A Two-Frame National Geospatial Reference System Accounting for Geodynamics

Nic Donnelly, Chris Crook, Richard Stanaway, Craig Roberts, Chris Rizos, and Joel Haasdyk

Abstract

This paper presents a high level proposal for how a Local Reference Frame (LRF) could be implemented alongside the International Terrestrial Reference Frame (ITRF) as part of a two-frame national geospatial reference system. By accounting for both local and global geodynamic effects using time-dependent transformations, the LRF can minimize the complexity that results when objects that are fixed with respect to the ground have continuously time-varying coordinates in a global frame.

The role of the national geospatial reference system, of which the reference frame is a core component, has changed. Whereas traditionally a national geodetic datum of the highest available precision has been required for accurate surveying and positioning, GNSS-derived positioning now provides easy access to precise global reference frames such as ITRF. However, the exponential growth of spatial data sets has created a need for a geospatial reference system providing coordinates that are "ground-fixed". That is, the system provides coordinates that can be used to locate and relate physical features, and to align spatial data sets acquired at different times. This requires the definition of a LRF and reference epoch, with clear traceability to a global reference frame such as ITRF.

The ITRF has long been adopted as the most precise means of accessing a LRF using Precise Point Positioning (PPP) and global post-processing services, or for applications where the highest precision is required. However, transformation to the local frame has not always been carried out robustly, whether due to a lack of officially defined transformations or failure of systems to utilize time-dependent transformation parameters. Formal recognition of ITRF within a national spatial referencing system will support the increasingly broad range of users and applications utilizing high precision ITRF coordinates derived from absolute positioning, including rapidly emerging real-time PPP services and geodetic imaging techniques such as Lidar and InSAR.

While some of the implementation details will differ to reflect the local tectonic and legislative environment, the suggested framework could be used by any jurisdiction

N. Donnelly (✉)
Cooperative Research Centre for Spatial Information, University of New South Wales, Sydney, NSW, Australia

School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW, Australia

National Geodetic Office, Land Information New Zealand, Wellington, New Zealand
e-mail: ndonnelly@linz.govt.nz

C. Crook
National Geodetic Office, Land Information New Zealand, Wellington, New Zealand

R. Stanaway • C. Roberts • C. Rizos
School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW, Australia

J. Haasdyk
Cooperative Research Centre for Spatial Information, University of New South Wales, Sydney, NSW, Australia

Survey Infrastructure and Geodesy, NSW Land and Property Information, Bathurst, NSW, Australia

T. van Dam (ed.), *REFAG 2014*, International Association of Geodesy Symposia 146,
DOI 10.1007/1345_2015_188

considering an updated approach to defining the reference frame in its national geospatial reference system.

Keywords
Datum • Deformation Model • Reference frame • Transformation

1 Introduction

The *national geospatial reference system* (NGRS) for a country is the geodetic infrastructure which supports positioning to the highest levels of precision and robust management of spatial data. It includes survey marks and their coordinates, infrastructure and data providing connections to the reference frame, as well as tools, recommendations and standards to assist with its use (Johnston and Morgan 2010). At its core is the authoritative reference frame, supported (and in many cases mandated) by government for use in diverse spatial applications.

Prior to the advent of GNSS, accurate spatial positioning could only be achieved by measuring to nearby marks which defined the geodetic datum or by astronomical observations. GNSS-derived positions based on global reference frames have replaced this function, allowing ubiquitous and very accurate positioning without the need for intervisible local marks (although these are still useful for supporting some surveying techniques). GNSS technology dominates positioning to the extent that it is now very rare for a position to be calculated that does not utilize GNSS, albeit that the use may be indirect (for example, when positioning relative to an existing coordinate calculated from GNSS observations). It matters little whether the GNSS-derived position is direct or indirect; the outcome is that coordinates are natively in terms of a global reference frame, often with a high level of precision.

