UNSW AUSTRALIA

# Defining a Local Reference Frame using a Plate Motion Model and Deformation Model

Never Stand Still | Faculty of Engineering | School of Civil and Environmental Engineering

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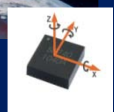
# The future of positioning circa 2030



multi-GNSS
+ augmentation (e.g. EGNOS, SBAS)
+ indoor positioning (e.g. Locata)
+ miniature inertial sensors

real-time
precise broadcast
orbits

## 4D GIS in the cloud

real-time positions

mm
accurate

active transformation model

real-time information currency

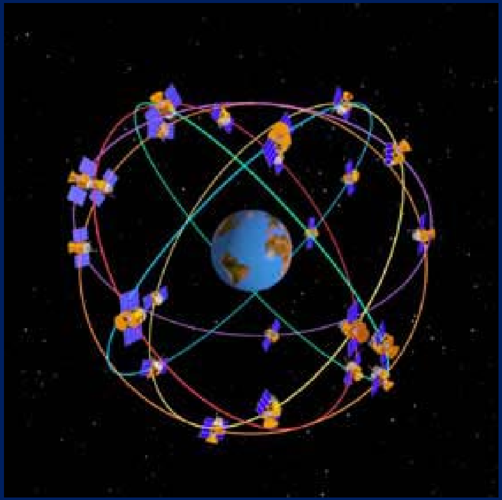
centralised data
+ clone

authoritative

ubiquitous


5G/6G wireless
and satellite comms.
(e.g. Beidou, Galileo)

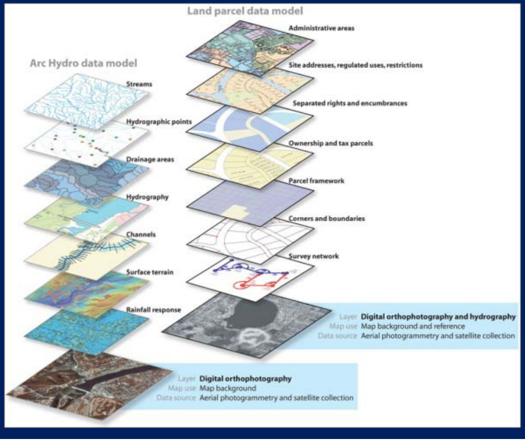
# Spatial Data and Positioning in the future



GNSS Positioning within ITRF / GGRF

Complex time dependent transformations & deformation modelling

Software matches epoch of positioning with epoch of data in order to maintain context



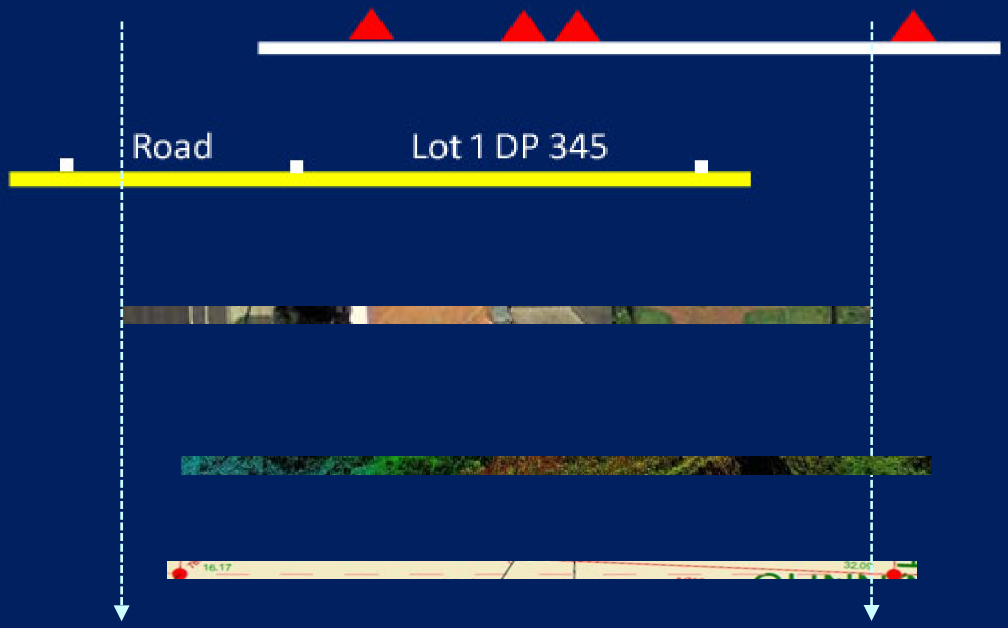

Kinematic Spatial Data & GIS

Data "tagged" with datum (e.g. ITRF) and epoch metadata

# So why do we need a Local RF?

**To integrate and analyse spatial data acquired at different epochs (e.g. GIS, mapping, cadastral data, engineering & utility surveys)**

