Defining a Local Reference Frame Using a Plate Motion Model and Deformation Model

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

Abstract

As GNSS point-positioning becomes more precise and accessible to a wider spectrum of users, the issue of misalignment between GNSS positioning reference frames and spatial data reference frames used in GIS will become more apparent. Positions of plate-fixed features within GNSS reference frames are kinematic in nature due to global plate motions and other geophysical phenomena including seismic deformation and post-glacial rebound. Coordinates within GIS and applications such as Google Earth on the other hand, are typically fixed to the Earth's surface and tectonic plate and may be misaligned with global reference frames unless a kinematic model is applied to the data.

The problem becomes more apparent when data acquired at different epochs are combined in the absence of a kinematic model. Should a GNSS point-position or baseline vector solution be transformed to the epoch of existing spatial data, or should the spatial data be transformed to the epoch of the point-position? In either case, data acquired at different epochs within a GNSS frame will need to be transformed to a common epoch for the purpose of combination, interpretation and analysis. Furthermore, localised deformation analysis studies using remote sensing techniques such as InSAR and Lidar require removal of any secular plate motion signal prior to meaningful analysis. Presently, it is more computationally efficient to transform GNSS observations to a formalised reference epoch for spatial data.

A logical approach to the problem is to develop a Local Reference Frame (LRF) which is fixed to the crust within a defined polygon, and which is also directly traceable to GNSS reference frames such as the International Terrestrial Reference Frame (ITRF) by means of a Plate-Motion Model (PMM) and residual Deformation Model (DM). In plate boundary zones where crustal deformation is significant such as New Zealand, a PMM is of limited application and an "Absolute" Deformation Model (ADM) can be used to describe the full transformation between reference frames. PMMs are specified by an Euler Pole which can also be defined by the rotation rates of the three Cartesian axes. The Euler Pole is estimated by inversion of a selection of station ITRF site velocities. A residual DM can be estimated by kriging or least-squares collocation of site-velocity residuals within the PMM and application of a fault locking model where elastic strain or seismic deformation is evident.

R. Stanaway (✉) • C. Roberts • C. Rizos
School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW, Australia
e-mail: richard.stanaway@student.unsw.edu.au; c.roberts@unsw.edu.au

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

J. Haasdyk
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_147

Use of a PMM and associated DM enables ITRF positions and vectors (e.g. from GNSS observations) to be transformed to a local frame to support GIS data integration and combination of data acquired using terrestrial positioning techniques such as Terrestrial Laser Scanning and conventional Total Station surveys. A case-study for the development of a new Australian Terrestrial Reference Frame is presented.

Keywords
Deformation model • Plate motion model • Reference frame

1 Introduction

The rapid improvement in mass-market positioning precision is presenting new challenges to users and managers of spatial data. GNSS positioning is inherently undertaken within reference frames closely aligned to ITRF (e.g. WGS84 for GPS and PZ-90 for GLONASS). In the near future it is anticipated that centimetre-level positioning precision will be attainable by a wide spectrum of users of personal navigation devices. This increase in precision will result from improvements to GNSS orbit products, GNSS augmentation systems and software. Such precision does pose a dilemma for managers of geodetic infrastructure and spatial data: Spatial data infrastructure is currently referenced to ground-fixed reference frames where coordinates of stable features are not expected to change significantly as a function of time, especially in tectonically stable regions. The dilemma arises where GNSS derived precise positions in terms of a kinematic global reference frame are used erroneously in the context of existing spatial data defined in ground-fixed frames (e.g. static geodetic datums).

Presently there are two approaches to resolving the misalignment between positioning and spatial data reference frames. One approach is to transform existing spatial data sets defined in a ground-fixed frame to the epoch of a GNSS precise position. Another approach is to transform GNSS precise positions to a local ground-fixed frame. Both approaches make use of a conformal transformation (e.g. a 14 parameter transformation) or time-dependent block shift derived from an ITRF site velocity model e.g. Stanaway et al. (2014). The first approach is not yet widely implemented or tested in GIS software and kinematic transformation algorithms are still in development. Furthermore, the computational overhead of transforming large volumes of spatial data "on-the-fly" can be a limitation with this approach. The second approach is presently in more widespread use (e.g. in geodetic analysis software) as it is well suited to current generation geodetic datums which are inherently fixed to the Earth's crust at a defined reference epoch. Either approach must be used to combine and analyse spatial data acquired at different epochs of ITRF. In the absence of metadata, the difference between a GNSS precise position and a precise spatial database can be significant.

