A High-Precision Deformation Model to support Geodetic Datum Modernisation in Australia

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Abstract

This paper describes a gridded kinematic representation of a deformation model that can be used to support kinematic geodetic datum applications for high precision users. The kinematic model is comprised of a site velocity model (for coordinate prediction and to model inter-seismic deformation and plate motion) and an epoch correction model. The epoch correction model estimates distortion between reference frames at the reference epoch and can include episodic deformation arising from seismic activity.

The kinematic model presented enables seamless interaction between precision GNSS positioning and related systems, GIS and static spatial datasets within a kinematic coordinate environment with centimetre precision.

The next generation Australian Geodetic Datum will be realised within a kinematic reference frame in order to capture the highest resolution deformation of the Australian tectonic plate. This represents a paradigm shift from classical geodetic datums which are realised by coordinates of geodetic monuments fixed at a specified reference epoch (static geodetic datums). Centimetre precision positioning will be available to the mass market in the near future and the disparity between static geodetic datums (and spatial data products derived from them) and ITRF due to the effects of Earth deformation will be become more apparent. As development of deformation models within GIS is still in its infancy, there is still an ongoing requirement to provide static coordinates to users to enable positioning within a kinematic reference frame to maintain alignment with existing spatial datasets (e.g. cadastral, utilities, roads, infrastructure, mining, precision agriculture, imagery and LiDar). Furthermore, a four-dimensional GIS, when developed, will still require a precise deformation or kinematic model to enable spatial data collected at different epochs to be integrated harmoniously.

The current strategy used in Australia to transform between a specified epoch of ITRF and GDA94 (the current ITRF aligned geodetic datum fixed at epoch 1994.0) is to use a 14 parameter conformal transformation but approach does not capture the full complexity and variation of the deformation field at the highest resolution for some users, and so a variable resolution gridded deformation model is proposed here as an alternative.

Introduction

Increasingly, precise positioning services e.g. AusPOS (Commonwealth of Australia, 2013), NRCan-PPP (Government of Canada, 2013) and OPUS (US Government, 2013) are providing coordinates within the latest realisation of the International Terrestrial Reference Frame (ITRF), currently ITRF2008, or other global reference frames closely aligned with ITRF such as WGS84 and IGS08. The positional uncertainty of these services is typically less than 10 millimetres for horizontal coordinates and less than 25 millimetres for ellipsoidal heights for submitted static dual-frequency carrier phase observations of several hours duration. The application of these services is therefore sensitive to tectonic displacement. Repeat observations made on a geotechnically stable geodetic monument within a time span of even a few months can show centimetre changes in coordinates. Many of the online ITRF based processing services also transform the ITRF coordinates at the epoch of measurement to a localised reference frame where global scale tectonic deformation effects have been largely modelled out (e.g. GDA94 in AusPOS, NAD83(CSRS) in NRCan, and NAD83(2011)/SPCS in OPUS). Removal of the underlying tectonic deformation signal (in particular the absolute plate rotation component) in most instances enables repeatability of coordinate estimation within a localised reference frame over very long periods. Coordinate stability at a specific reference epoch is an essential requirement for integration of spatial data acquired at different epochs within a localised reference frame (Stanaway and Roberts, 2011).

This paper presents a gridded kinematic representation of a tectonic deformation model for the Australian continent that can be utilised to project or propagate ITRF coordinates at a kinematic epoch to a fixed reference epoch for applications that require temporally stable centimetre-level absolute positioning accuracy. The current geodetic datum officially adopted in Australia is the Geocentric Datum of Australia 1994 (GDA94) which is a realisation of ITRF92 at epoch 1994.0 (ICSM, 2013). In 2012 the realisation of GDA94 was updated in order to reduce the formal uncertainties of the fiducial network from 30 mm (horizontal) and 100 mm (vertical) to less than 10 mm (Commonwealth of Australia, 2012). Despite this, many stations in the Australian National Network (ANN) still have uncertainties of up to 300 mm due to distortions in the original geodetic adjustment of the ANN (Haasdyk and Roberts, 2013). The proliferation of CORS networks streaming RTK and NRTK in Australia is already highlighting the disparity between GDA94 derived from CORS and the GDA94 coordinates of passive geodetic control in distorted secondary and tertiary networks (Haasdyk and Janssen, 2012).

