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A Simplified Parameter Transformation Model from ITRF2005 to any Static Geocentric Datum (e.g. GDA94)

Richard Stanaway
School of Surveying and Spatial Information Systems,
University of New South Wales, Sydney, Australia
ph. +61 3 9486 7845 fax +61 2 9313 7493
email: richard.stanaway@student.unsw.edu.au

Craig Roberts
School of Surveying and Spatial Information Systems,
University of New South Wales, Sydney, Australia
ph. +61 2 9385 4464 fax +61 2 9313 7493
email: c.roberts@unsw.edu.au

ABSTRACT

The majority of PPP, global GNSS post-processing and RTK services (e.g. OmniStar, AUSPOS and OPUS) initially produce coordinates in either ITRF or WGS84 reference frames. Unless these services transform the coordinates into a local static geocentric datum such as GDA94 using a kinematic model, positional coordinates will also be kinematic, changing by up to several cm a year as a result of motion of the underlying tectonic plate. The precision of many GNSS systems currently in widespread use is sufficient to detect this movement over short periods of time. Unless this motion is modelled correctly, repeat surveys using the same technique over a span of a year or more will become misaligned.

This paper describes a strategy whereby ITRF or WGS84 coordinates can be transformed to a regional static geocentric datum by using a four parameter model derived from absolute rigid plate kinematic models. Within tectonically stable areas such as the Australian continent, this transformation strategy is shown to have a precision of 20 mm on decadal timescales, and is ideally suited for most surveying and positioning applications. A simplified parameterisation from ITRF2005 to GDA94 is described as an example of how this strategy can be applied in practice.

KEYWORDS: Kinematic datums, transformation, plate models, PPP

1. INTRODUCTION

Use of global differential services (e.g. AUSPOS, OPUS and OmniStar) and Precise Point Positioning (PPP) services (e.g. the Canadian NRCan service) are now widespread. Depending upon the quality and duration of observations, and quality of receiver, these services deliver coordinates to users with an absolute precision of between 10 mm and 1 m (Table 1). It is envisaged that the accuracy of pseudorange point positions using GNSS broadcast ephemerides (e.g. from handheld GNSS devices) will improve from several metres to around 1 metre with the continuing modernisation and integration of existing and proposed GNSS systems.

Service	ITRF precision	Processing method	Latency	Datums
AUSPOS	10-20 mm (24 hr dataset)	Double Differencing	Post processed (30 min-2 hrs)	ITRF2005 GDA94
NRCan	10-20 mm (24 hr dataset)	Point Positioning (using IGS orbit & clocks)	Post processed (1 min-10 min)	ITRF2005 NAD83(CSRS)
OPUS	10-20 mm (24 hr dataset)	Double Differencing	Post processed (15 min-2 hrs)	ITRF2005 NAD83(NSRS) SPCS
OmniStar -HP	70-100 mm	Double Differencing	RTK (20-30 mins)	ITRF2005 User defined
OmniStar -VBS	500-1000 mm	Double Differencing	RTK (5-10 mins)	ITRF2005 User defined
GNSS (PP only)	3000-8000 mm	Pseudorange Point Positioning	Real-time	WGS84 User defined

Table 1. PPP and global differential services

All of these services initially compute positions in the latest realisation of the International Terrestrial Reference Frame (ITRF) or closely aligned WGS84(G1150) (NGA, 2004). With the exception of AUSPOS, NRCan and OPUS, transformation from ITRF to a localised geodetic datum is solely at the discretion of the user by means of precomputed or user-defined parameters. Precomputed parameters used in most GNSS and GIS software are those published by the US National Geospatial-Intelligence Agency (NGA) (NGA, 2004). These parameters relate a local static geodetic datum to WGS84 and are considered to be sufficiently precise for most GNSS and GIS users at a level of a few metres. The NGA parameters are static and therefore do not account for tectonic motion of the defined geodetic datum/frame within WGS84.

Absolute positioning services and national geodetic agencies adopt different strategies to accommodate deformation of a regional geodetic datum within ITRF and WGS84. Geoscience Australia’s (GA) AUSPOS service uses a 14-parameter model (7 static parameters and associated rates of change) to transform ITRF2000 coordinates to the Geocentric Datum of Australia 1994 (GDA94) (Dawson and Steed, 2004). However, this transformation is only valid within the stable portion of the Australian tectonic plate. Similarly, the NRCan and OPUS services, transform ITRF2005 coordinates to NAD83 with validity within North America. NRCan uses a 10 parameter transformation (7 static parameters with time dependence of the rotation parameters) to transform ITRF2005 to NAD83(CSRS) (Craymer, 2001). OPUS uses an indirect, site velocity dependant transformation method described more fully in Soler and Snay (2004).

ITRF2005 coordinates processed by OmniStar, AUSPOS outside Australia, and NRCan/OPUS outside North America all require a kinematic transformation strategy in order to fully utilise the precision of the service with respect to a local static geodetic datum. Unfortunately, many users of instantaneous ITRF2005 and WGS84 positions are unaware of the kinematic nature of coordinates in these systems, particularly where the precision of the technique is sensitive to movement of the underlying tectonic plate. At present, this precision is on the margin of significance for pseudorange positions using broadcast ephemerides, however for users of post-processed or RTK systems using international GNSS reference station networks, the errors can become significant.

This paper describes a simplified transformation strategy that can be easily incorporated into GNSS and GIS software to model plate tectonic deformation. Implementation of this strategy will significantly improve the Positional Uncertainty (PU) (ICSM, 2007; Roberts *et al.*, 2009) and repeatability of positions for users of PPP and global differential systems with respect to a static geodetic datum, particularly within tectonically stable regions. A simplified transformation strategy will be described and tested using GDA94.

2. AN APPROACH TO DEVELOPING A RIGID PLATE TRANSFORMATION MODEL

2.1 Rigid Plate Models

The Earth’s surface is comprised of a number of tectonic plates (Figure 1). These plates collide, rift apart, or slip past adjoining plates along the plate margins at rates of up to several centimetres a year. Major earthquakes and volcanic activity predominantly occur within these plate boundary zones. In general, tectonic plates are internally rigid and stable away from the plate boundaries. Baselines measured between any two geologically and structurally stable geodetic stations located on a rigid plate are unlikely to change by more than a few mm/yr. Conversely, within plate boundary zones and regions of diffuse deformation (e.g. Tibetan plateau and the Eastern Mediterranean), baseline changes become significant and highly variable depending upon the strain regime prevalent within the deformation zone. Larger earthquakes can result in coseismic displacement (and baseline changes) of up to several metres almost instantaneously.