Local Reference Frames (LRF) fixed to stable portions of the Earth's crust are ideally suited to support spatial data integration over longer periods of time as site velocities are minimised with respect to the local frame. However, there remains the issue of how GNSS precise positions relate to spatial data defined in a ground-fixed frame and the 14 parameter transformation and gridded deformation model approaches each have their limitations. 14 parameter transformations include scale and scale-rate parameters which, if non-zero, implicitly define uniformly distributed deformation of the local frame. Gridded deformation models can better accommodate localised and variable deformation, however they maybe inefficient over large areas of stable tectonic plates. For tectonically stable regions, a plate motion model (PMM) (Altamimi et al. 2011, 2012) can be used to transform GNSS point positions to a local frame. Where higher precision is required a residual deformation model can also be applied if intraplate deformation is significant. In the USA, residual deformation and block-rotation models have been used in Horizontal Time-Dependent Positioning (HTDP) software (Snay 1999; Pearson and Snay 2012) since 2000.

The advantage of a PMM is that it is inherently distortion-free as it is defined by the rotation of a stable portion of the tectonic plate. Localised or intraplate deformation is more clearly visualised where the rigid plate rotation component is removed.

Regional Reference Frames (RRF) fixed to tectonic plates such as ETRF89 (Boucher and Altamimi 1992), NAD83 (Schwarz 1983) and GDA94 (Steed 1995) have been defined from earlier realisations of ITRF, and 14 parameter transformations are required to transform positions within these RRF to ITRF at a specified epoch. Furthermore, residual deformation within these RRF are evident as non-zero station velocities for stations in deforming zones within the RRF.

This paper shows how a PMM and residual DM can be used to define an LRF. The simplest realisation of a LRF is by a four parameter transformation from ITRF to the local frame: three rotation rate parameters of the Cartesian axes of the local frame within ITRF and an epoch-difference parameter. A case-study in support of a new Australian Terrestrial Reference Frame is presented.

2 Plate Motion Models

The Earth's surface comprises of a series of stable tectonic plates rotating slowly over the mantle and deforming zones generally located near plate boundaries. Recent studies e.g. Bird (2003), DeMets et al. (2010), Altamimi et al. (2011), Argus et al. (2011) and Kreemer et al. (2014) have better defined the extent of smaller tectonic plates (microplates) and stable crustal blocks within these deforming zones. Euler Poles estimated for each of these plates and crustal blocks can be adapted to define a stable LRF to support land surveying and GIS activities. Where deformation of a plate or block is significant a residual DM can be applied for higher precision applications. Estimation of Euler Poles of tectonic plates using space geodetic and geophysical observations is well documented e.g. DeMets et al. (1990). An Euler Pole can be defined using space geodetic techniques by least-squares inversion of n sites with ITRF site velocities estimated from analysis of the ITRF site time-series (Eqs. 1–9) adapted from Goudarzi et al. (2014). Site velocities are typically defined during the interseismic period, so any known coseismic and postseismic deformation should be isolated from the time-series analysis. Elastic strain accumulation arising from locked faults near a site should also be modelled using elastic half-space models in order to estimate interseismic back-slip (McCaffrey 2002).

$$\boldsymbol{\Omega}^{plate} = \left(\mathbf{A}^T\mathbf{W}\mathbf{A}\right)^{-1}\left(\mathbf{A}^T\mathbf{W}\mathbf{L}\right) \quad (1)$$

where,

$$\boldsymbol{\Omega}^{plate} = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \quad \mathbf{A} = \begin{bmatrix} 0 & z_1 & -y_1 \\ -z_1 & 0 & x_1 \\ y_1 & -x_1 & 0 \\ \vdots & \vdots & \vdots \\ 0 & z_n & -y_n \\ -z_n & 0 & x_n \\ y_n & -x_n & 0 \end{bmatrix}_{ITRF} \quad \mathbf{L} = \begin{bmatrix} Vx_1 \\ Vy_1 \\ Vz_1 \\ \vdots \\ Vx_n \\ Vy_n \\ Vz_n \end{bmatrix}_{ITRF}$$

and,

$\boldsymbol{\Omega}^{plate}$ is the Euler Pole (rotation rate of axes ω_x ω_y ω_z in Rad/year)

A is the design matrix of ITRF cartesian site coordinates (m) x_1 y_1 z_1 to x_n y_n z_n