Geodetic imaging describes any technique which uses massive point clouds (or pixels) to produce an image which is georeferenced to a level typically associated with geodetic coordinates (0.1 m or better). Examples include precise photogrammetry, pictometry, Lidar, Terrestrial Laser Scanning (TLS) and InSAR. The points generated by these images are often defined in terms of a global reference frame, due to the combination of the imaging sensor with a GNSS receiver. The use of geodetic imaging is increasing rapidly and the massive volume of data generated greatly exceeds that from direct GNSS positioning. Reference systems need to support this technology.

At the same time the need for coordinate reference systems for GIS has greatly increased. These systems require coordinates that represent physical features and their relative real-world spatial relationships. A requirement of GIS is that the coordinate can be used to relocate the feature in the future if needed and that the coordinates provide good relative precision, both horizontally and vertically. Most GIS systems assume static relationships between these features and do not account for movement or deformation over time. In the absence of any localized deformation, spatial data acquired over long periods of time over a common area should be spatially aligned in a LRF. The requirement for accurate calculations based on coordinates (for example, distances at geodetic type accuracies) is of much lower priority for a LRF. There is, however, a requirement for moderate local accuracy, particularly to determine which features are coincident, overlapping, or within a specified distance of each other. For many users, these needs are better met by the traditional geodetic datum of well-placed marks with fixed coordinates, subject to understanding the limitations of relative precision that ensues from this where there is non-negligible deformation. Thus a LRF in which coordinates are generally constant over time remains very useful.

For many applications, heights related to the gravity field are of most interest, since these will reliably represent fluid flow. Traditionally, this has led to local vertical reference frames based on mean sea level and precise levelling. Increasingly, the trend is for modern vertical reference frames to be defined in terms of the geoid or quasigeoid and accessed using GNSS-derived ellipsoidal heights and a geoid model. For example, New Zealand implemented a quasigeoid-based vertical reference frame in 2009 (Amos 2009). This paper does not further consider the vertical reference frame, except to note that analysis is required to determine how deformation modelling should be incorporated into a vertical reference frame, if at all, given that many engineering applications require that vertical deformation is visible in measurements. These decisions about handling deformation will impact on the relationship between the vertical and geometric reference frames.

Overall, a national geospatial reference system consisting of both global and local reference frames may better meet current and future requirements than a system consisting of a single frame.

2 Classifying Reference Frames

The consistent use of clearly defined, unambiguous terminology greatly assists with understanding the concepts associated with the geospatial reference system. Without a sound understanding of the concepts, there is a significantly increased risk that geospatial datasets are incorrectly managed. In particular, many users are now managing datasets of sufficiently high precision that they must correctly account for geodynamic effects. Unfortunately, some of the terminology commonly used to describe elements of the national geospatial reference system adds to user confusion.

The term *reference frame*, as distinct from *datum*, correctly describes contemporary geospatial reference systems, which are usually based on a realisation of the International Terrestrial Reference System (ITRS). The term *datum* describes the relationship between a reference system and reference frame (origin, axes orientation and scale) (Drewes 2009). Thus *datum* was appropriate to use prior to the availability of the ITRF, when the datum was typically fixed to the Earth's surface by fixing the coordinates of at least two stations to define the origin, orientation and scale. In the case of ITRF (and any LRF aligned to ITRF), station coordinates are not fixed; they may change due to improved observations and/or land movement. The fact that the coordinates of features may change with time is a new concept for many users, so in addition to being technically correct, the use of *reference frame* highlights that coordinate behaviour may be different to that associated with traditional geodetic datums.