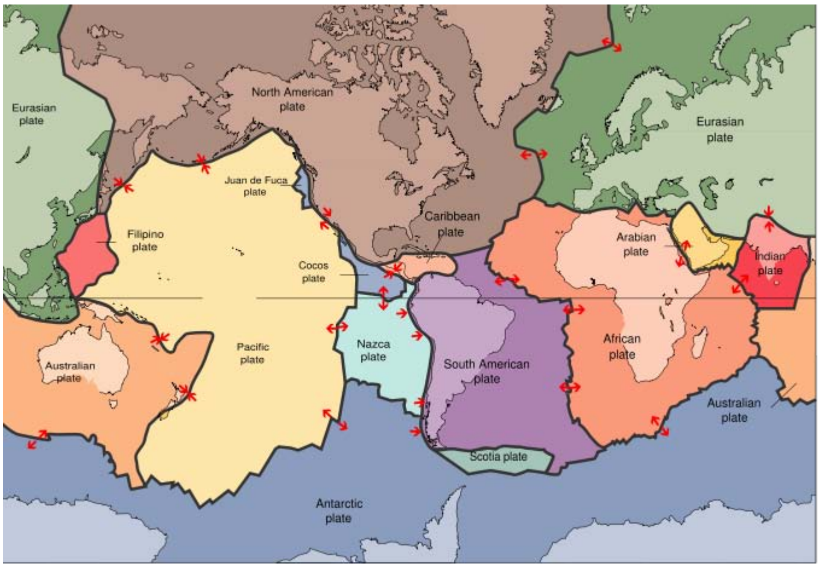

Figure 1. Principal tectonic plates (http://commons.wikimedia.org/wiki/File:Plates_tect2_en.svg)

Tectonic plate motion is typically defined by the axis and rate of rotation of the rigid plate (defined geometrically as an irregular edged portion of a spherical cap) about an Euler pole (Figure 2). An almost spherical Earth is assumed. An absolute Euler pole of rotation of a tectonic plate is defined by the axis of rotation with respect to a rotation free Earth reference system. The rotation can be described in two ways:

a. latitude and longitude of the Euler pole and rate of rotation in degrees per million years (Φ, Λ, and ω),

b. rotation of the rigid plate about the Earth's three Cartesian axes in radians per million years. (Ω_X, Ω_Y, and Ω_Z)

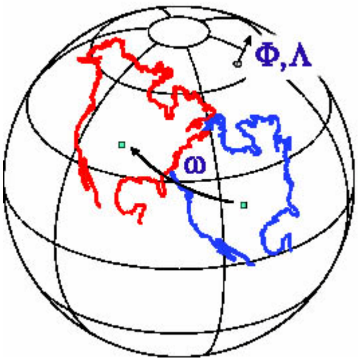

Figure 2. Euler Pole defining a plate rotation

Rotation rates about the Cartesian axes can be computed from the Euler pole definition using the following expressions (where Φ, Λ, and ω are converted to radians)

$$\Omega_X = \mathrm{COS}(\Phi)\,\mathrm{COS}(\Lambda)\omega \qquad (1)$$

$$\Omega_Y = \mathrm{COS}(\Phi)\,\mathrm{SIN}(\Lambda)\omega \qquad (2)$$

$$\Omega_Z = \mathrm{SIN}(\Phi)\omega \qquad (3)$$

Until the 1990s, models of plate motion had been derived solely from analysis of volcanic hotspot motion, paleomagnetism (to measure sea-floor spreading), inversion of seismic slip vectors, and other geophysical studies (De Mets *et al.* 1990; 1994). Space geodetic techniques have been sufficiently precise over the last twenty years to estimate site motion (i.e. site velocities) on the Earth's surface directly. Instantaneous (on a geological time scale) plate motion (actual) models have been estimated by inversion of these site velocities (Sella *et al.*, 2002; Bird, 2003; Kreemer *et al.*, 2006; Altamimi *et al.*, 2007; Drewes, 2009) (Table 2). ITRF2005 absolute rotation poles (Altamimi *et al.*, 2007) are listed in Table 3 for reference.

Author/ Reference	**Plate Model**	**No. of Rigid Plates**	**No. of Deforming Zones**	**Fixed Plate**	**Input Data**
De Mets *et al.*(1990)	NUVEL-1	14	0	Pacific	Geological
De Mets *et al.*(1994)	NNR-NUVEL-1A	14	0	Absolute	Geological
Sella *et al.*(2002)	REVEL2000	19	0	Absolute	mostly GPS
Bird (2003)	PB2002	52	13	Pacific	Geol. + Geod.
Kreemer *et al.*(2006)	GSRM-NNR-2	19	0	Absolute	Geodetic
Altamimi *et al.*(2007)	ITRF2005	15	0	Absolute	Geodetic
Drewes (2009)	APKIM2005D	17	5	Absolute	Geodetic

Table 2. Recent plate motion models

Plate	**Euler pole of rotation**			**Equivalent Cartesian angular velocity**		
	Φ (°)	**Λ (°)**	**ω (°/Ma)**	**Ω_X(Rad/Ma)**	**Ω_Y(Rad/Ma)**	**Ω_Z(Rad/Ma)**
Amurian	56.3	-102.8	0.269	-0.000577	-0.002543	0.003904
Antarctica	59.8	-125.3	0.223	-0.001131	-0.001597	0.003364
Arabia	49.6	5.1	0.579	0.006518	0.000577	0.007700
Australia	32.4	37.4	0.628	0.007354	0.005616	0.005874
Caribbean	39.3	-104.3	0.241	-0.000803	-0.003154	0.002665
Eurasia	56.3	-96.0	0.261	-0.000263	-0.002512	0.003791
India	49.8	21.8	0.614	0.006417	0.002572	0.008188
Nazca	45.1	-101.4	0.642	-0.001569	-0.007752	0.007937
N. America	-4.3	-87.4	0.192	0.000152	-0.003338	-0.000251
Nubia	50.0	-82.5	0.269	0.000394	-0.002995	0.003594
Okhostk	-32.0	-132.9	0.083	-0.000836	-0.000899	-0.000769
Pacific	-62.6	112.9	0.682	-0.002131	0.005052	-0.010565
S. America	-16.8	-129.6	0.121	-0.001290	-0.001557	-0.000610
Somalia	53.7	-89.5	0.309	0.000026	-0.003196	0.004344
Yangtze	59.4	-109.7	0.310	-0.000929	-0.002590	0.004658