**A 4D GIS still requires an epoch for data combination!**
**(i.e. a temporal or fixed epoch Local RF)**




Geodetic Control layer (Kinematic Datum) e.g. epoch 2026.45

Cadastral Layer (e.g. epoch 1994.0)

Imagery Layer (e.g. epoch 2010.095)
**(Raster layer can be adopted as common epoch and Local RF for computational efficiency)**

Elevation Layer (e.g. LiDar) (e.g. 2014.98)

Water utility Layer (e.g. 2014.0)

**A Local RF is a stable frame for deformation monitoring, analysis and modelling**

# Why should we care about epochs?

# Advantages of Local Reference Frames

Can be defined by Euler pole of the local tectonic plate or block (Frame moves with stable portion of the plate or crustal block)

Station velocities wrt stable plate/block are therefore <u>minimised</u>

Epoch metadata error or assumption has minimal impact on 2D-3D GIS accuracy

Distortion free (no scale parameter – scale = ITRF)

Linkable directly to ITRF by 3 parameter transformation + $\Delta$epoch (without loss of precision if defined at common reference epoch)

Localised deformation can be better visualised and analysed

Supports stability of GIS data management until 4D GIS architecture is fully developed, tested and implemented

Option of residual deformation (displacement) model for higher precision usage

# Hierarchy of Terrestrial Reference Frames and Datums

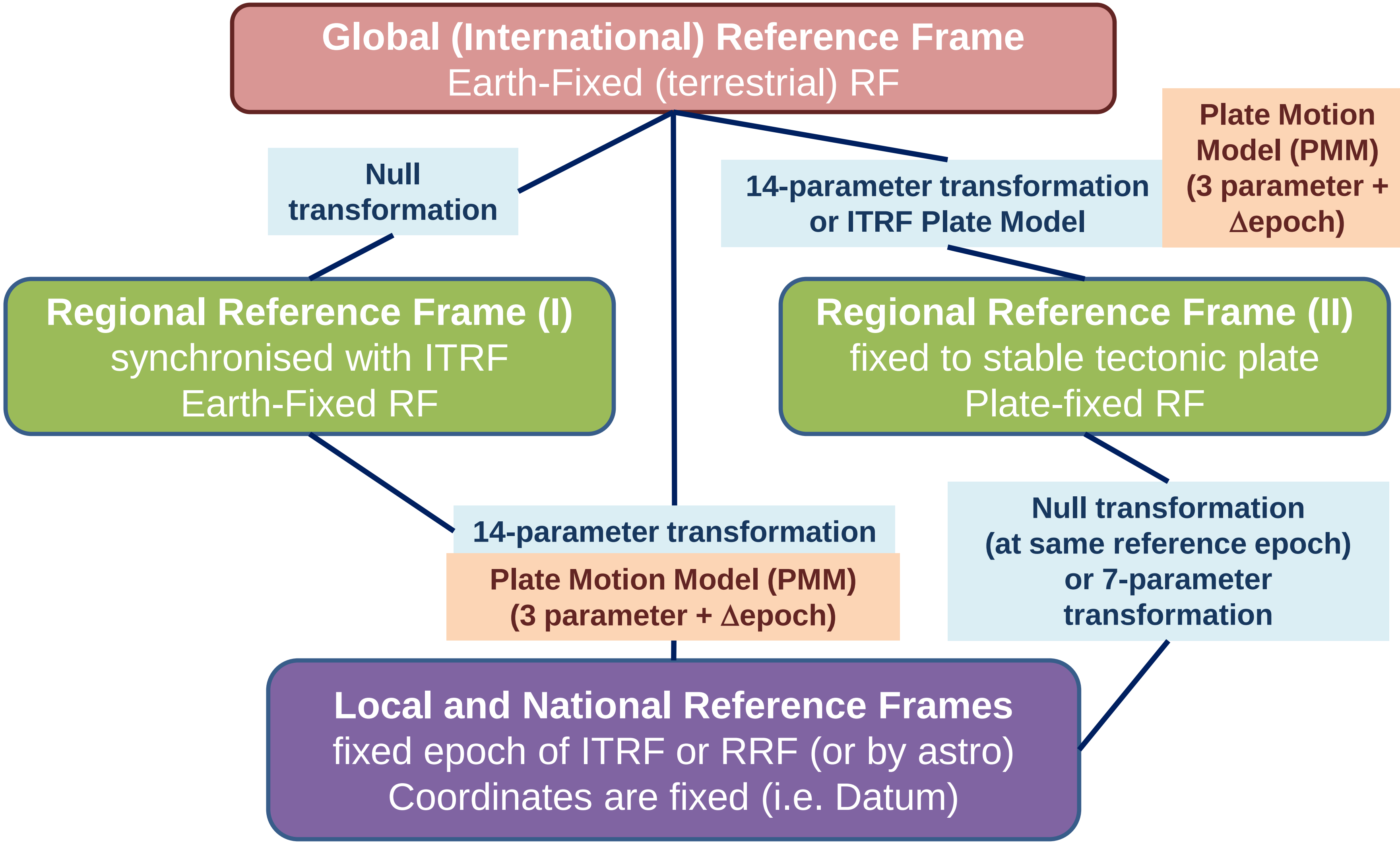
**Global (International) Reference Frame**
***Earth-Fixed (terrestrial) RF***
Coordinates are kinematic wrt geocentric ITRS
(e.g. ITRF2008)