W is the weight matrix (if applicable)

L is the observation matrix of ITRF site velocities (m/year) Vx_1 Vy_1 Vz_1 to Vx_n Vy_n Vz_n

The Euler Pole can also be expressed using Eqs. (2–4):

$$\text{Pole rotation rate (in Rad/yr)} \quad \omega_{plate} = \sqrt{\omega_x{}^2 + \omega_y{}^2 + \omega_z{}^2} \quad + \text{is anti} - \text{clockwise about pole)} \quad (2)$$

$$\text{Pole latitude} \quad \phi_{plate} = \tan^{-1}\frac{\omega_z}{\sqrt{\omega_x{}^2 + \omega_y{}^2}} \quad (3)$$

$$\text{Pole longitude} \quad \lambda_{plate} = \frac{\omega_y}{\omega_x} \quad (4)$$

Site velocities (m/year) for any specific point can be computed directly from the Euler Pole model using (5):

$$\begin{bmatrix} Vx \\ Vy \\ Vz \end{bmatrix} = \begin{bmatrix} \omega_Y z - \omega_Z y \\ \omega_Z x - \omega_X z \\ \omega_X y - \omega_Y x \end{bmatrix} \quad (5)$$

The Euler Pole can be expressed as a three parameter conformal transformation as follows:

(rotation rates in radians per year)

$$\dot{r}_x = -\omega_x \quad \dot{r}_y = -\omega_y \quad \dot{r}_z = -\omega_z \quad (6)$$

(Note: Equation (6) uses the coordinate frame rotation convention. If the position vector notation convention is used, the signs of rotation rates and derived rotations are reversed)

The rotation rates in Eq. (6) can be expressed conventionally as arcseconds per year using (7).

$$r_{(\text{arc sec}/yr)} = \frac{648000\,\omega_{(Rad/yr)}}{\pi} \quad (7)$$

Velocity residuals are computed using Eq. (8)

$$\mathbf{v} = \mathbf{A}\boldsymbol{\Omega}^{plate} - \mathbf{L} \quad (8)$$

The reference standard deviation for the Euler Pole inversion is computed using Eqn. (9)

$$S_o = \sqrt{\frac{\mathbf{v}^{\mathbf{T}}\mathbf{W}\mathbf{v}}{r}} \quad (9)$$

where r is the degree of freedom ($r = 2n - 3$) where n is the number of stations used in the inversion.

The standard deviation of each of the rotation parameters is derived by scaling the square-root of diagonal components of the variance-covariance matrix or inverted normal matrix $(\mathbf{A}^T\mathbf{W}\mathbf{A})^{-1}$ by S_o

3 Residual Deformation Models

Analysis of site velocity residuals with respect to plate rotation can be used to visualise interseismic deformation and to develop a residual DM. Such a model can be developed by kriging or least-squares collocation (LSC). Alternatively, a fault locking model (McCaffrey 2002) can be used to estimate back-slip on known locked faults to form an apriori deformation model. Site velocity residuals can then be correlated with estimated back-slip from the apriori model to further refine the deformation model. This approach has been used in HTDP software used in the USA (Snay 1999). The deformation model can be presented as a grid model of velocity residuals with respect to the stable plate. An Absolute Deformation Model (ADM) can be formed by combination of the residual DM and a PMM in grid format to represent the velocity field in terms of ITRF. The ADM approach has been used in the development of the New Zealand Deformation Model 2000 (NZDM2000) (LINZ 2015).

4 Australian Case-Study: Stable Australian Plate Reference Frame (SAPRF)

To illustrate how the PMM and residual DM approach for defining a LRF can be applied in practice, a case-study is presented showing development of a Stable Australian Plate Reference Frame (SAPRF2014). Geoscience Australia have published the latest IGb08 (GPS realisation of ITRF2008) (Rebischung et al. 2012) set-of-station coordinate (SSC) solution (Geoscience 2014a) and associated SINEX file for the Asia-Pacific Reference Frame (APREF) encompassing the extent of the Australian continent (Geoscience 2014b). GPS data for all continuous GPS (CORS) sites forming the APREF network were processed using the Bernese GPS software Version 5.0 (Dach et al. 2007) and the ITRF site velocities for all stations in the network were estimated using the CATREF software (Altamimi et al. 2004). Known coseismic and equipment change offsets were isolated from the velocity estimation and a power-law noise model applied to estimate more realistic station velocity uncertainties from the APREF GPS time-series (John Dawson, personal communication).