More generally, there is confusion resulting from conflicts between the terminology used by the International Organization for Standardization (ISO) and that in long-standing usage by the International Astronomical Union (IAU) and International Association of Geodesy (IAG) through the International Earth Rotation and Reference Systems Service (IERS). The IAU/IAG distinguish between the *reference system*, being a set of conditions that need to be met to define spatial references, and the *reference frame*, being the realization of that reference system by precisely determining coordinates at physical points (Petit and Luzum 2010). For the wider geospatial community, the definitions of the ISO standard 19111: Geographic Information – Spatial Referencing by Coordinates are more widely used. This standard uses the term *datum* in preference to *reference frame* and *coordinate reference system* to describe how coordinates are expressed in terms of a datum/reference frame (for example: geocentric or geographic) (ISO 2007). The *coordinate reference system* of ISO is not the same as the *reference system* of the IERS. This paper utilizes the terminology of the IERS, but until such time as there is agreement on preferred terminology between the geodetic and wider geospatial communities, it is important that the meaning of these terms is clearly defined within each national geospatial reference system.

Frequently, the terms *dynamic*, *semi-dynamic* and *static* are used to describe reference frames (or geodetic datums). Use of these terms causes confusion for reference frame managers and users alike. For example, when a reference frame is described as *dynamic*, this means that the coordinates for a ground-fixed feature are time-varying within that frame. Thus it is not the reference frame, but the coordinates which are "dynamic". Even when referring to coordinates, the term "dynamic" is not rigorously correct, as technically this implies force in the coordinate movement, which is not necessarily the case. "Kinematic" is a more appropriate term, as it implies nothing about the cause of the motion. Thus ITRF, which is sometimes described as a "dynamic datum", is in reality a static reference frame with kinematic coordinates for ground-fixed physical features.

Similarly, "semi-dynamic" has been used to describe a reference frame where coordinates change with time, but only periodically, with the period between updates being determined subjectively by the reference frame manager. Coordinate updates may be triggered either by localized deformation, or secular movement over a sufficiently long period that discrepancies with global frames become problematic. Otherwise, the coordinates in a semi-dynamic frame are static, and a time-dependent model is used to ensure that consistent coordinates can be calculated from observations made at various times. Conceptually, there is no clear factor that differentiates a "semi-dynamic" from a "static" frame. In fact, coordinates in traditional static geodetic datums have also been updated as required to reflect localized deformation, although the official coordinates usually represent only the current state. For example, coordinates affected by the 1987 Edgecumbe earthquake in New Zealand were updated, even though the geodetic datum at the time was static. Similarly, there are static reference frames that make use of time-dependent transformations, so this characteristic is not unique to semi-dynamic frames. An example is the Geocentric Datum of Australia 1994 (GDA94), which utilizes a time-dependent 14-parameter transformation to transform coordinates from ITRF (Dawson and Woods 2010).

A better way to classify reference frames is to consider the body onto which they are fixed. The concept of an *Earth-fixed* frame is that it is fixed to the whole solid Earth at a depth where no tectonic movement occurs. In practice, this may be difficult or impossible to achieve as even deep beneath the surface there are geodynamic processes which would likely compromise attempts to define a stable reference frame. Thus the Earth-fixed frame may be realized using the no-net-rotation condition, as is the case for ITRF (Altamimi et al. 2011). The concept of a *plate-fixed* frame is that it is fixed to (and therefore moves with) a tectonic plate (or plates in the case of a country which straddles a plate boundary). Again this concept may be challenging to implement in practice in those regions where there is non-uniform plate motion. In effect, the reference frame is deforming with the plates, which needs to be accounted for using a deformation model. Despite the implementation issues, these terms are useful as they relate explicitly to the reference frame and the body to which it is fixed, rather than trying to describe the behaviour of coordinates of features within the frame.

Reference frames can also be classified as global or local. This terminology is reasonably intuitive, and correlates well with the use of "global" to describe the likes of the Global Positioning System, which is familiar to both spatial professionals and the general populace. The term "local" used here describes a geographical area, no larger than continental-scale, over which the relevant authorities have determined that a single reference frame is required. It could vary from a few square kilometres for a small island nation to covering an entire continent, as would be the case for Australia. In many parts of the world, such as Europe and South America, regional reference frames provide a continent-wide frame on which the local frames of individual countries (if required) are based to ensure consistency across borders. Some countries may decide that the regional reference frame is sufficient to act as the local frame. The discussions relating to plate-fixed local frames generally also apply to a plate-fixed regional reference frame.

