stations or spatial data not included in the national adjustment could be easily transformed to the new datum by a dense grid transformation, similar to the NTv2 grids used in AGD-GDA94 transformations (Collier *et al*., 1997; Collier & Steed, 2001). Such a grid transformation would be computed based on the differences between existing GDA94 coordinates and the new adjustment coordinates at common points. There are costs and risks associated with transforming existing datasets, and the benefits of improved accuracy must be weighed up by the data manager. Of course, any spatial data of lower accuracy than the expected coordinate corrections (e.g. worse that 0.5 metre accuracy) need not be transformed.

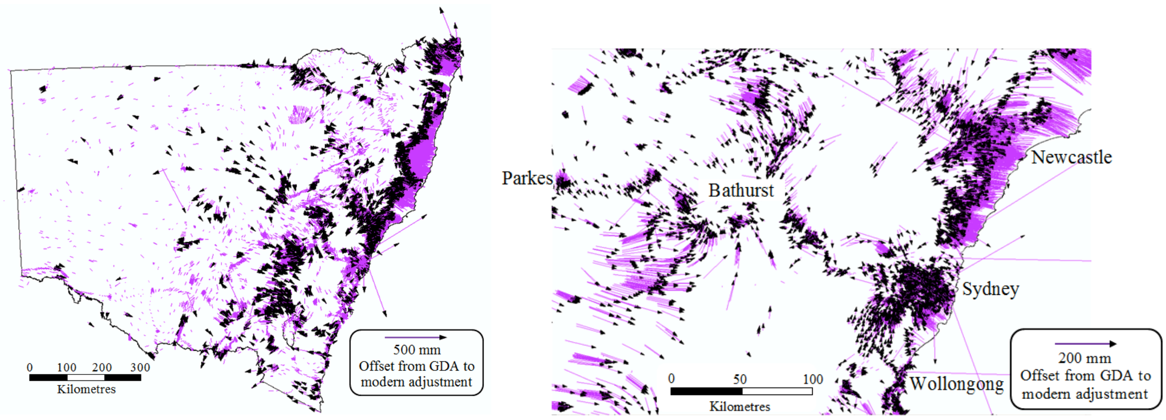


Figure 2: Expected horizontal changes to GDA94 coordinates in NSW Australia after a national adjustment.

### 3.2 Updating to the latest ITRF

A second option for datum modernisation is to adopt the improvements in accuracy and stability of the latest ITRF, currently ITRF2008. Note that ITRF2013 is currently under preparation and will likely be available by the completion of the Australian national adjustment. ITRF has been updated seven times since ITRF92 resulting in horizontal corrections of less than 4 cm, and a vertical correction of 9 cm (Stanaway & Roberts, 2013). APREF (and eventually ATRF, refer to section 2.1) offers a further densification of the current ITRF in the Australasian region, and is an ideal platform on which to realise the modernised datum.

### 3.3 Past, Present or Future Reference Epoch

The reference epoch represents a date and time that is conventionally agreed upon, to assist with the meaningful transfer of coordinates, measurements or other parameters. For example, coordinates for a physical feature expressed at reference epoch 2000.0 would be a description of the location of that feature at 00:00:00 01 Jan 2000 in the given datum. To describe that feature at a different point in time requires the application of parameters which describe change with respect to time, i.e. a deformation model. Note that application of a conventional deformation model removes the need to define a reference epoch, however many users (and software) are currently comfortable with the use of reference epochs and will require time to transition to the idea of a fully-dynamic datum.

Intuitively, reference epochs have historically described a ‘snap-shot’ of coordinates at some time in the past. This is particularly salient in that any new spatial data coordinates acquired in WGS84 or ITRF currently need to be transformed and propagated back to the GDA94 epoch of 1994.0. Existing 14-parameter transformation methods may introduce additional uncertainties to the result when propagating across a period of 20 years (Haasdyk & Janssen, 2011). Newer deformation models (e.g. section 2.4) could achieve propagation to a 1994.0 epoch with an accuracy of several millimetres, but may still be subject to undetected deformation.