**Regional Reference Frame (I)**
synchronised with ITRF
***Earth-Fixed RF***
Coordinates are kinematic
wrt geocentric ITRS
(e.g. APREF, SIRGAS)

**Regional Reference Frame (II)**
fixed to stable tectonic plate
***Plate-fixed RF***
Coordinates are kinematic
wrt plate frame / Euler pole
(e.g. ETRF89, NAD83, NAD20??)

**Local and National Reference Frames**
fixed epoch of ITRF or RRF (or by astro)
Coordinates are fixed (i.e. a datum)
(e.g., BEREF, LUREF, DHDN, RGF93,
OSGB36, GDA94)

# Relationship between Reference Frames and Datums



# Design considerations for a Local Reference Frame

**Selection of reference epoch**

consider epoch of parent GRF/RRF and adjoining datums or frames
consider effects of plate rotation on GNSS baseline vectors
consider PPP/SBAS user precision viz-a-viz local frame epoch (offset)
reference epoch ideally within current observation time-series

**Intraplate stability of the tectonic plate encompassed by the Local Frame**

Is a deformation/displacement model required? – consider precision requirements for users if deformation is ignored
Define polygons for stable crustal blocks (consider tolerances)

**Models for coseismic offsets and postseismic relaxation**

to manage spatial data across a deformation event
consider updating of coordinates at reference epoch to "reflect reality"
issues with positioning and dimensional precision – especially across fault rupture zones

# Data selection criteria and pre-processing

Select stable sites (anchored to bedrock wherever possible)
Use site velocities with horizontal uncertainty <0.5 mm/yr if possible (typically any CORS with > 2.5 years of observations)
(consider draconitic period within time-series, seismic and slow-slip offsets, site velocity changes, offsets due to equipment or firmware changes or local site observing conditions),
Compute local horizontal component of site-velocity vector
(as Euler pole inversion is only defined by tangential velocities)

Estimate elastic strain correction due to fault locking (if applicable)
Estimate post-seismic decay correction (if applicable)
Estimate velocity correction (horizontal part) due to GIA effects

Other considerations:
Effect of spherical assumption on Euler pole inversion.
Geocentre translation rate
Adoption of a single local origin and epoch (ignoring plate rotation)

# LS inversion of plate rotation rate from ITRF velocities

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

unweighted inversion

weighted inversion

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

Euler Pole
(as defined by
rotation rate of axes
Rad/yr)

Design matrix
of ITRF site coordinates
$x_1\ y_1\ z_1$ to $x_n\ y_n\ z_n$

Observation matrix of ITRF
site velocities (m/yr)
$Vx_1\ Vy_1\ Vz_1$ to $Vx_n\ Vy_n\ Vz_n$