Table 3. ITRF2005 plate absolute rotation poles (Altamimi *et al*,. 2007)

Tectonic plates move over the Earth's surface, so an Earth-Centred Earth-Fixed (ECEF) reference system needs to be defined with respect to the upper mantle, which represents the component of the Earth's structure that has been most coupled with the Earth's rotation throughout recent geological history (the last 2 Million years). Mantle plumes emanating from the lower mantle and mantle-core boundary rupturing the Earth's crust at volcanic hotspots (e.g. the Hawaiian-Emperor seamount chain) provide a means of estimating motion of the overlying plate relative to the upper mantle. The Pacific Plate has a number of hotspot traces, and inversion of these has enabled the absolute motion of the Pacific Plate to be estimated and used as a basis for global plate rotation models (Gripp & Gordon, 2002). By ensuring that the summation of the angular momenta of all other tectonic plates (including the Pacific Plate) and deforming zones is equal to zero, a no-net-rotation condition (NNRC) is created between the lithosphere and the upper mantle. The ITRF is a realisation of the ECEF reference system defined by the NNRC, Earth Orientation Parameters (EOP) and the geocentre (Altamimi *et al.*, 2007).

The magnitude of plate rotation rates and the Earth's inverse flattening are very small, so an assumption that the rigid plate is a spherical cap and not an ellipsoidal cap results in insignificant variations in site velocity estimates (Drewes, 2009).

Approximately 94% of the Earth's land surface area can be considered to be on a rigid tectonic plate (including microplates and rigid blocks) (Figure 3). This percentage is derived from Kreemer *et al.* (2003) who identify areas defined as being rigid where the second invariant strain rates are less than ~$1\text{x}10^{-9}\text{yr}^{-1}$. Significant earthquakes do occur within rigid plates (e.g. New Madrid, Missouri, USA, 1811-1812; Bhuj, Gujarat, India, 2001; Tennant Creek, Australia, 1987-1988) (USGS Earthquake database - http://neic.usgs.gov/neis/epic), however these are rare and their locations are widely distributed (Stein, 2007).

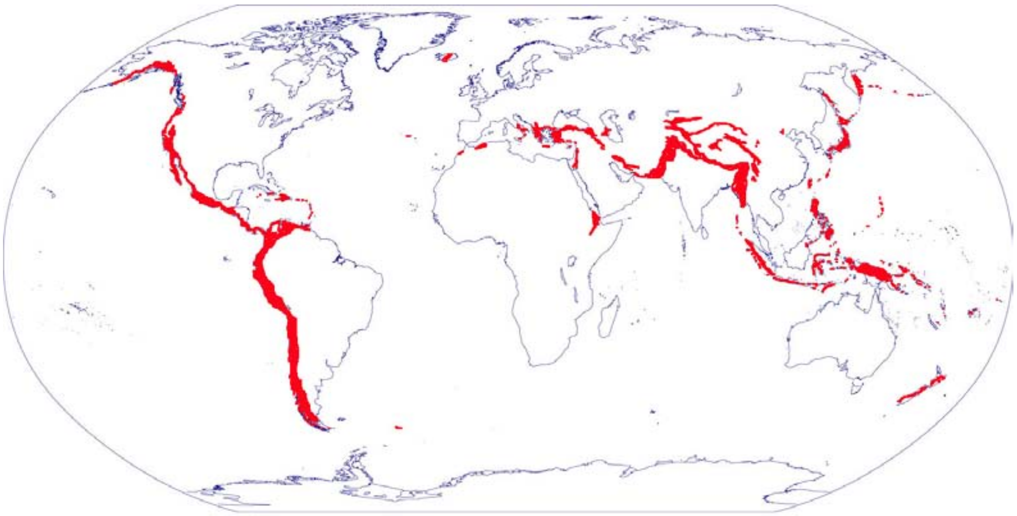

Figure 3. Deformation zones on land (in red) (Kreemer *et al.* 2003)

2.2 Developing Kinematic Transformation Parameters from a Rigid Plate Rotation Model

In regions where a geodetic datum is coupled with a rigid tectonic plate or stable block, a simplified transformation strategy can be developed from a plate rotation model to relate instantaneous ITRF coordinates to the datum at an arbitrary fixed epoch. The Cartesian plate rotation parameters therefore can equate to kinematic parameters for transformation between a kinematic and static datum.

A site velocity in Cartesian format ($\dot{X}, \dot{Y}, \dot{Z}$ in metres) can be computed for any given location (X, Y, Z in metres) on a rigid plate defined by (Ω_X, Ω_Y, Ω_Z in radians per million years) (from a rigid plate rotation model, e.g. ITRF2005, Table 3) using:

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} \Omega_Y Z - \Omega_Z Y \\ \Omega_Z X - \Omega_X Z \\ \Omega_X Y - \Omega_Y X \end{bmatrix} \cdot 1\text{E-6} \qquad (4)$$

By introducing a reference epoch t_0 and an epoch of measurement t (epochs in decimal years), the ITRF coordinates of any point on a rigid plate at a reference epoch (X_0, Y_0, Z_0 in metres) can be computed from the coordinates at epoch t (X_t, Y_t , Z_t in metres) using:

$$\begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} = \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} + \begin{bmatrix} \Omega_Y Z_t - \Omega_Z Y_t \\ \Omega_Z X_t - \Omega_X Z_t \\ \Omega_X Y_t - \Omega_Y X_t \end{bmatrix} (t_0 - t) \cdot 1\text{E-6} \qquad (5)$$