3 The Two-Frame System: Global and Local

3.1 Global Frame

The first frame in the proposed two-frame system is the Earth-fixed, global reference frame. This should be the most recent ITRF (currently ITRF2008 (Altamimi et al. 2011)), to ensure consistency with data and products used to compute high-precision positions, such as the precise orbit and clock products of the International GNSS Service (IGS). This also ensures that coordinates calculated using techniques such as Precise Point Positioning (PPP), or derived from such techniques (as may be the case for a geodetic imaging point cloud), are immediately in terms of the official global reference frame.

As new (improved) ITRF realisations are released, these should be incorporated into the national geospatial reference system, replacing the previous realisation. The exact timing of the adoption of a new ITRF would be determined by the national geodetic agency and would likely not take place until organisations such as the IGS were providing products in terms of the new ITRF. The current stability of successive ITRFs means that for many applications, the impact of adopting a new ITRF would be negligible. However, the adoption of any new ITRF is important if the national geospatial reference system is to support the highest-precision geodetic applications.

The adoption of the ITRF as an official reference frame for a jurisdiction formalizes the long-standing practice of carrying out processing in the ITRF, before transforming to a LRF if necessary. Making it an official frame within the country recognizes that there are some computations that cannot be accurately carried out in a local frame. One example is GNSS processing, which must be carried out in a global reference frame to remove biases due to plate rotation and enable use of precise global data products, such as orbit and clock parameters. Another is precise engineering design in a deforming area, where LRF coordinates may not sufficiently represent the physical kinematic reality. Precise engineering requirements could provide a trigger to update the LRF, where precision tolerances for large scale engineering projects are exceeded.

Adoption of the ITRF will make it easier to support applications related to navigation, such as automated aircraft guidance systems, where the use of the ITRF-aligned WGS84 is mandated (ICAO 2002). It will also be easier to support geodetic imaging techniques generating large sets of ITRF-aligned coordinates. In the near future, the volume of data being collected using these systems and techniques is likely to be so much greater than the volume of data in existing datasets that it may be more efficient to bring these existing datasets to the epoch of the geodetic imaging dataset, rather than transforming the geodetic imaging dataset to the local frame. Another possibility is to provide large geodetic datasets in the local frame (data are transformed once) whilst retaining the original in ITRF for future data combinations or transformations. Duplication of data is perhaps less of an issue than repeated transformations of data both in terms of risk and computing cost.

There are also non-technical advantages. Defining a global frame officially within the country emphasizes to decision-makers and the spatial community that the global reference frame is of critical importance to GNSS-derived positioning. In some jurisdictions, this may make it easier to justify contributions to the infrastructure and analysis required to develop and maintain the ITRF. Direct linkage of the LRF to ITRF is also of value at jurisdictional boundaries.

In the context of a national geospatial reference system, the global frame may be a specific ITRF-aligned realization computed by the reference frame manager, or adopted from an organization such as the IGS. It is not necessarily the exact reference frame published by the IERS. The key requirements are that the global frame used within a jurisdiction is as consistent as practicable with the official ITRF and that details of the procedure used to generate coordinates and velocities is well-documented and publically accessible.

3.2 Local Frame

The second frame in the proposed two-frame system is the plate-fixed, local reference frame. Where possible, it is fixed to the stable portion of a tectonic plate at a particular epoch, which becomes the reference epoch for the frame. In some countries, such as New Zealand, there is no stable plate but the LRF could still be precisely fixed to the deforming tectonic plates at a chosen reference epoch.