# Converting plate rotation rates about ITRS axes to Euler pole notation

Pole rotation rate

$$\omega_{plate} = \sqrt{\omega_x{}^2 + \omega_y{}^2 + \omega_z{}^2}$$

(in Rad/yr + is anti-clockwise about pole)

$$\omega_{(\deg/Ma)} = \omega_{(Rad/yr)} \cdot \frac{180E6}{\pi}$$

Pole latitude

$$\phi_{plate} = \tan^{-1} \frac{\omega_z}{\sqrt{\omega_x{}^2 + \omega_y{}^2}}$$

Pole longitude

$$\lambda_{plate} = \frac{\omega_y}{\omega_x}$$

# Converting plate rotation rates about ITRS axes to conformal transformation rotation parameters

Rotation rates (in 14-par)

$$\dot{r}_x = -\omega_x$$

$$\dot{r}_y = -\omega_y$$

$$\dot{r}_z = -\omega_z$$

Rotation (in 7-par)

$$r_x = -\omega_x \left(t - t_0\right)$$

$$r_y = -\omega_y \left(t - t_0\right)$$

$$r_z = -\omega_z \left(t - t_0\right)$$

$$r_{(\sec/yr)} = \frac{0.648\omega_{(Rad/Ma)}}{\pi}$$

$t$ position epoch (decimal years)

$t_0$ reference epoch (decimal years)

Velocity estimation from PMM

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

# Case Study: Stable Australian Plate Reference Frame (Yet another acronym!)

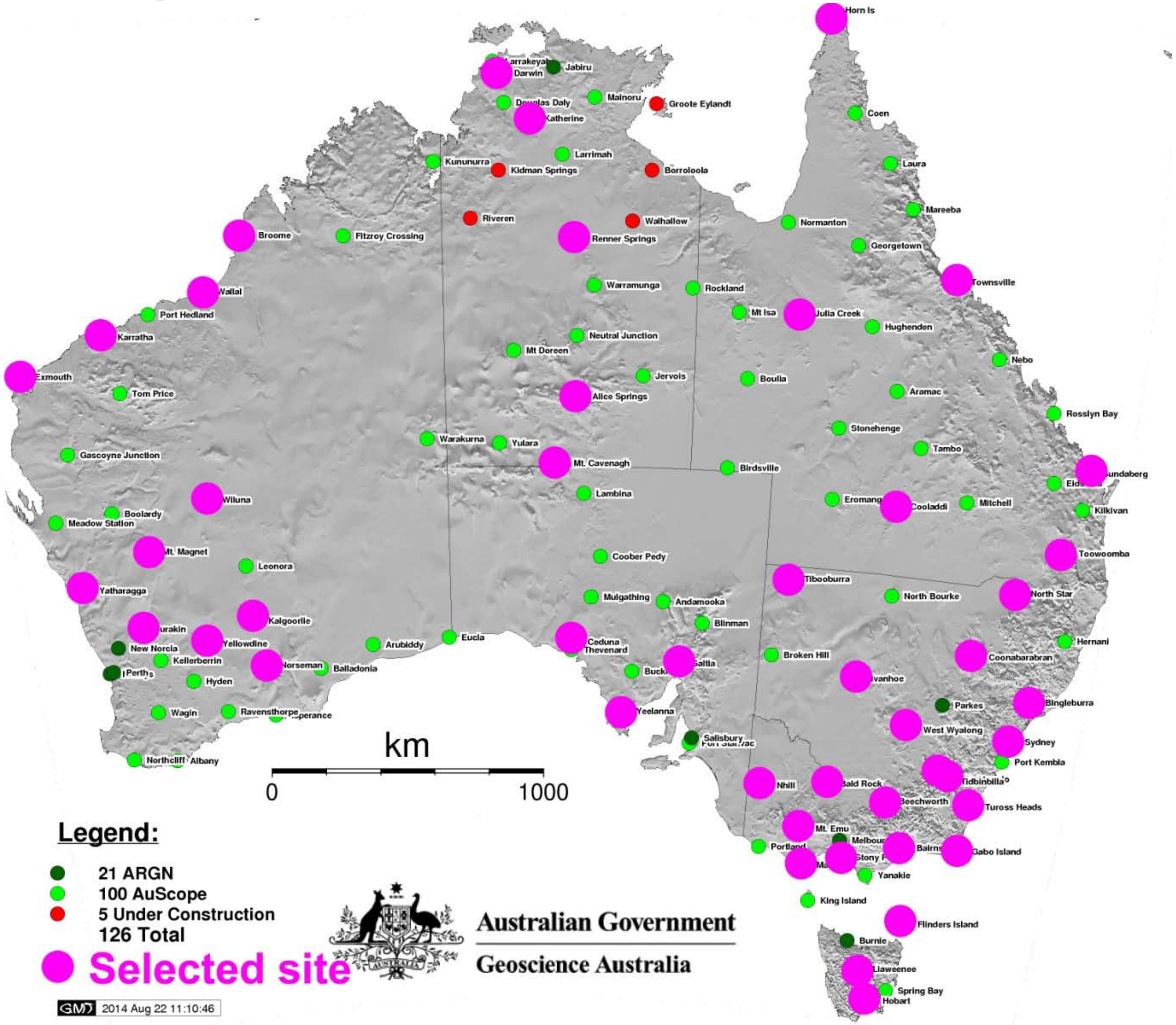
**Site selection criteria:**
CORS (or forced-centred geodetic monitoring stations)
Antenna mounts and reinforced concrete pillars anchored to cratonic bedrock