It is possible, however, to define a reference epoch for the datum at a more contemporary epoch (e.g. 2015.0). The advantages of using such a reference epoch are that any new spatial data acquired with coordinates in the WGS84 or ITRF are, by default, in close alignment with the datum without the need for any data propagation. Unfortunately, tectonic motion will inevitably cause Australian and international datums to diverge at ~7 cm/yr with resulting differences in spatial data coordinates again reaching 0.5 metres in less than eight years. Any spatial data at higher accuracies will soon again need to be adjusted onto the national datum using appropriate transformation and/or deformation models.

A reference frame with an epoch in the future (e.g. 2020.0) can just as easily be defined using assumptions about future deformation (secular tectonic motion being quite predictable), and computing reference coordinates accordingly. In this way the 'life-span' of the datum would be increased, as the offset with respect to WGS84 or ITRF would first *decrease* by ~7 cm/yr until 2020. This is particularly advantageous for those users who either purposely or inadvertently would not apply the necessary transformation and/or deformation models, such as the current mass-market. Unfortunately these benefits might still be considered to be quite short lived. Even if 20 cm accuracy in future mass-market devices is achieved, then a static datum which deviates by ~7 cm/yr should always be defined with a reference epoch only 2 or 3 years away from the current date.

Some users may have practical reservations about describing or 'predicting' the future location of monuments as localised deformation cannot usually be easily predicted. However, it should be noted that the same issue applies when propagating data to past reference epochs, using imperfect transformation and deformation models. This is especially true for new physical features whose coordinates at the past reference epoch must be inferred, but also applies in areas where past deformation has not been directly measured. Coordinates expressed at any reference epoch are simply a representation (or description) that assists spatial data comparison, and do not necessarily reflect the actual current location of surface points.

Note that regardless of the reference epoch adopted, there will always be a need to transform and propagate spatial data, whether existing and/or newly collected, depending on its spatial accuracy. For example, a change to epoch 2015.0 would necessitate a coordinate shift of ~1.5 metres for all existing GDA94 spatial datasets of metre-level accuracy or better. If mass-market devices do indeed achieve centimetre-level accurate coordinates then manufacturers must either rely on pre-transformed data, or must apply deformation model(s) directly on the device to propagate new data or existing datasets 'on-the-fly'. In either case, a universal improvement in coordinate precision will drive a need for ubiquitous and accurate coordinate propagation and eventually most geospatial software, including on mass-market devices, would ideally apply deformation models commensurate with their location on the globe and their desired positioning accuracy.

### 3.4 Static vs. Semi-Dynamic vs. Dynamic Datum

#### 3.4.1 Static Datum

As defined above, a static datum is insensitive to any deformation and represents coordinates as fixed in time. The advantages of a static datum are its simplicity and unchanging coordinates, and the minimal overheads in maintaining relationships with other national and international spatial data and datums. Users are accustomed to using such 'fixed' coordinates, but now that positions are increasingly derived from satellite orbits in ITRF (or similar reference frames) which are unaffected by tectonic movements on the Earth's surface, they must now grapple with this extra complication.

The disadvantage is the inability of a static datum to communicate that deformation and tectonic plate motion are measurable and have magnitudes which exceed the positional uncertainty of datum control stations. Coordinates expressed with respect to a static datum can only represent where physical features were at any one point in time.

It is important to note that modern measurements can still be transformed or propagated to a static datum. Consider, for example, how ITRF2008 coordinates in the current epoch are transformed back to GDA94 using the 14-parameter transformation of Dawson and Woods (2010), or how ITRF89 is propagated to ETRF89 by applying a tectonic plate motion model. In general, however, transformation and propagation are easily overlooked by users who may be unaware that modern measurements are at a better accuracy than the underlying spatial data, or simply because the deformation model is not defined *as part of* the datum.

#### 3.4.2 Semi-Dynamic Datum

A semi-dynamic datum has the benefit of reporting coordinates at a single reference epoch, while also incorporating an official deformation model which describes actual movement of physical features between epochs. Coordinates at the reference epoch represent where physical features are/were at a particular point in time. The advantage of a semi-dynamic datum is that it can appear for all intents and purposes as a simple static datum for users of low-precision datasets (e.g. decametre-level), yet still account for deformation in high-accuracy datasets.