46 AuScope and Australian Regional GNSS Network (ARGN) stations (Fig. 1) were used for the inversion of the Euler Pole of the Australian plate that fitted the following criteria:

1. Station located within the Australian continental landmass including Tasmania
2. Antenna mounts and reinforced concrete pillars anchored to cratonic bedrock
3. ITRF site velocity (horizontal component) uncertainty <0.45 mm/year (rooftop, tower, jetties or clay soil locations are excluded from analysis – e.g. MOBS, ADE1, PERT, BUR2)
4. Well distributed selection of stations over the Australian continental landmass

The mean horizontal velocity uncertainty of the 46 stations is 0.4 mm/year with a standard deviation of 0.04 mm/year, hence no weighting was applied to the inversion. Figure 2 shows the ITRF site velocities of the selected network.

The ITRF2008 Euler Pole (Rad/year) for the Australian plate was estimated by inversion of the 46 site velocities using Eq. (1)

$$\mathbf{\Omega}^{AustPlate} = \begin{bmatrix} 7.2905\text{E}^{-9} \\ 5.7479\text{E}^{-9} \\ 5.8807\text{E}^{-9} \end{bmatrix}^p$$

The standard deviation of the rotation rates using (Eqns. 8 and 9) are:

$$\sigma_{\omega_x} = 4.512\text{E}^{-11}\text{Rad/yr} \quad \sigma_{\omega_y} = 4.147\text{E}^{-11}\text{Rad/yr}$$
$$\sigma_{\omega_z} = 3.652\text{E}^{-11}\text{Rad/yr}$$

The equivalent Euler Pole rates using (Eqns. 2, 3 and 4) are:

$$\omega_p = 0.630^\circ/\text{Ma} \quad \phi_p = 32.35^\circ \quad \lambda_p = 45.17^\circ$$

The SAPRF2014 Euler Pole is closely aligned with the published ITRF2008 Euler Pole for the Australian Plate which was estimated from a sparser network of 19 sites forming a subset of the 46 sites used in this paper (Altamimi et al. 2012). Site velocities estimated using the ITRF2008 PMM differ by 0.3 mm/year from velocities estimated from SAPRF2014.

The equivalent SAPRF2014 to ITRF2008 transformation parameters and uncertainties were computed using (Eqns. 6 and 7):

$$\dot{r}_x = -1.5038\text{E}^{-3}\text{arcsec/yr} \quad \dot{r}_y = -1.1856\text{E}^{-3}\text{arcsec/yr}$$
$$\dot{r}_z = -1.2130\text{E}^{-3}\text{arcsec/yr}$$
$$\sigma_{\dot{r}_x} = 9.31\text{E}^{-6}\text{arcsec/yr} \quad \sigma_{\dot{r}_y} = 8.55\text{E}^{-6}\text{arcsec/yr}$$
$$\sigma_{\dot{r}_z} = 7.53\text{E}^{-6}\text{arcsec/yr}$$

The rotation rates are multiplied by an epoch-difference (Δt) to compute the rotation parameters between ITRF2008 and SAPRF2014 at different epochs.

The rotation rate parameters can be used in a 14 parameter transformation model with zeros for all other parameters.