There are two approaches that could be used to define a LRF. The first is to explicitly define a set of coordinates using a suitably precise GNSS campaign, as undertaken in Europe for EUREF. The second approach is to define the LRF implicitly through its relationship to the global frame via transformation and/or deformation models, as done in New Zealand. Regardless of which approach is chosen, permanent GNSS stations and other precise geodetic observations are then used to monitor and update the relationship between the local and global frames. In this discussion we assume the second approach has been taken, although similar outcomes are achieved with either approach.

Use of a local frame removes uniform plate rotation and various non-uniform deformation effects. Within this frame the coordinates of fixed features are stable – and the velocities are minimized (near-zero) – see Fig. 1. The accuracy with which a coordinate identifies a ground-fixed point over time is determined by the extent to which plate motion and deformation is accounted for in the time-dependent models used to transform between the global and local frames. Since official time-dependent models are specified by the national geodetic agency, new versions of the time-dependent models can be produced to respond to local requirements. For example, after the 2010 and 2011 Canterbury earthquake sequence in New Zealand, there was strong demand from spatial professionals for LRF coordinates to be updated to reflect the post-earthquake relationships among physical features. However, there has been little demand for the reference epoch of the secular deformation component to be updated. Thus a new version of the deformation model was developed that updated coordinates to reflect earthquake movements but did not update coordinates to reflect the 10 years of secular motion (Crook and Donnelly 2013). This flexibility ensures that the LRF is responsive to user needs.

Within the local frame, any non-zero velocities or coordinate changes for ground-fixed physical features are indicative of land movement not accounted for in the time-dependent transformation models.

Provision of a LRF addresses the current difficulties with using kinematic coordinates for some applications. Some of these problems are likely to reduce in the near future, as widely used GIS software better incorporates time-dependent transformation models. But for some applications, there are legal requirements that are difficult to change in the short term. For example, property boundaries are often described by physical relationships and/or fixed coordinates in terms of the LRF. While it may not be technically difficult to utilize kinematic coordinates in terms of a global reference frame, the legislative change that could be required is unlikely to occur quickly, given that there are unlikely to be advantages from making such a change for this application.

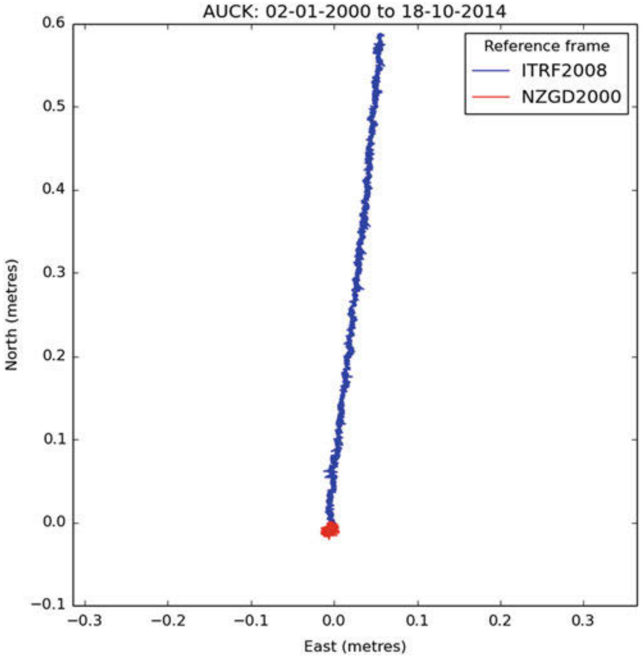

Fig. 1 Horizontal daily time series of the IGS station AUCK in terms of ITRF2008 (global frame), in *blue*, and New Zealand Geodetic Datum 2000 – NZGD2000 (local frame), in *red*. In this case the daily ITRF2008 coordinate is calculated by aligning to the official IERS coordinates of a regional subset of ITRF2008 stations. The trajectory in terms of the local frame is almost static