Most intuitively, the reference epoch would represent the epoch of a 'snap-shot' of existing physical features (i.e. coordinates at reference epoch 2000.0 describe where physical features were, in both an absolute and relative sense, at epoch 2000.0). Users could apply a deformation model, either a simple tectonic plate model, or a more complex model bases on velocities and 'patches', to retrieve the current coordinates of these physical features. If the deformation model is not applied, then an offset and/or distortions will remain between any newly observed coordinates and any existing spatial data described at the reference epoch. A significant disadvantage is that, in general, spatial data management systems and geospatial software (e.g. GIS applications) are not currently capable of applying complex deformation models. Although significant work is being undertaken to incorporate dynamics within geospatial software, this currently implies that the semi-dynamic datum is out of reach for all but the most simple deformation models, or the most sophisticated users.

As a compromise, 'reverse-patch' systems have been developed. For example NZGD2000 defines 'reference coordinates' at epoch 2000.0 by starting with the coordinates of physical features in epoch 2000.0 and then distorting them to represent any *relative* non-secular (episodic) deformation between 2000.0 and the current epoch, i.e. deformation due to distinct events such as earthquakes. To retrieve the *true absolute* coordinates in epoch 2000.0 from the 'reference coordinates' in epoch 2000.0, a series of 'reverse-patches' must be applied. (Blick *et al*., 2006; Winefield *et al*., 2010). This model caters well for two users groups: The majority of users are most interested in the current relative geometry between physical features and currently ignore the deformation model entirely. The high-precision geodetic, engineering or scientific user who has the computing power and education to apply the tectonic motion and reverse patches can derive the true coordinate from coordinates or measurements at the current epoch by applying the tectonic motion model and the reverse patches.

### 3.4.3 Dynamic Datum

A fully dynamic datum simply eschews the concept of reference epoch for the communication of spatial data, and describes coordinates of physical features at any epoch, generally the current epoch. The advantage of this option is that any newly acquired spatial data would be as accurate in the datum as the measurement equipment allows, without the need to apply any transformation and deformation models. Furthermore, this option could be considered to represent what most users of spatial data intuitively want: coordinates which reflect the location of objects today, not coordinates at a reference epoch sometime in the past or future, assuming of course that their map, plan or spatial data are also up-to-date and represented in the same epoch.

However, in order to compare or mix spatial data acquired at different epochs, *all* datasets would need to have the appropriate transformation and deformation models applied, or else they would suffer a commensurate loss of accuracy with respect to the current datum or each other. Further disadvantages include the confusion that could arise by not having an 'official' reference epoch for which all spatial data is referenced. Implicitly, this would require existing spatial data to be propagated to the current epoch (or other agreed convention) for all comparisons and applications, instead of the new spatial data being propagated 'back' in time (or 'forward' to the future) to an official reference datum/epoch. This potentially requires significant computation unless on-demand services become intelligent enough to only transform the data which is of immediate interest. As with the semi-dynamic datum, the fact that most geospatial software packages do not currently make provision for complex deformation models is a significant disadvantage.

Another complexity of a dynamic datum in practice is how local terrestrial measurements (e.g. made by total stations or terrestrial laser scanning) are to be referenced to the correct datum/epoch. For example, if the coordinates of the control stations used for these surveys are expressed in GDA94 and therefore in the reference epoch 1994.0, then the epoch of the surveyed coordinates should also be 1994.0, but could be misconstrued as the date the measurements were gathered.

### 3.5 Frequency of National Adjustment

The frequent re-adjustment of the ATRF would result in much smaller coordinate changes than those resulting from known tectonic or deformation processes. For example, a future re-adjustment of the national network which includes the latest measurements would improve estimates of positional and relative uncertainty of the control stations in question, and should only correct the coordinates of the control stations within their estimated positional uncertainty. States and territory administrators can shield their users from these 'insignificant' updates by broadcasting coordinate revisions only when significant corrections (due to previous errors or biases) are made.