ITRF site velocity (horizontal component) uncertainty < 0.4 mm/yr (rooftop, tower, jetties or clay soil locations excluded from analysis – e.g. MOBS, ADE1, PERT, BUR2)

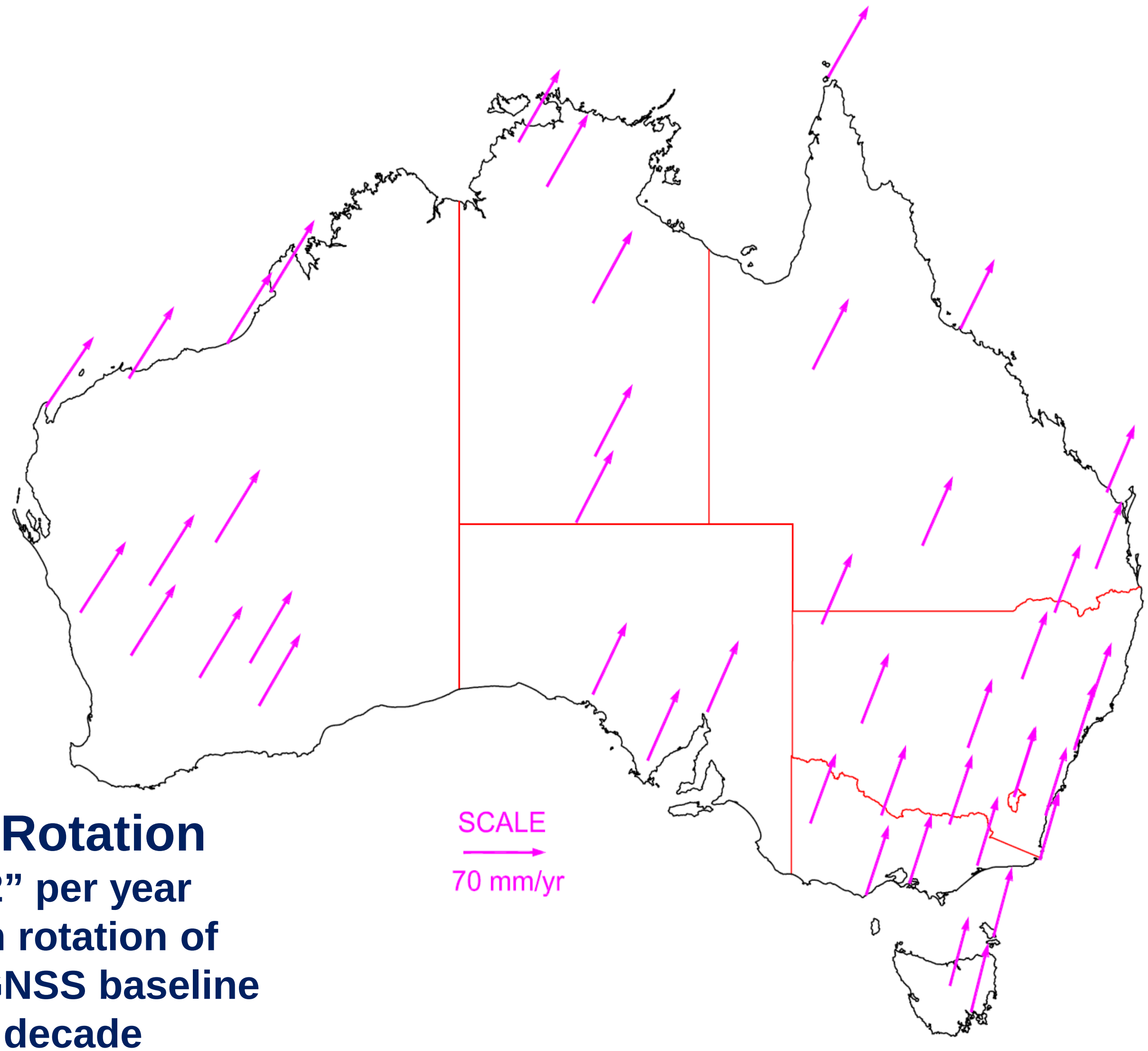
**Data source:** Geoscience Australia (GA)
ITRF2008 (epoch 2014.0) APREF IGSb08 GPS SSC 2014.0 solution and associated SINEX file for VCV data
data processed and analysed using Bernese 5.0 and CATREF (courtesy of John Dawson and Guorong Hu, GA)