4 Time-Dependent Transformation Models

In a two-frame system, the term *time-dependent transformation model* refers to any model which describes the relationship between the global and local frames, enabling coordinates to be transformed between the two frames. Reference frame transformation models, plate motion models (PMMs) and deformation models are all examples of models which could be required in the two-frame system. A key feature of the transformation approach is that it would be possible for users requiring different precisions to apply different layers / portions of the transformation model(s), based on their accuracy requirements and/or computational resources. The full transformation path is shown in Fig. 2. Note that the order in which the reference frame transformation, PMM and

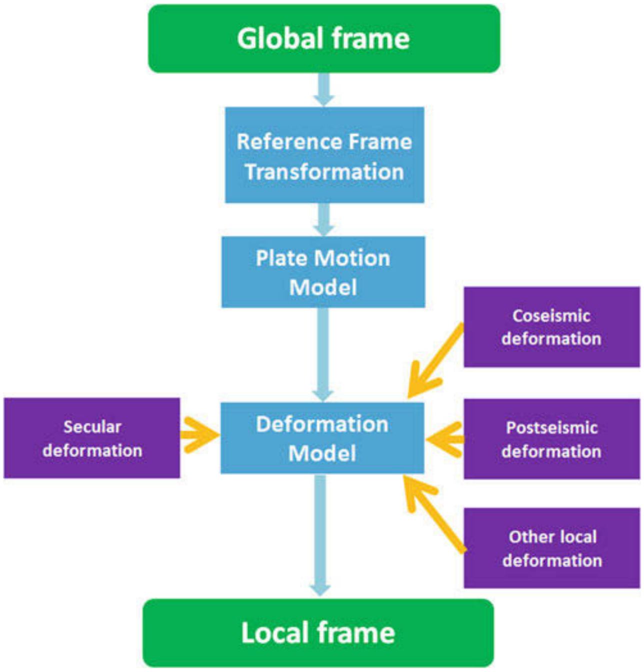

Fig. 2 Transformation path between the global and local frames. This figure assumes that the PMM and deformation model are defined in terms of the local frame, so the reference frame transformation is carried out first

deformation model should be applied depend on how these have been defined.

The reference frame transformation model is required where the local frame is aligned to a different ITRF realisation. For example, New Zealand's local frame is currently aligned to ITRF96, so a 14-parameter transformation is required when transforming coordinates from ITRF2008 (three translations, three rotations, one scale parameter and their time-dependent equivalents). The coordinate epoch is differenced from the reference epoch for the transformation to appropriately calculate the time-dependent parameters which apply over that period.

The PMM describes the impact of rigid plate motion on the coordinates being transformed. It can be defined using three rotation-rate parameters. As with the reference frame transformation, the coordinate epoch is differenced from the reference epoch for the transformation to appropriately calculate the specific rotation to apply to the coordinate over that period. In stable countries such as Australia, the PMM would remove almost all of the effect of land movement (Stanaway et al. 2014).

The deformation model accounts for the changes in the relative position of features due to geophysical processes. It may consist of a number of submodels, each of which relates to a particular deformation event (or type of deformation).

For example the New Zealand deformation model comprises submodels for a secular deformation component and for a number of earthquakes. Each submodel may include multiple components to represent different types of deformation associated with the event. Thus an earthquake event might include a component for coseismic deformation and one or more postseismic components.

Figure 3 shows a representation of part of the deformation model used in New Zealand. Two submodels are shown, one for the 2007 George Sound earthquake and one for the 2009 Dusky Sound earthquake. The George Sound submodel has a single component modelling the coseismic deformation. However the Dusky Sound submodel has two components, to model both coseismic and postseismic deformation.

The deformation model may also include some rigid plate movement where it is not possible or practical to reliably separate this component into a PMM. For example, Tregoning et al. (2013) identify potential rigid plate movement in the far north of New Zealand, but it may be simpler to implement a single secular deformation model than to divide a region up into discrete microplates or crustal blocks, each defined by a PMM. However, a limitation of a single deformation model is how the model is interpolated across active faults and plate boundaries. An advantage of a polygon based model is that the boundaries of crustal blocks can be defined along active bounding faults. A deformation model can be overlain on the PMM to define intraplate and interseismic plate boundary deformation (back-slip) (Stanaway et al. 2015). Note that the deformation model excludes highly localized monument damage or disturbance. It also does not include smaller deformation events (either tectonic or human induced) which are either not significant, or for which there is currently insufficient data to model reliably.