Additionally, centimetre to millimetre-level dynamics are of increasing importance to earth observation efforts such as by the Global Geodetic Observing System (GGOS) (Plag *et al*., 2009), and could be accounted for by a much more frequent realisation of the datum. Such a concept is being explored for major space geodesy techniques, with the creation of weekly 'epoch reference frames' consistent with ITRF to describe non-linear movements, and to provide updates with a short time delay after deformation events (IAG, 2013). Global dynamic phenomena such as atmospheric and hydrological mass loading occurring on a frequency of hours to years could be incorporated into the datum and/or deformation model for the highest-accuracy users who need to account for them.

Initially it is suggested that from 2015 onward, the national adjustment will be re-run annually to incorporate any new measurements (and possibly retire older, superseded measurements). After that period this frequency could be increased as required, even to the point of weekly or daily re-adjustments to support a fully dynamic datum at the 'current epoch'. Such high-frequency adjustments would only benefit geodetic applications, and could be ignored by most users as high-accuracy 'versions' of the datum with little benefit for centimetre or decimetre-level datasets.

Regardless of the frequency of the national adjustment, states and territories will also continue to compute and publish coordinates and measurements for new ground control stations as required in the intervening period.

## 4 Comparison of Probable Modernised Datum Realisations

While there are many combinations and permutations of the options presented above, only a few scenarios are likely for the realisation of the modernised datum or ATRF. Several options are almost certain to be adopted, such as the creation of an homogenous national datum using all modern measurements which removes known distortions, and the adoption of the most recent ITRF for the definition of the datum. The frequency of re-adjustment is essentially an academic argument, resulting in millimetre-level changes of importance only to the geodetic user, but still improving the *density and accuracy* of control stations without significantly changing their coordinates. Users will be free to adopt newer adjustments to achieve increased accuracy in their derived datasets, but can, in large part, be shielded from updates of little consequence by correct application of the metadata regarding the version of datum and deformation model applied.

The remaining options of significant concern therefore are the adoption of a ‘static’, ‘dynamic’ or ‘semi-dynamic’ datum, and the chosen reference epoch. The debate revolves around minimising the overall cost and risk to users associated with correctly upgrading existing datasets and obtaining, developing and learning new tools for data manipulation, while still ensuring the highest possible rigour and accuracy required for all user groups.

For the purposes of this paper, the following options for datum realisation are deemed plausible. These are compared in Table 1 and further discussed below:

Option 1) ITRF92(1994.0): Do nothing, maintain (static) GDA94.

Option 2) ITRF92(1994.0): National Adjustment to correct GDA94 distortions only, expressed in ITRF92.

Option 3) ITRF2013(1994.0): National Adjustment to correct GDA94 distortions, expressed in latest ITRF.

Option 4) ITRF2013(2015.0): National Adjustment to contemporary reference epoch.

Option 5) ITRF2013(2020.0): National Adjustment to future reference epoch.

Option 6) ITRF2013(current): National Adjustment to ITRF2013(current) coordinates: A Dynamic Datum.

Option 7) ITRF2013(current) plus ITRF(2013) 1994.0.

Note that either a static or semi-dynamic datum can be defined for each of Options 1 through 5, as each requires the definition of a reference epoch. As previously discussed, decimetre-accurate data must either be gathered within several years of the reference epoch, or have a deformation model applied to propagate the data to the reference epoch, in order to account for the motion of the Australian tectonic plate. Of course, ad hoc adoption of deformation models is possible in a static datum, but the provision of official national deformation model(s) is far more desirable for traceability and consistency. A semi-dynamic datum provides the familiarity for most spatial data consumers, of coordinates which are for all intents and purposes static at a defined epoch, but which also incorporates an official deformation model. For these reasons adoption of a new static datum, as in Option 1, is considered untenable, and the discussion below assumes a semi-dynamic datum for all remaining options except Options 6 and 7.