Equation (5) can also be used to realise a static geocentric datum aligned with ITRF at a specific reference epoch. Instantaneous ITRF positions measured at different locations and at different epochs on the same rigid plate can be related to the static datum at the reference epoch by using the same parameters (Ω_X, Ω_Y, Ω_Z, t_0). In instances where a geocentric datum is offset from ITRF (for example, a datum aligned with an earlier realisation of ITRF or WGS84), three additional parameters (T_X, T_Y ,T_z) can be added to the transformation model to account for the translation of the ITRF origin from the datum at the reference epoch using:

$$\begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} = \begin{bmatrix} X_t \\ Y_t \\ Z_t \end{bmatrix} + \begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix} + \begin{bmatrix} \Omega_Y Z_t - \Omega_Z Y_t \\ \Omega_Z X_t - \Omega_X Z_t \\ \Omega_X Y_t - \Omega_Y X_t \end{bmatrix} \left(t_0 - t\right) \cdot 1\text{E-6} \qquad (6)$$

Equations 4 to 6 are accurate within rigid plate zones, however within deforming zones additional parameters derived from deformation models (e.g. Finite Element Model and Fault Locking models) are required in order to maintain consistency between different epochs (Stanaway, 2004; Blick *et al.*, 2005; Beavan & Blick, 2006; Drewes, 2009). In addition, coseismic and postseismic terms need to be added, to model seismic deformation of affected site positions.

3. A SIMPLIFIED PARAMETERISATION FOR TRANSFORMATION FROM ITRF TO GDA94

To illustrate the application of this simplified strategy, parameters derived from plate motion models are compared for transformations from ITRF2005 to GDA94. GDA94 is the current geodetic datum used in Australia and is a realisation of ITRF92 at epoch 1994.0. The Australian continent constitutes a rigid part of the Australian Plate with intraplate deformation not believed to exceed 2 mm/yr (Tregoning, 2003) and is therefore an ideal case study to test this strategy.

GDA94 is realised by the Australian Fiducial Network (AFN) which is a network of eight stations covering the Australian continent (Morgan *et al.*, 1996). Seven AFN stations are included in the ITRF2005 GPS set of station coordinates (SSC) listing (IERS, 2007), and are used in this study (Tables 4 & 5; Figure 4).

Location	Site ID	X	Y	Z
Yarragadee	YAR1	-2389025.394	5043316.852	-3078530.860
Tidbinbilla	TIDB	-4460996.069	2682557.144	-3674443.874
Darwin	DARW	-4091358.744	4684606.844	-1408580.642
Hobart	HOB2	-3950071.274	2522415.218	-4311638.511
Karratha	KARR	-2713832.155	5303935.187	-2269515.197
Alice Springs	ALIC	-4052051.767	4212836.216	-2545106.026
Ceduna	CEDU	-3753472.126	3912741.040	-3347961.031

Table 4. AFN GDA94 coordinates (m) (ITRF92 epoch 1994.0) included in the ITRF2005 GPS SSC (IERS, 2007)

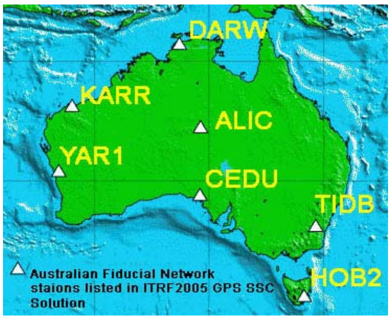

Figure 4. AFN Stations included the ITRF2005 GPS SSC

Location	Site ID	X	Y	Z	$\dot{X}$	$\dot{Y}$	$\dot{Z}$
Yarragadee	YAR1	-2389025.674	5043316.892	-3078530.575	-0.0476	0.0094	0.0499
Tidbinbilla	TIDB	-4460996.239	2682557.081	-3674443.556	-0.0371	0.0006	0.0455
Darwin	DARW	-4091358.908	4684606.712	-1408580.294	-0.0350	-0.0146	0.0569
Hobart	HOB2	-3950071.478	2522415.210	-4311638.238	-0.0403	0.0087	0.0408
Karratha	KARR	-2713832.395	5303935.107	-2269514.854	-0.0445	0.0014	0.0540
Alice Springs	ALIC	-4052051.959	4212836.105	-2545105.682	-0.0395	-0.0056	0.0541
Ceduna	CEDU	-3753472.368	3912741.008	-3347960.718	-0.0417	0.0007	0.0511

Table 5. AFN ITRF2005 coordinates and velocities at epoch 2000.0 (from ITRF2005 GPS SSC)

A selection of models of the Australian Plate (Table 6) are assessed by comparing ITRF2005 coordinates at epoch 1994.0 (t_0 =1994.0) computed from the ITRF2005 GPS SSC solution epoch 2000.0 coordinates and site velocities, with model predictions using equation (5). The ITRF2005 solution was used to compute the ITRF2005 plate model, so small residuals would be expected in this case.

Plate Model	Euler pole of rotation			equivalent Cartesian angular velocity		
	Φ (°)	Λ (°)	ω (°/Ma)	Ω_X (Rad/Ma)	Ω_Y (Rad/Ma)	Ω_Z (Rad/Ma)
NNR-NUVEL-1A	33.9	33.2	0.646	0.007831	0.005124	0.006288
REVEL2000	34.9	38.3	0.627	0.007043	0.005563	0.006261
ITRF2005	32.4	37.4	0.628	0.007354	0.005616	0.005874
APKIM2005D	33.2	36.3	0.633	0.007450	0.005473	0.006049

Table 6. Selected models of Australian plate motion

The computed residuals (Table 7) show that all selected Australian plate models provide sub centimetre precision using the three Cartesian rotation parameters derived from the kinematic plate model. Differences in height are not shown, as plate motion models using Euler poles do not adequately model vertical deformation. The small residuals also confirm that there is no significant intraplate deformation within the Australian continent over a six-year period, with sub mm/yr intraplate deformation indicated by the residuals. The small residuals also show that the simplified parameterisation described here, using a geodetically derived (actual) absolute plate model, can be used anywhere on a rigid tectonic plate such as the Australian plate to transform ITRF2005 coordinates to a reference epoch with a precision of a few mm. In a similar way, kinematic parameters for any regional geodetic datum aligned with ITRF can be computed if the datum is coupled to a rigid tectonic plate or crustal block.