**46 stations (**AUSCOPE and ARGN CORS) fitted the criteria – distributed over the Australian continental landmass.

# CORS selection used to estimate pole of stable Australian plate



# Observed ITRF site velocities at selected CORS




## Plate Rotation

**0.0012" per year**
**= 3 mm rotation of**
**a 50 km GNSS baseline**
**per decade**

# Computed stable Australian plate Euler pole

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

(rotation rates in Rad/yr - multiply by 1E6 to obtain pole rotation rates in Rad/Ma)

$\sigma$ of rotation rates: 4.512E-11 4.147E-11 3.652E-11

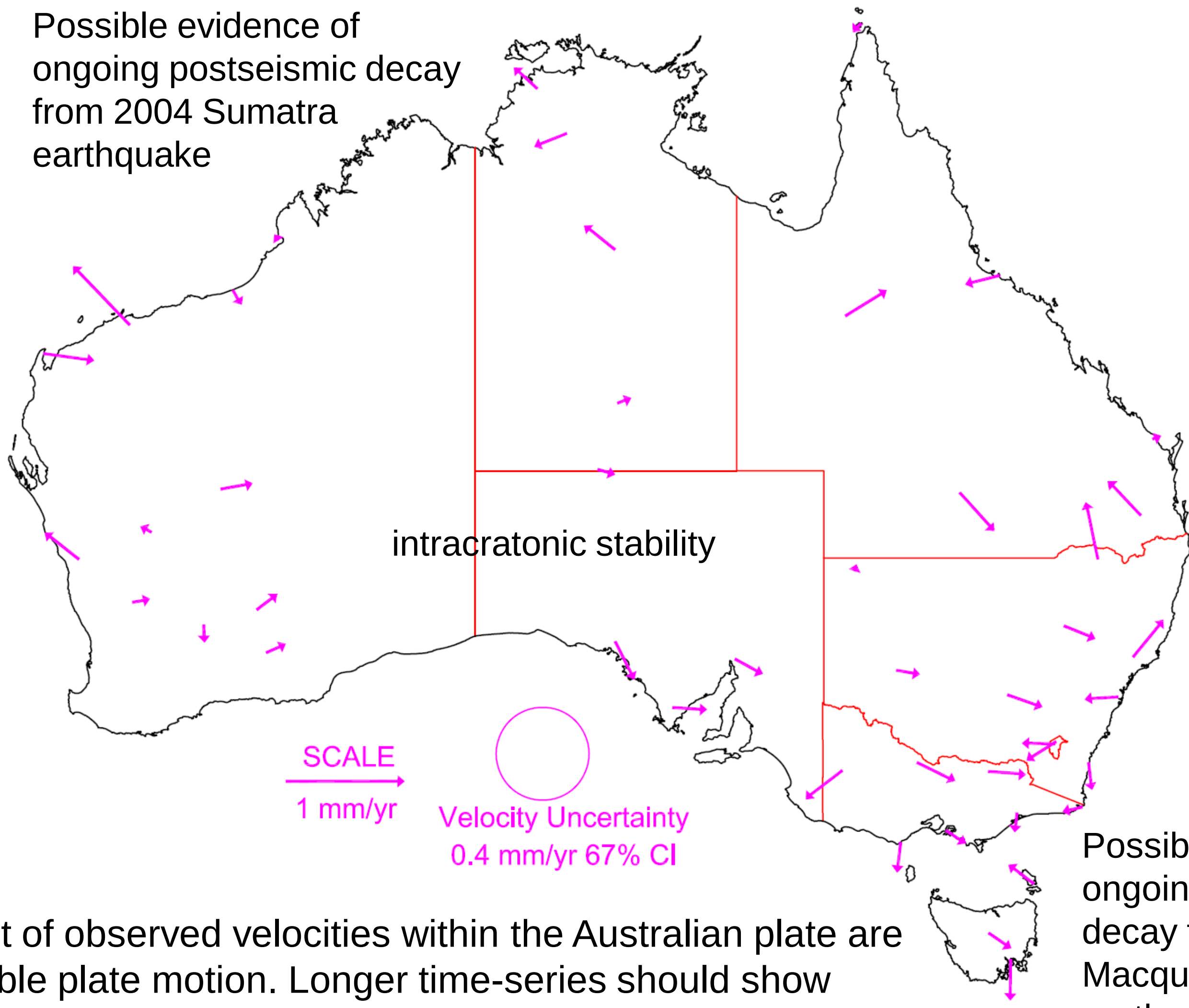
Pole rotation rate (+ is anti clockwise) $\omega_p = 0.630^\circ / \mathrm{Ma}$