Options 2 and 3 include a new national adjustment to correct known distortions within GDA94, in order to ensure the highest *relative* accuracy possible. Note that option 3 also accounts for the centimetre-level horizontal bias and decimetre-level height bias between ITRF92 and ITRF2008, while option 2 does not. By retaining the existing GDA94 reference epoch of 1994.0, the main advantage of these options is to minimise the cost and risk of transforming existing GDA94 datasets to a new reference epoch; only data better than approximately 0.5 metre accuracy will need to be transformed. Other benefits to users include a direct agreement between CORS-derived differential positioning and the remainder of the control station network, thus eliminating the need to determine site-specific transformation parameters. Large engineering projects should no longer highlight distortions in the local realisation of the datum, but rather be able to confidently make use of existing control infrastructure. These options do not directly cater for the ~1.5 metre offset due to tectonic motion since 1994.0, which introduces a potential misalignment when new spatial data is acquired using modern GNSS techniques. However, as long as an appropriate deformation model is correctly applied all data could be compared to the 1994.0 epoch at centimetre-level accuracy.

Options 4 and 5 define reference epochs which are either contemporary, or in the future. These options allow the acquisition of new spatial data directly in, or near, the reference epoch. A deformation model is then required to propagate existing data forward from GDA94. This is to cater for new measurements, especially from mass-market users who do not (or cannot) propagate back to epoch 1994.0, or are unaware of datum-related issues. However, if the anticipated decimetre-level precision of new mass-market positioning devices is achieved, specific reference epochs may have unrealistically short life-spans of less than two or three years. Option 5 aims to extend this life-span by allowing the Australian plate to drift towards and then away from its position at the reference epoch, but even then it appears likely that a new reference epoch would need to be proclaimed every five or so years (e.g. 2020, 2025, etc). This would provide users with a set of official common reference epochs in which to collect and compare their data. A disadvantage of these options is that data managers will be forced to undertake the potentially costly effort of transforming existing datasets to align them to one, or likely several, of the adopted reference epochs. The risk of mis-identification of the data will grow with the adoption of multiple official reference epochs.

Table 1: Comparison of modernised datum realisation options.

| Option | **Option 1** ITRF92 (1994.0) | **Options 2,3** ITRF92 or ITRF2013 (1994.0) | **Option 4** ITRF2013 (2015.0) | **Option 5** ITRF2013 (2020.0) | **Option 6** ITRF(current) | **Option 7** ITRF(current) & ITRF2013(1994.0) |
|---|---|---|---|---|---|---|
| Description | Do nothing: retain static GDA94 | New national adjustment + deformation model | New national adjustment + new modern ref. epoch + deformation model | New national adjustment + new future ref. epoch + deformation model | New national adjustment + dynamic datum, current epoch + deformation model | Option 6 (e.g. for GNSS, PPP) + Option 3 (for data comparison) |
| Decimetre distortions in GDA94 corrected | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Alignment with existing GDA94 data | ✓ | ✓ | ✗ ~1.5m offset | ✗ ~1.8m offset | ✗ ~1.8m offset and growing | ✓ |
| New data acquired in WGS84 / ITRF are compatible without further data manipulation | ✗ Bias currently greater than metre-level & 9 cm ITRF92 vertical bias | ✗ Bias currently greater than metre-level | ✓ However bias increases (~7cm/a) from 2015 | ✓ However bias increases (~7cm/a) from 2020 | ✓ No bias for new data | ✓ |
| Accounts for rotation of tectonic plate without further data manipulation | ✗ 7 mm / 30 km baseline from 2015 | ✗ 7 mm / 30 km baseline from 2015 | ✓ Bias increases from 2015 | ✓ Bias increases from 2020 | ✓ No bias for new data | ✓ |
| Datum accuracy if deformation model is applied | cm-level | sub cm-level | mm-level (limited lifespan) | mm-level (limited lifespan) | mm-level | mm-level |

Option 6 defines a fully dynamic datum which caters specifically for two user-groups. Existing geodetic users of spatial data are already familiar with the use of dynamic datums such as ITRF. These users require raw, untransformed data, in its original epoch, for the assessment of global dynamic phenomena. They are often pushing the bounds of available accuracy, and may be testing the assumptions and algorithms underlying official deformation models and other un-modelled dynamic phenomena. In terms of emerging spatial data markets, a fully dynamic datum ensures that mass-market devices are positioning implicitly in the Australian datum. However this would require the frequent (and external) transformation of datasets prior to uploading to the device. This may prove to be more troublesome than applying the transformations directly on the device, in order to propagate the new data to a conventional reference epoch as in Option 5.