Model AFN Station	NNR-Nuvel-1A		REVEL2000		ITRF2005 Model		APKIM2005D	
	ΔE	ΔN	ΔE	ΔN	ΔE	ΔN	ΔE	ΔN
YAR1	0.000	-0.009	-0.014	0.009	0.002	0.000	-0.001	-0.001
TIDB	0.006	0.012	-0.014	0.012	0.003	0.005	0.001	0.008
DARW	-0.007	-0.006	-0.015	0.004	0.002	-0.004	-0.003	-0.003
HOB2	0.009	0.011	-0.014	0.012	0.003	0.005	0.002	0.008
KARR	-0.004	-0.008	-0.015	0.010	0.001	0.000	-0.003	0.000
ALIC	0.001	0.002	-0.013	0.010	0.004	0.002	0.001	0.003
CEDU	0.008	0.002	-0.009	0.010	0.008	0.002	0.005	0.003
Mean Δ	**0.002**	**0.001**	**-0.013**	**0.010**	**0.003**	**0.001**	**0.000**	**0.003**
σ	**0.006**	**0.009**	**0.002**	**0.002**	**0.002**	**0.003**	**0.003**	**0.004**

Table 7 . Predicted minus observed ITRF2005 (horizontal components)
at epoch 1994.0 (computed from the ITRF2005 GPS SSC solution)

The ITRF2005 solution computed for epoch 1994.0 using the ITRF2005 site velocities (Table 8) is compared with GDA94 (Table 4). This not only provides an assessment of the alignment between ITRF92 and ITRF2005 over the Australian continent, but also the quality of the original GPS observations, models and analysis (Morgan *et al.*, 1996). Differences between the Cartesian and topocentric (East, North & Up components) computations are shown in Table 9.

Location	**Site ID**	**X**	**Y**	**Z**
Yarragadee	YAR1	-2389025.388	5043316.836	-3078530.874
Tidbinbilla	TIDB	-4460996.016	2682557.077	-3674443.829
Darwin	DARW	-4091358.698	4684606.800	-1408580.635
Hobart	HOB2	-3950071.236	2522415.158	-4311638.483
Karratha	KARR	-2713832.128	5303935.099	-2269515.178
Alice Springs	ALIC	-4052051.722	4212836.139	-2545106.007
Ceduna	CEDU	-3753472.118	3912741.004	-3347961.025

Table 8. AFN ITRF2005 coordinates at epoch 1994.0

Location	**Site ID**	**Cartesian Coordinates**			**Topocentric coordinates**		
		ΔX	**ΔY**	**ΔZ**	**ΔE**	**ΔN**	**ΔHt**
Yarragadee	YAR1	0.006	-0.016	-0.014	0.002	-0.020	-0.009
Tidbinbilla	TIDB	0.053	-0.067	0.045	0.030	-0.010	-0.092
Darwin	DARW	0.046	-0.044	0.007	-0.006	-0.007	-0.064
Hobart	HOB2	0.038	-0.060	0.028	0.030	-0.023	-0.066
Karratha	KARR	0.027	-0.088	0.019	0.016	-0.015	-0.091
Alice Springs	ALIC	0.045	-0.077	0.019	0.021	-0.017	-0.087
Ceduna	CEDU	0.008	-0.036	0.006	0.019	-0.012	-0.030
	Mean Δ	**0.032**	**-0.056**	**0.016**	**0.015**	**-0.015**	**-0.068**
	σ	**0.019**	**0.025**	**0.019**	**0.015**	**0.006**	**0.031**

Table 9. Differences between ITRF2005 epoch 1994.0 (using ITRF2005 site velocities) and GDA94 (Δ = ITRF2005(1994.0) - GDA94) for the AFN.

The residuals in Table 9 indicate good agreement between epoch 1994.0 horizontal components of ITRF92 and ITRF2005 at a level of better than 2 cm for most AFN stations, which confirms the high precision of the original realisation (Morgan *et al*. 1996). The larger differences in ellipsoid heights can be explained by scale and geocentre variations between ITRF92 and ITRF2005. The ITRF2005 plate rotation model (Table 3) is now used to parameterise the transformation to compute epoch 1994.0 coordinates from the model. The parameters are used in equation (5) and the differences with GDA94 computed (Table 10).

Location	**Site ID**	**Cartesian residuals**			**Topocentric residuals**		
		ΔX	**ΔY**	**ΔZ**	**ΔE**	**ΔN**	**ΔHt**
Yarragadee	YAR1	0.002	-0.012	-0.018	0.004	-0.021	-0.002
Tidbinbilla	TIDB	0.048	-0.068	0.049	0.034	-0.005	-0.091
Darwin	DARW	0.049	-0.050	0.003	-0.004	-0.012	-0.069
Hobart	HOB2	0.030	-0.059	0.029	0.033	-0.017	-0.061
Karratha	KARR	0.023	-0.084	0.018	0.018	-0.014	-0.085
Alice Springs	ALIC	0.042	-0.080	0.022	0.025	-0.014	-0.088
Ceduna	CEDU	0.009	-0.047	0.014	0.026	-0.010	-0.041
	Mean Δ	**0.029**	**-0.057**	**0.017**	**0.019**	**-0.013**	**-0.063**
	σ	**0.019**	**0.025**	**0.021**	**0.015**	**0.005**	**0.032**

Table 10. Differences between estimated ITRF2005 epoch 1994.0 (using ITRF2005 plate model) and GDA94 (Δ = ITRF2005(1994.0) - GDA94) for the AFN using a 4-parameter plate transformation.

The analysis (Table 10 & Figure 6) shows that a simplified four parameter transformation model from ITRF2005 to GDA94 has a horizontal accuracy of 30 mm and vertical accuracy of 100 mm for the AFN, which is suitable for medium and low precision GNSS applications (e.g. OmniStar HP and DGPS) and GIS transformations. The precision is also sufficient for cadastral surveys where a Positional Uncertainty (PU) of less than 30 mm is acceptable for surveys connected to GDA94 (Roberts, 2006; Roberts *et al.*, 2009).

The accuracy of the plate model derived transformation can be improved by the addition of three parameters to translate the origin of ITRF2005 to GDA94. The selected AFN stations are well distributed around the Australian continent, so that the mean of the Cartesian residuals (Table 10) for the AFN stations with their sign changed can be used to define the translation (T_X, T_Y, T_z) = (-0.029, 0.057, -0.017). The small residuals between the ITRF2005 Australian plate model and the ITRF2005 coordinates of the AFN stations at epoch 1994.0 show that the parameterisation retains precision over a 6 year time span between the sample epoch (2000.0 in Table 5) and a reference epoch of 1994.0. Intraplate deformation and uncertainties in ITRF2005 velocity estimates will only become apparent at a level of 15 mm by 2020.