Pole latitude $\phi_p = 32.35^\circ$

Pole longitude $\lambda_p = 45.17^\circ$

# Velocity residuals for stable Australian plate

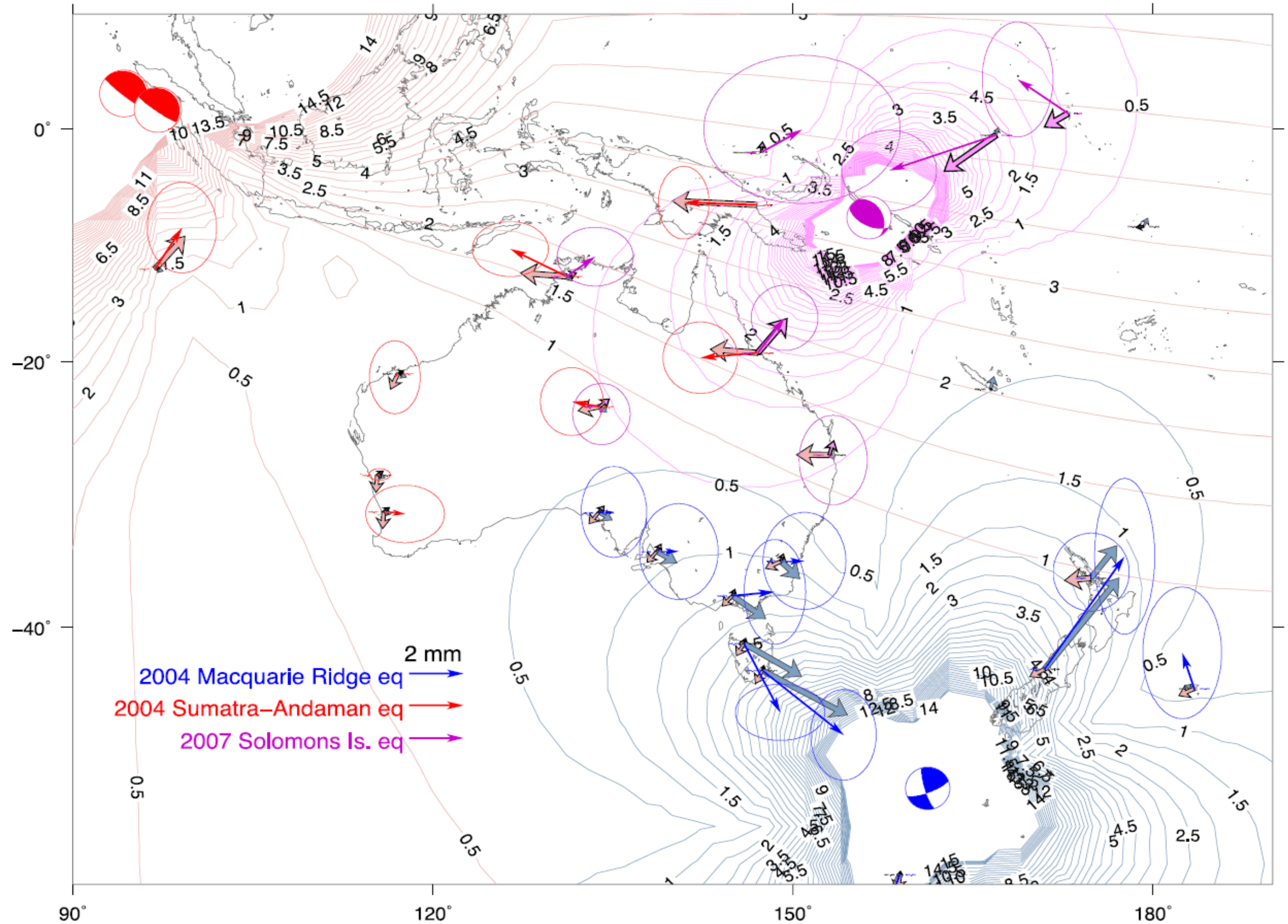
Possible evidence of ongoing postseismic decay from 2004 Sumatra earthquake