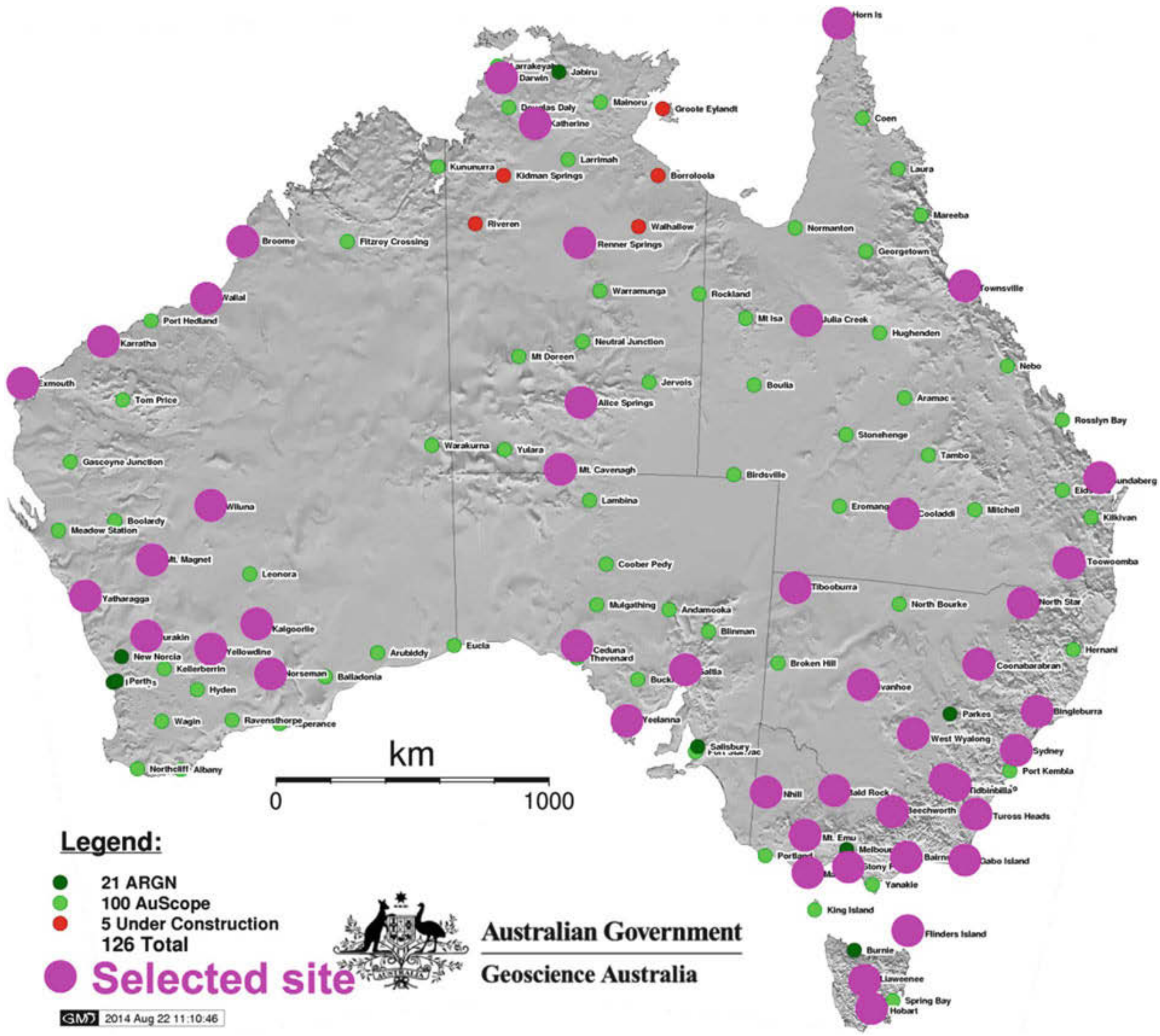

Fig. 1 CORS selection used to estimate pole of stable Australian plate

The velocity residuals were then computed using Eq. (8) and are shown in Fig. 3. The velocity residuals are largely within the uncertainty of the site velocities used for the inversion and indicates that the Australian continent is stable at the level of uncertainty of the observations during periods of interseismic stability. Tregoning et al. (2013) show that large regional plate boundary earthquakes result in observable deformation within the Australian continent at the 10 mm level. Their study shows agreement between observed seismic deformation (both coseismic and postseismic) and modelling. As the uncertainties currently exceed any interseismic deformation signal no residual DM has been developed for SAPRF2014. By 2016 many of the AuScope stations (Fig. 1, green circles) used for the inversion of a refined SAPRF will have a sufficiently long time-series to improve the uncertainties of the site velocities and better quantify the magnitude of any intraplate deformation.

5 Application of SAPRF2014 in Practice

SAPRF2014 can be used as a basis for representation of spatial data in Australia as coordinates of stable features (e.g. bedrock) within the SAPRF2014 will change by less than 0.4 mm/year in the absence of any seismic deformation (local or large regional earthquakes). Kinematic ITRF2008 coordinates can be transformed to SAPRF2014 coordinates by a four parameter transformation (three rotation rates and a difference in epoch). The reference epoch for SAPRF2014 can be arbitrary, however in Australia GDA94 (ITRF92 realised at epoch 1994.0) has been the mandated national geodetic datum since 2000 (Intergovernmental Committee on Surveying and Mapping (ICSM) 2014), and so a reference epoch of 1994.0 would be beneficial to support data integration and surveying until spatial software improvements