The residuals using the 7-parameter plate model transformation are shown in Table 11 and Figure 6.

Location	**Site ID**	**Cartesian residuals**			**Topocentric residuals**		
		ΔX	**ΔY**	**ΔZ**	**ΔE**	**ΔN**	**ΔHt**
Yarragadee	YAR1	-0.027	0.045	-0.035	-0.015	-0.008	0.060
Tidbinbilla	TIDB	0.019	-0.011	0.032	0.015	0.008	-0.029
Darwin	DARW	0.020	0.007	-0.014	-0.023	0.001	-0.007
Hobart	HOB2	0.001	-0.002	0.012	0.014	-0.004	0.001
Karratha	KARR	-0.006	-0.027	0.001	-0.001	-0.001	-0.023
Alice Springs	ALIC	0.013	-0.023	0.005	0.006	-0.001	-0.026
Ceduna	CEDU	-0.020	0.010	-0.003	0.007	0.003	0.021
	Mean Δ	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
	σ	**0.019**	**0.024**	**0.021**	**0.014**	**0.005**	**0.032**

Table 11. Differences between estimated ITRF2005 at epoch 1994.0 (using ITRF2005 plate model) and GDA94 (ITRF2005 - GDA94) for the AFN using a 7-parameter plate transformation.

3.1 Testing the Simplified Plate Based Parameterisation (ITRF2005 to GDA94)

The four and seven parameter models are now validated by tests on six Australian Regional GPS Network (ARGN) stations that are not part of the AFN (Table 12, Figure 5). The equivalent ITRF2005 coordinates at epoch 2000.0 are also provided (Table 13). The SYDN IGS site is not included in the ITRF2005 GPS SSC, however as Sydney is Australia's largest city, it was included in this study to test the parameterisation. AUSPOS was used to process nine days of data (from the IGS archive) in 2005, 2007 and 2009. The ITRF2005 site velocity for SYDN was computed from this sample data set and epoch 2000.0 coordinates computed.

Location	Site ID	X	Y	Z
Mt. Stromlo	STR1	-4467102.253	2683039.505	-3666949.947
Perth	PERT	-2368686.846	4881316.573	-3341796.339
Jabiru	JAB1	-4236442.675	4559929.626	-1388624.813
Townsville	TOW2	-5054582.681	3275504.571	-2091539.886
Melbourne	MOBS	-4130635.780	2894953.104	-3890531.457
Sydney	SYDN	-4648239.981	2560636.542	-3526319.012

Table 12. Selected ARGN GDA94 coordinates used to test the parameterisation

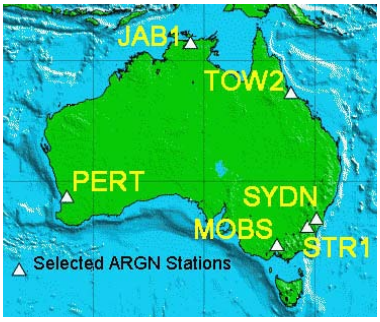

Figure 5. Selected ARGN stations.

Location	Site ID	X	Y	Z	$\dot{X}$	$\dot{Y}$	$\dot{Z}$
Mt. Stromlo	STR1	-4467102.470	2683039.473	-3666949.669	-0.0377	0.0006	0.0448
Perth	PERT	-2368687.105	4881316.535	-3341796.005	-0.0468	0.0059	0.0529
Jabiru	JAB1	-4236442.903	4559929.554	-1388624.475	-0.0353	-0.0132	0.0592
Townsville	TOW2	-5054582.794	3275504.413	-2091539.548	-0.0321	-0.0136	0.0522
Melbourne	MOBS	-4130635.982	2894953.078	-3890531.170	-0.0390	0.0019	0.0467
Sydney	SYDN	-4648240.172	2560636.487	-3526318.710	-0.0327	-0.0030	0.0467

Table 13. Selected ARGN ITRF2005 coordinates and velocities at epoch 2000.0 (from ITRF2005 GPS SSC and AUSPOS solutions for SYDN)

Using the ITRF2005 plate model Cartesian rotations (Ω_X, Ω_Y, Ω_Z) from Table 3, and a reference epoch parameter (t_0 = 1994.0), the ITRF2005 epoch 2000.0 coordinates of the selected ARGN stations are transformed to GDA94 using equation (5). The topocentric coordinates from the transformation (Latitude/North, Longitude/East, Height/Up) are compared with GDA94 (Table 14, Figure 6). The transformation is repeated (equation 6) using the 7-parameter model (including the three translation parameters that relate the ITRF2005 and GDA94 origin (-0.029, 0.057, -0.017)) and the GA 14-parameter model. Residuals are shown (Table 14, Fig. 6). ITRF2005 coordinates were first transformed to ITRF2000 at epoch 2000.0 using the parameters published in Altamimi *et al.* (2007) for use in the GA 14-parameter model, as no direct ITRF2005 to GDA94 transformation model has yet been published.

Location	Site ID	4-parameter topocentric residuals			7-parameter topocentric residuals			14 -parameter* topocentric residuals		
		ΔE	**ΔN**	**ΔHt**	**ΔE**	**ΔN**	**ΔHt**	**ΔE**	**ΔN**	**ΔHt**
Mt. Stromlo	STR1	0.030	-0.005	-0.021	-0.003	0.014	0.033	0.000	0.004	0.058
Perth	PERT	0.021	-0.021	-0.108	0.022	-0.002	-0.044	0.003	0.001	-0.054
Jabiru	JAB1	0.004	0.000	0.026	-0.014	-0.003	0.090	-0.008	0.004	0.114
Townsville	TOW2	0.021	-0.012	-0.102	-0.011	-0.010	-0.044	-0.005	-0.013	-0.007
Melbourne	MOBS	0.025	-0.018	-0.056	-0.005	0.003	-0.001	-0.004	-0.009	0.018
Sydney	SYDN	0.032	0.007	-0.049	-0.004	0.021	0.004	0.000	0.013	0.032
	Mean Δ	**0.022**	**-0.008**	**-0.052**	**-0.003**	**0.004**	**0.006**	**-0.003**	**0.000**	**0.027**
	σ	**0.010**	**0.011**	**0.050**	**0.013**	**0.011**	**0.051**	**0.004**	**0.009**	**0.057**