Possible evidence of ongoing postseismic decay from 2004 Macquarie Ridge earthquake

99.6% component of observed velocities within the Australian plate are attributable to stable plate motion. Longer time-series should show evidence of intraplate deformation and residual post-seismic deformation

# Far field coseismic and postseismic deformation




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

# Residual deformation or displacement model

Kriging or LSC of residual site velocities directly or apply fault locking model then krig residuals wrt locking model

Grid model of interpolated residuals (e.g. NTv2 or other grid data format used for residual site velocities wrt stable plate)

Absolute (ITRF) Deformation/displacement model in NTv2 or other grid format can also be applied and is suited to computing block-shifts for centroid of raster data (e.g. Imagery).

ISO standard for gridded geodetic data and interpolation method is important – to ensure standard approach in different GIS and geodetic software.

# Application of Local RF and deformation model in practice

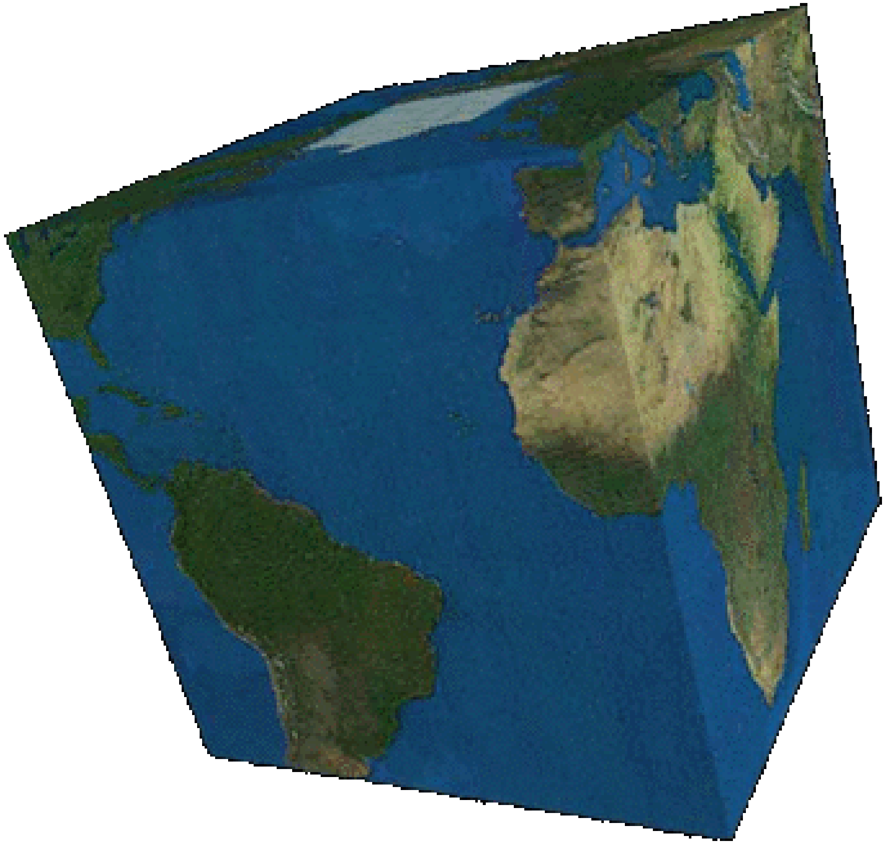
ITRF at measurement epoch used for baseline processing and PPP

Euler pole (as rotation parameters in a conformal transformation) used to transform ITRF coordinates at measurement epoch to Local Reference Frame

in Australia – precision is ~0.3 mm/yr  or
6 mm if reference epoch of 1994.0 is used (current datum epoch)

Residual secular deformation model (NTv2 format) then applied for higher precision transformation (0.1 mm/yr or 2 mm for 1994 ref epoch)

Apply patch model for seismic offsets (if required)



# Thank you!