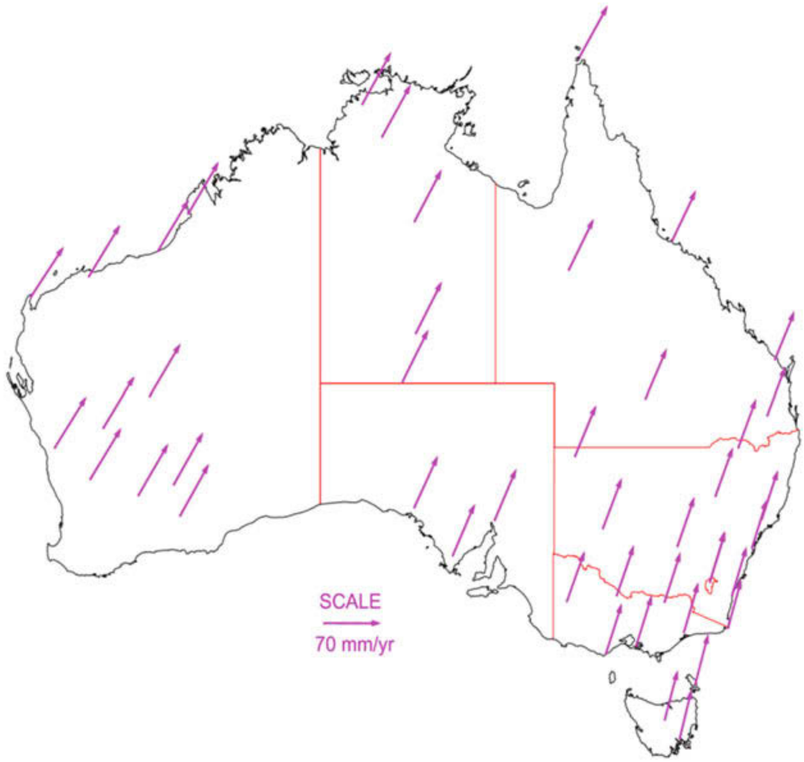

Fig. 2 ITRF site velocities for selected ARGN and AuScope stations

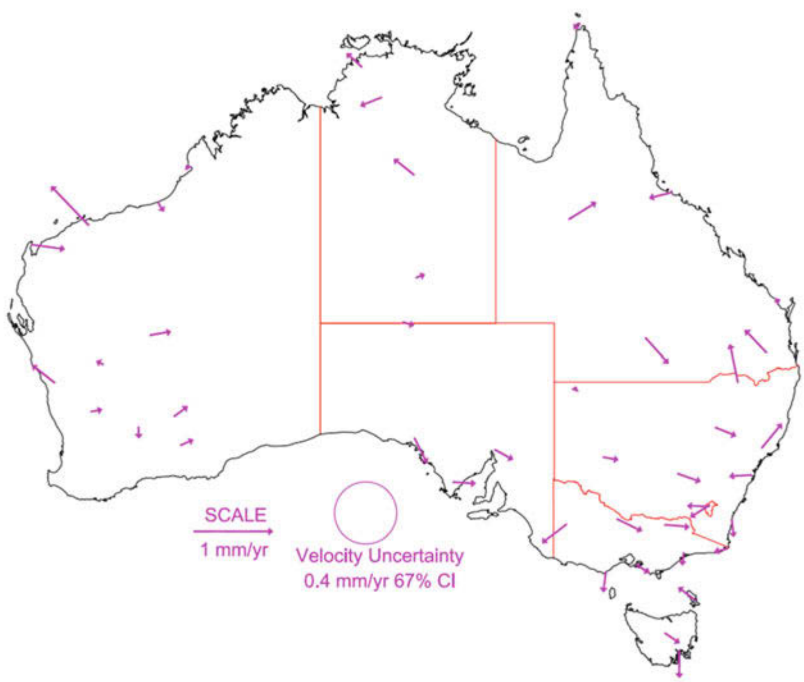

Fig. 3 Velocity residuals for stable Australian plate. The uncertainty of the velocities (0.4 mm/year) are generally greater than the velocity residuals which indicates that intraplate deformation is currently insignificant during interseismic periods

can handle kinematic ITRF coordinates in a robust and assured fashion. Adoption of a 1994.0 epoch for SAPRF2014 in order to maintain consistency with the existing datum would at present result in an increase of uncertainties of up to 5 mm for most locations on the Australian continent (from 3 mm at the current epoch). This uncertainty would be expected to decrease once intraplate deformation rates are better defined. SAPRF2014 at epoch 1994.0 could be described as SAPRF2014(1994.0) in order to clearly show the reference epoch for frame coordinates and velocities. GDA94 currently has significant distortions of up to 300 mm (Haasdyk et al. 2013) and a datum update or readjustment is warranted to minimise these existing distortions. SAPRF ellipsoid heights would be fully consistent with ITRF and