Table 14. Differences between estimated ITRF2005 at epoch 1994.0 (using the ITRF2005 Model) and GDA94 for selected ARGN stations using simplified plate models and the GA 14-parameter model. (* ITRF2005 coordinates were first transformed to ITRF2000 at epoch 2000.0 using Altamimi *et al.*, (2007))

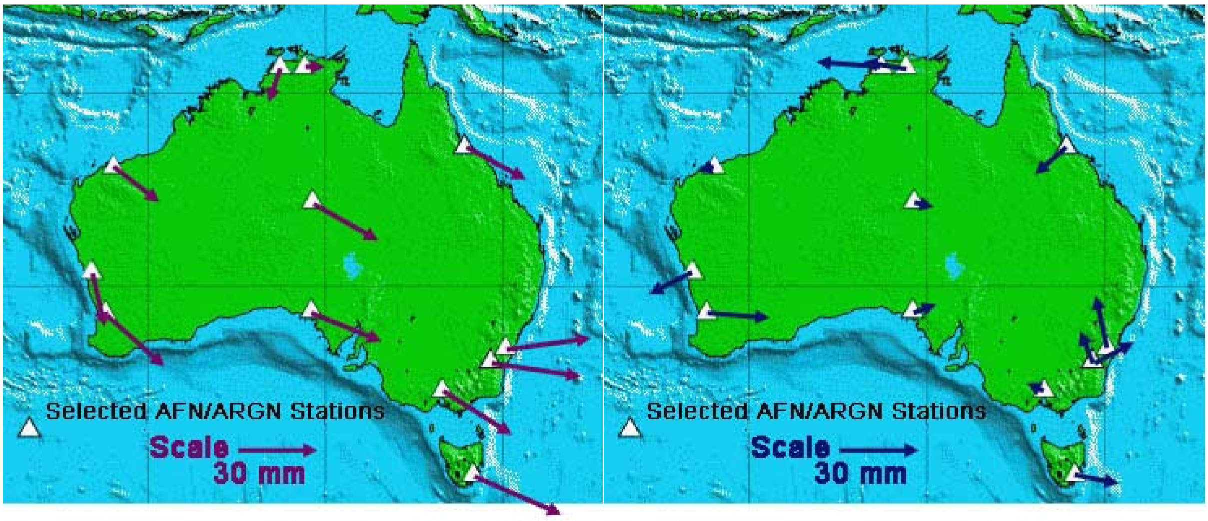

Figure 6. Differences between estimated ITRF2005 at epoch 1994.0 (using ITRF2005 Plate Model) and GDA94 (ITRF2005 minus GDA94) for selected ARGN stations **(left)** using a 4-parameter plate transformation, and **(right)** using a 7-parameter plate transformation.

The residuals verify that a 4-parameter model can be used to transform ITRF2005 and WGS84 coordinates to GDA94 anywhere on the Australian continent with a precision of 10-30 mm. Using a 7-parameter model improves the precision of the transformation to 5-20 mm. Both simplified transformation models compare favourably with the 14-parameter model published by GA (with ITRF2005 coordinates transformed to ITRF2000 beforehand).

4. DISCUSSION

The simplified parameterisation described to transform ITRF2005 to GDA94 in the Australian context provides acceptable precision for most users. 14-parameter transformation models such as the one developed by Geoscience Australia, should continue to be used for high precision transformations between kinematic and static datums, however the parameterisation strategy described here may be more easily incorporated into GNSS and GIS software, using generic plate models and reference epochs to define a static datum.

Actual plate models are computed by inversion of geodetic site velocities spanning a tectonic plate. Static geodetic datums are generally defined on a national or provincial scale (e.g. Australia uses GDA94, the USA uses NAD83 and State Plane Coordinates, and the UK uses OSGB36). Some improvement in the parameterisation may be gained by computing a localised rigid plate model (particularly in deforming zones) using inversion of site velocities only within a specific jurisdiction. Another strategy that has not been examined in this study is to compute false Euler poles to account for the inherent differences (translations and rotations) between ITRF2005 and a localised datum directly, especially in the cases where a datum is not geocentric. Figure 6 shows a consistent shift across the Australian continent using a 4-parameter model. By using a false Euler pole (e.g. a GDA94 Euler pole), the precision of a 4-parameter model may be improved significantly. Alternatively, the three translation parameters could be substituted with three rotation parameters to account for datum misfits.

The very close agreement between actual plate model predictions and ITRF2005 at different epochs within Australia suggests that any future datum or readjustment of GDA94 can be achieved by simply adopting ITRF2005 (or a later realisation of ITRF) at epoch 1994.0. Retaining the 1994 epoch will minimise coordinate differences at a level of less than a 3 cm between subsequent realisations of GDA. If a new datum or adjustment does indeed eventuate, a 3-parameter plate transformation can be used and still provide a precision of better than a cm on a decadal timescale.

Kinematic coordinates are an annoyance and source of error for most users of GNSS and GIS systems (Stanaway, 2007). Incorporating plate model based transformation parameters into GNSS and GIS software can ensure that any pseudorange or precise point positions and datum transformations from ITRF and WGS84 are more consistent within a localised reference frame. High precision kinematic reference frames such as ITRF2005 should be used specifically for scientific purposes (e.g. geodynamics studies and hazard monitoring) and geodetic datum maintenance. For most other users of spatial information, however, kinematic coordinates for “fixed” locations within a local reference frame undermines the concept of legal traceability, and unnecessarily complicates the integration of surveys at different epochs and management of spatial data.

5. CONCLUSIONS

The lack of an empirical methodology to relate kinematic ITRF2005 and WGS84 coordinates to a localised static geodetic reference frame impacts on the accuracy and utility of global PPP, differential GNSS systems and GIS transformations. 94% of land surface area of the Earth lies on a rigid tectonic plate where intraplate deformation (and baseline changes) are less than 2 mm/yr. Using a rigid plate motion model derived by inversion of site velocities estimated from space geodetic observations, provides a means to relate ITRF to a local static geodetic datum coupled with the rigid plate using a simplified parameterisation.