5 Versioning of Models

The time-dependent transformation models are versioned, which leads to a versioned realization of the LRF. That is, coordinates in the local frame may change if a new version of the deformation model is published. For example, a new version of the deformation model might be released within a few days of a significant earthquake, based only on CORS and seismometer data. An improved version might be released a year later, based on a much wider range of data, such as campaign GNSS and InSAR, or incorporating postseismic deformation.

6 Referencing Coordinates

A fully referenced dataset must have information to enable the coordinates to be reliably updated when a new version of one of the time-dependent transformation models is released.

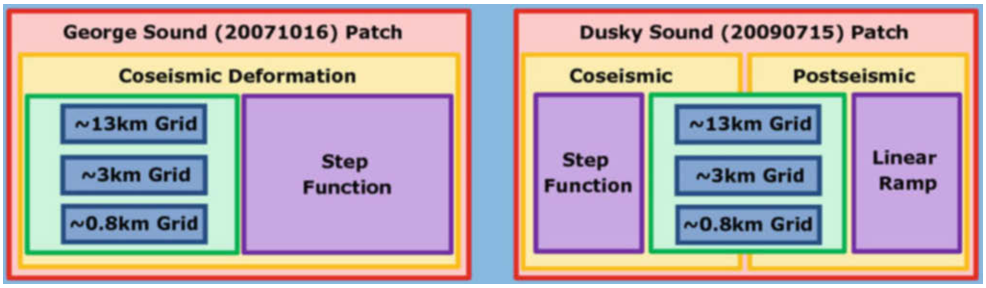

Fig. 3 Representation of part of the NZGD2000 deformation model, available from Land Information New Zealand (2015)

This could either be accomplished by retaining a primary copy of the raw untransformed ITRF data, or more simply by recording the following key metadata items:

1. Reference frame
2. Transformation model version(s) used to calculate coordinates
3. Coordinate epoch

The coordinate epoch is the epoch at which the coordinate was observed. This enables improvements to models of continuous deformation to be applied to coordinates. To illustrate, consider New Zealand's original deformation model, NZGD2000v20000101, which modelled the secular deformation of the country. In 2013 an improved secular deformation model, using data over a much longer time span, was published as part of NZGD2000v20130801 (Crook and Donnelly 2013).

Consider a set of LRF coordinates transformed from ITRF2008 coordinates at epoch 2010.0 using NZGD2000v20000101. The ITRF2008 coordinates were not retained. To improve the precision of these LRF coordinates using the new version NZGD2000v20130801, NZGD2000v20000101 must first be used to recalculate the coordinates at epoch 2010.0. NZGD2000v20130801 is then used to calculate improved coordinates at the reference epoch. Without knowledge of the coordinate epoch, it is not possible to update coordinates when models of continuous deformation are improved.

7 Time-Dependent Models for Trajectory Estimation

The trajectory of a ground fixed feature in the global reference frame can be estimated using the PMM and/or deformation model (as applicable). This enables ITRF coordinates for the feature to be calculated for any desired epoch, which is useful for visualization or analysis of datasets collected or archived at various epochs. It is also necessary for CORS-NRTK and GNSS RTK and post-processing if the reference coordinates are epoch fixed.

8 Concluding Remarks

The official inclusion of two reference frames into a national geospatial reference system would overcome some of the key challenges to implementing a reference frame that meets the needs of a diverse range of users and applications. Critical to the success of a two-frame system is the provision of time-dependent transformation models and the coordinate metadata required to utilize them. Both New Zealand and Australia are likely to implement some form of two-frame system, with some of the concepts, particularly relating to deformation models and descriptions of reference frames, already being used in New Zealand to make improvements to the existing local frame.