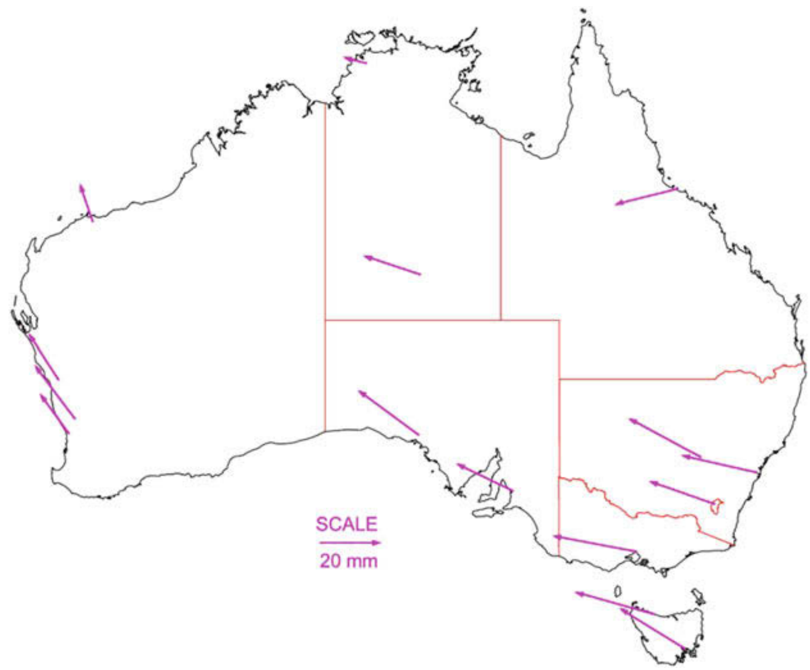

Fig. 4 SAPRF2014 and GDA94 coordinate difference (GDA94 minus SAPRF2014 at epoch 1994.0) at ARGN stations that realise GDA94 as published in 2012

the difference between the GDA94 and ITRF2008 ellipsoid is between 70 and 120 mm (Stanaway and Roberts 2015). Figure 4 shows the differences between GDA94 (as gazetted in 2012) (Commonwealth of Australia 2012) and SAPRF2014 at epoch 1994.0 for the stations which define GDA94 on the Australian continent. The mean distortion is 20 mm in the East component, 10 mm in the North component. The difference is predominantly due to imprecision of the original ITRF92 realisation, coseismic deformation and postseismic relaxation arising from large plate boundary earthquakes. The distortion between GDA94 and ITRF2008 at epoch 1994.0 could be estimated by kriging of observed residuals between the two realisations and presented in a grid format for high precision transformations between GDA94 and SAPRF2014 (1994.0).

6 Conclusion

This paper shows that the inherent stability of many tectonic plates can be used to provide a temporally stable local reference frame to support integration, analysis and management of spatial data. A Plate Motion Model (PMM), which is distortion free, provides a simple four parameter transformation (three rotation rates and epoch difference) allowing reversible transformations between local and global reference frames such as ITRF2008. Using a PMM to describe the uniform movement of a tectonic plate also allows any localised and intraplate residual deformation to be better visualised with the option of higher precision deformation modelling to facilitate higher precision applications.

The Australian case-study describing the development of a Stable Australian Plate Reference Frame shows that the described approach is an improvement on the current mandated geodetic datum in Australia, but still features coordinates that can be considered static for all but the most precise applications.

Acknowledgements John Dawson and Guorong Hu from Geoscience Australia provided the APREF 2014 combination solution and associated SINEX file used in this paper. Their assistance and support is greatly appreciated.