The Australian case study presented shows that a rigid plate kinematic model can be used to transform ITRF2005 and WGS84 to a static datum (GDA94) with a precision of less than 30 mm using only four parameters. A readjustment of GDA94 (e.g. to ITRFxx at epoch 1994.0) would be expected to improve this precision further as is shown by the close agreement between coordinates predicted from actual plate models and observed ITRF coordinates. This level of positional uncertainty is acceptable for most users of the datum, particularly in rural areas. The precision of GNSS point positions within the extent of a localised datum would be improved if datum transformation algorithms can include a simplified plate based transformation model. The improvement would be particularly noticeable if sub-metre point positioning precision is attained in the future, as is envisaged with GNSS modernisation and improved augmentation. The simplified transformation strategy can be used for any geodetic datum coupled with a rigid plate and can be incorporated into generic point positioning and differential services such as OmniSTAR and CORS networks which use kinematic ITRF coordinates. Implementation will significantly improve consistency in coordinates for fixed locations on decadal timescales using these services. The implementation of plate motion model parameters in RTCM correction messages and user GNSS and GIS software warrants further investigation.

REFERENCES

Altamimi Z, Collileux J, Legrand J, Garayt B, Boucher C (2007); ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters, *Journal of Geophysical Research*, Vol. 112, B09401, doi:10.1029/2007JB004949

Beavan J, Blick G (2006); Limitations in the NZGD2000 Deformation Model, *Dynamic Planet : Monitoring and Understanding a Dynamic Planet with Geodetic and Oceanographic tools*; IAG Symposium, Cairns, Australia, 22-26 August 2005, IAG Symposia Vol. 130, Springer-Verlag

Bird P (2003); An updated digital model of plate boundaries, *Geochemistry Geophysics Geosystems*, Vol. 4, No. 3, 1027, doi:10.1029/2001GC000252

Blick G, Crook C, Grant D, Beavan J (2005); Implementation of a Semi-Dynamic Datum for New Zealand, *A Window in the Future of Geodesy:* Proceedings of the International Association of Geodesy IAG General Assembly Sapporo, Japan June 30 – July 11, 2003; IAG Symposia Vol. 128, Springer-Verlag

Craymer M, (2001); ITRF-NAD83 Transformation & Definition of NAD83(CSRS), Geodetic Services Division, Natural Resources Canada, (http://www.naref.org/transf/nad83itrf.txt accessed July 2009)

De Mets C, Gordon R, Argus D, Stein S (1990); Current plate motions, *Geophysical Journal International*, 101, 425-478

De Mets C, Gordon R, Argus D, Stein S (1994); Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, *Geophysical Research Letters*, Vol. 21, No. 20, 2191-2194

Dawson J, Steed J (2004); International Terrestrial Reference Frame (ITRF) to GDA94 Coordinate Transformations, Geoscience Australia (http://www.ga.gov.au/image_cache/GA3795.pdf accessed July 2009)

Drewes H (ed.) (2009); The Actual Plate Kinematic and Crustal Deformation Model APKIM2005 as Basis for a Non-Rotating ITRF, *Geodetic Reference Frames*, International Association of Geodesy Symposia 134, Springer-Verlag

Gripp A, Gordon R (2002); Young tracks of hotspots and current plate velocities, *Geophysical Journal International*, 150, 321-361

ICSM (Inter-Governmental Committee On Surveying And Mapping), (2007), *Standards and Practices for Control Surveys (SP1), Version 1.7,* http://www.icsm.gov.au/icsm/publications/sp1/sp1v1-7.pdf accessed July 2009, IERS (International Earth Rotation and Reference Frame Service), (2007), *ITRF2005 GPS Set-of-Station (SSC) Coordinates*, (http://itrf.ensg.ign.fr/ITRF_solutions/2005/doc/ITRF2005_GPS.SSC.txt) accessed July 2009,

Kreemer C, Holt W, Haines A (2003); An integrated global model of prsent-day plate motions and plate boundary deformation, *Geophysical Journal International*, 154, 8-34

Kreemer C, Lavalle´e D, Blewitt G, Holt W (2006) On the stability of a geodetic no-net-rotation frame and its implication, *Geophysical Research Letters*, Vol. 33, L17306, doi:10.1029/2006GL027058,

Morgan P, Bock Y, Coleman R, Feng P, Garrard D, Johnston G, Luton G, McDowall B, Pearse M, Rizos C, Tiesler R (1996); A zero order GPS network for the Australian region. *UNISURV Report. S46*, School of Geomatic Engineering, The University of New South Wales.

NGA (US National Geospatial-Intelligence Agency) (2004), (Addendum to NIMA TR 8350.2: Implementation of the World Geodetic System 1984 (WGS 84) Reference Frame G1150; http://earth-info.nga.mil/GandG/publications/tr8350.2/Addendum%20NIMA%20TR8350.2.pdf accessed July 2009

Roberts C (2006); GNSS and the convergence of Geodesy and the Cadastre in Australia, *FIG 2006*, *TS33, paper 273*, Munich, Germany 9 – 13 Oct.

Roberts C, Ozdemir S, McElroy S (2009); Where is Positional Uncertainty? *Proceedings of SSC 2009 Spatial Diversity:* The National Biennial Conference of the Spatial Sciences Institute, Hobart, 28 Sept – 2 Oct 2009.

Sella G, Dixon T, Mao A (2002); REVEL: A model for Recent plate velocities from space geodesy, *Journal of Geophysical Research*, 107, B4, 10.1020/2000JB000033

Soler T, Snay R, (2004); Transforming Positions and Velocities between the International Terrestrial Reference Frame of 2000 and North American Datum of 1983, *Journal of Surveying Engineering*, May, 49

Stein S (2007); Approaches to continental intraplate earthquake issues, *Continental Intraplate Earthquakes, Geological Society of America, Special Publication 425*

Stanaway R (2004); *Implementation of a Dynamic Geodetic Datum in Papua New Guinea: A case study*, MPhil thesis, The Australian National University, Canberra, Australia, (http://dspace.anu.edu.au/bitstream/1885/42082/1/stanaway2004.pdf accessed July 2009)

Stanaway R (2007); *GDA94, ITRF, WGS84: What's the difference? Working with Dynamic Datums*, Spatial Sciences Institute - Biennial Conference, Hobart, 14th - 18th May 2007, (http://www.quickclose.com.au/stanawayssc2007.pdf accessed July 2009)

Tregoning P (2003); Is the Australian Plate deforming? A space geodetic perspective, *Geological Society of Australia Special Publication, 22 and Geological Society of America Special Publication*, 372, 41-48,