Many of the implementation details of the two-frame system are still to be determined. In many cases these will be strongly influenced by local circumstances, but the framework outlined here is sufficiently flexible to be implemented in diverse tectonic and regulatory settings. What is clear is that any modern reference frame will require regular updates and successfully propagating these updates into the geospatial community will be critical to the success of the geospatial reference system.

Acknowledgements This work has been supported by the Cooperative Research Centre for Spatial Information, whose activities are funded by the Australian Commonwealth's Cooperative Research Centres Programme.

References

Altamimi Z, Collilieux X, Metivier L (2011) ITRF2008: an improved solution of the international terrestrial reference frame. J Geod 85:457–473

Amos M (2009) New Zealand Vertical Datum 2009. N Z Surveyor 300:5–16

Crook C, Donnelly N (2013) Updating the NZGD2000 deformation model. In: Proceedings of the 125th New Zealand Institute of Surveyors Conference, Dunedin, 29–31 August 2013. http://www.nzisltsurveybook.org.nz/sites/all/files/joint%20proceedings%20nzis%20sircnz_V1.pdf. Accessed 20 Aug 2011

Dawson J, Woods A (2010) ITRF to GDA94 coordinate transformations. J Appl Geod 4:189–199

Drewes H (2009) Reference systems, reference frames, and the geodetic datum – basic considerations. In: Sideris M (ed) Observing our changing earth. Proceedings of the 2007 IAG General Assembly, Perugia, Italy, July 2–13, 2007, International Association of Geodesy Symposia, vol 133, pp 3–9

ICAO (2002) World Geodetic System – 1984 (WGS-84) manual, 2nd edn, Doc 9674, AN/946, International Civil Aviation Organization. http://www.icao.int/NACC/Documents/Meetings/2014/ECARAIM/REF08-Doc9674.pdf. Accessed 4 July 2015

ISO (2007) ISO19111:2007 geographic information – spatial referencing by coordinates. International Organization for Standardization

Johnston G, Morgan L (2010) The status of the national geospatial reference system and its contribution to global geodetic initiatives. In: Proceedings of XXIV FIG World Congress, 11–16 April 2010, Sydney, Australia. http://www.fig.net/pub/fig2010/papers/ts06c%5Cts06c_johnston_morgan_4116.pdf. Accessed 4 July 2015

Land Information New Zealand (2015) NZGD2000 deformation model. http://www.linz.govt.nz/data/geodetic-system/datums-projections-and-heights/geodetic-datums/new-zealand-geodetic-datum-2000. Accessed 4 July 2015

Petit G, Luzum B (eds) (2010) IERS conventions (2010), IERS technical note 36. Verlagdes Bundesamts für Kartographie und Geodäsie, Frankfurt am Main, Germany. http://www.iers.org/IERS/EN/Publications/TechnicalNotes/tn36.html. Accessed 4 July 2015

Stanaway R, Roberts C, Blick G (2014) Realisation of a geodetic datum using a gridded absolute deformation model (ADM). In: Rizos C, Willis P (eds) Earth on the edge: science for a sustainable planet. Proceedings of the IAG General Assembly, Melbourne, Australia, June 28 to July 2, 2011. International Association of Geodesy Symposia, vol 139, pp 259–256

Stanaway R, Roberts C, Rizos C, Donnelly N, Crook C, Haasdyk J (2015) Defining a local reference frame using a plate motion model and deformation model. In: Proceedings of IAG Commisison 1 Symposium 2014: Reference Frames for Applications in Geosciences (REFAG2014), 13–17 October, Kirchberg, Luxembourg

Tregoning P, Burgette R, McClusky SC, Lejeune S, McQueen H, Watson CS (2013) A decade of horizontal deformation from great earthquakes. J Geophys Res 118. doi:10.1002/jgrb.50154