Finally, Option 7 provides a combination of datum products, both fully and semi-dynamic, to cater for all user requirements. For example, dynamic ITRF (or ATRF) coordinates at the current epoch are determined for any initial GNSS positioning (e.g. PPP), baseline processing, adjustment, Lidar and other remote sensing techniques. All spatial data would be archived without changes in ITRF (or ATRF) at the epoch of acquisition, to facilitate high-precision geodetic analysis and/or propagation to another epoch in the future. An official deformation model (e.g. Stanaway & Roberts, 2013) would be used to propagate coordinates and datasets with sub-centimetre-level accuracy to an updated GDA94 (re-realised as ITRF2013 at epoch 1994.0) Eventually, improvements in GIS technology will enable 4D coordinates (3D + epoch) to be modelled seamlessly within the GIS, and the need for a fixed epoch will diminish. The mixed option presented here provides the best of both worlds, while minimising cost and risk to nearly all users. It also promotes sound data management principles by encouraging the storage of data in the most accurate reference frame (ITRF or ATRF at the epoch of data acquisition), and treating coordinates for the dataset in the national datum as a derived product to facilitate easy integration of datasets. Importantly, the choice of a single reference epoch at 1994.0 minimises the risk of maintaining multiple similar datasets and therefore reduces the potential for confusion.

In this debate the importance of metadata must be stressed. It is widely recognised that metadata management is rarely approached with appropriate rigour, and that large datasets are often manipulated without the maintenance and propagation of appropriate metadata. The potentially large number of reference epochs, deformation models and adjustments discussed above mean that metadata will become just as important as the data themselves. It is important that all data remain 'traceable' back to its source so as to allow, for example, for future application of updated deformation models if and when they become available. All data should carry metadata about the epoch, datum, method of acquisition, and estimated uncertainty. Where possible the original raw data should be stored unchanged at the epoch of acquisition, and at the very least, by properly recording any transformations or alterations undertaken, the raw data can be re-processed for future use.

## 5 Concluding Remarks

The development of a modernised datum for Australia – what the authors refer to here as the Australian Terrestrial Reference Frame – is currently underway. However there are still a variety of options to consider regarding the final realisation of the datum. The discussion above concludes that there is obvious benefit in adopting the most accurate and homogenous datum based on the most recent ITRF, a national adjustment of all available measurements, and an accurate deformation model. It is imperative to construct the most rigorous datum possible, designed for the highest-precision geodetic applications, but which will also cater for all other users. Another static realisation of the datum cannot account for recent technological improvements, not to mention the inexorable movement of the Australian tectonic plate.

The major remaining issues are the choice between a semi-dynamic or full-dynamic datum realisation, the selection of reference epoch, and the complexity of the deformation model. Ultimately, the options under consideration each cater for different user groups, and a combination of datum products is the best solution for all users. In particular, the combination of a fully dynamic ATRF defined in the latest ITRF(current epoch), along with a 'derived datum' with all relevant data propagated to the 1994.0 epoch, would provide for the highest accuracy applications as well as the burgeoning but 'uninformed' positioning mass-market, while still minimising the costs and risks associated with data manipulation and metadata mis-management.

Regardless of the option(s) chosen for datum realisation, tools are yet to be developed that correctly apply the highest-accuracy transformation and deformation models. A new variable gridded deformation model for the Australian continent has been proposed but it has yet to be rigorously tested. There will be a need for user-education, at the level of the geospatial practitioner and data-manager, and tools to insulate the mass-market user from unnecessary complications. Although most geospatial software packages can perform simple transformations, they are not explicitly designed to routinely propagate coordinates through time and definitely cannot cater for more complex deformation modelling. However, the market drive to do so is increasing and the Australian geospatial profession has a great opportunity to drive the development of these high-accuracy products.

While the focus of this paper has been on datum development in Australia, by also attempting to cater for changing technologies and complex deformation, the concepts discussed herein are applicable to national and international datum development across the globe.

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