References

Altamimi Z, Sillard P, Boucher C (2004) CATREF Software : combination and analysis of terrestrial reference frames. Publication LAREG SP08, Institut Géographique National

Altamimi Z, Collilieux X, Métivier L (2011) ITRF2008: an improved solution of the international terrestrial reference frame. J Geod 85(8):457–473

Altamimi Z, Métivier L, Collilieux X (2012) ITRF2008 plate motion model. J Geophys Res Solid Earth 117(B7), B07402

Argus D, Gordon R, DeMets C (2011) Geologically current motion of 56 plates relative to the no-net-rotation reference frame. Geochem Geophys Geosyst 12:Q11001. doi:10.1029/2011GC003751

Bird P (2003) An updated digital model of plate boundaries. Geochem Geophys Geosyst 4(3):1027. doi:10.1029/2001GC000252

Boucher C, Altamimi Z (1992) The EUREF terrestrial reference system and its first realizations. EUREF Meeting, Bern, March 4–6

Commonwealth of Australia (2012) ComLaw, National Measurement Act 1960 – Recognized-value standard of measurement of position 2012 (No. 1)

Dach R, Hugentobler U, Fridez P, Meindl M (eds). (2007) Bernese GPS Software version 5.0. user manual, Astronomical Institute, University of Bern, Bern

DeMets C, Gordon R, Argus D, Stein S (1990) Current plate motions. Geophys J Int 101:425–478
DeMets C, Gordon R, Argus D (2010) Geologically current plate motions. Geophys J Int 181(1):1–80. doi:10.1111/j.1365-246X.2009.04491.x
Geoscience Australia (2014a) APREF Network Solution ftp://ftp.ga.gov.au//geodesy-outgoing/gnss/solutions/misc/combination.xyz.vel.2014.0. Accessed 30 Oct 2014
Geoscience Australia (2014b) APREF SINEX file ftp://ftp.ga.gov.au//geodesy-outgoing/gnss/solutions/misc/XVSOLFIN.SNX. Accessed 30 Oct 2014
Goudarzi M, Cocard M, Santerre R (2014) EPC: Matlab software to estimate Euler pole parameters. GPS Solutions 1:153–162. doi:10.1007/s10291-013-0354-4
Haasdyk J, Roberts CA (2013) Monitoring station movement using a state-wide simultaneous 'adjustment of everything' – implications for a next-generation Australian datum. In: Proceedings of the IGNSS symposium 2013 (IGNSS2013), 16–18 July 2013, Gold Coast, 15 pp
Intergovernmental Committee on Surveying and Mapping (ICSM) (2014) Geocentric Datum of Australia 1994 (GDA94) http://www.icsm.gov.au/gda/. Accessed 30 Oct 2014
Kreemer C, Blewitt G, Klein E (2014) A geodetic plate motion and Global Strain Rate Model. Geochem Geophys Geosyst 15:3849–3889. doi:10.1002/2014GC005407
LINZ (2015) New Zealand Deformation Model 2000. http://www.linz.govt.nz/data/geodetic-system/datums-projections-and-heights/geodetic-datums/new-zealand-geodetic-datum-2000. Accessed 25 May 2015
McCaffrey R (2002) Crustal block rotations and plate coupling. In: Stein S, Freymueller J (eds) Plate boundary zones, vol 30. AGU Geodynamics Series, pp 101–122
Pearson C, Snay R (2012) Introducing HTDP 3.1 to transform coordinates across time and spatial reference frames. GPS Solutions. doi:10.1007/s10291-012-0255-y
Rebischung P, Griffiths J, Ray J, Schmid R, Collilieux X, Garayt B (2012) IGS08: the IGS realization of ITRF2008. GPS Solutions 16(4):483–494
Schwarz C (ed) (1983) North American Datum of 1983, NOAA Professional Paper NOS2, National Geodetic Survey, National Oceanic and Atmospheric Administration, US. Department of Commerce
Snay R (1999) Using the HTDP software to transform spatial coordinates across time and between reference frames. Surv Land Inf Syst 59(1):15–25
Stanaway R, Roberts CA (2015) A high-precision deformation model to support geodetic datum modernisation in Australia. In: Rizos C; Willis P (eds) Proceedings of the IAG Scientific Assembly, Potsdam, 1–6 September 2013, International Association of Geodesy Symposia, vol 143
Stanaway R, Roberts CA, 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–July 2, 2011, International Association of Geodesy Symposia, vol 139. pp 259–256
Steed J (1995) The Geocentric Datum of Australia – a co-ordinate system for the 21st century. Second Australian National GIS in the Geosciences Forum, Canberra Australia, pp 29–31
Tregoning P, Burgette R, McClusky SC, Lejeune S, McQueen H, Watson CS (2013) A decade of horizontal deformation from great earthquakes. J Geophys Res. doi:10.1002/jgrb.50154