The model described here enables propagation of any epoch of the current ITRF realisation (ITRF2008) to a projected frame that is closely aligned with the current realisation of GDA94 with a precision of 10 mm at 95% Confidence Interval (CI). This level of precision is sufficient for the majority of precision users of the datum. The model can be utilised in GIS, GNSS positioning and GNSS post-processing software. Utilisation of the model in services such as Google Earth and mass-market positioning devices can ensure that precision ITRF position estimation can be aligned closely with an underlying map or image base that is tied to a fixed epoch of ITRF via a local reference frame consistently over periods of several decades. This alleviates the requirement to keep local reference frames in constant alignment with ITRF.

Advantages of gridded deformation models over conformal transformation models

A commonly used strategy to transform ITRF coordinates to a localised reference frame is to apply a 14 parameter conformal transformation (7 parameters and their rates of change), or to use a model of rigid plate motion (e.g. Stanaway and Roberts, 2010). 14 parameter transformation models have been developed between each realisation of ITRF and GDA94 (Dawson and Woods, 2010) and these have enabled ITRF coordinates computed from positioning services such as AusPOS to be transformed to GDA94 for submitted observation data within Australia. AusPOS processing is undertaken within the IGS08 reference frame using Bernese software (Dach *et al*., 2007).

Conformal transformation approaches assume that deformation of the local reference frame with respect to ITRF is secular and well distributed. The major disadvantage of these approaches is that localised and non-conformal deformation is either unaccounted for, or propagates errors into the parameter estimation if monuments located in regions of localised deformation are constrained in a least squares estimation of parameters. Gridded deformation models overcome the limitations of parametric approaches because localised deformation can be isolated within the model. Furthermore, non-linear deformation effects such as complex plate boundary interseismic deformation can be modelled and interpolated with greater precision. In regions of localised deformation, or where positioning tolerances are smaller (e.g. urban areas), a denser deformation grid can be developed (Winefield et al., 2010).

Development of a gridded kinematic model for Australia

A gridded kinematic modelling approach using a schema outlined in LINZ (2013) and Stanaway *et al*., (2014) is presented in this paper for the Australian continent. The approach described separates two modes of deformation; interseismic motion (modelled site velocity) and episodic deformation (coordinate shift at a defined epoch). This approach has been used in Japan (Hiyama *et al*., 2011) and in New Zealand (Crook and Donnelly, 2013). While Australia is more tectonically stable than Japan and New Zealand, there is still observable intraplate deformation that warrants a high precision kinematic model for the highest precision applications. Postseismic deformation is typically exponential in character and a third deformation mode defined by a grid of exponential decay parameters could also be implemented to model non-linear deformation arising from postseismic deformation where this is significant. In the Australian context, the magnitude of postseismic decay from regional earthquakes is at present not sufficiently significant to warrant separate inclusion in the Australian deformation model and is not discussed further.

The Australian continent lies wholly within the stable portion of the Australian tectonic plate. With the exception of isolated intraplate earthquakes e.g. Tennant Creek, Meckering, Newcastle (Leonard *et al.*, 2007), no significant (>1.0 mm/yr baseline changes across the continent) intraplate deformation between stable geodetic monuments fixed to bedrock has been observed in the interseismic period. Since the year 2000, large regional earthquakes along the margins of the Australian tectonic plate have resulted in observable far-field deformation at the millimetre level within the Australian Plate (Tregoning *et al*., 2013). Sites located on regolith and sedimentary basins where groundwater abstraction, coal seam gas extraction and underground mining is occurring are also subject to observable vertical deformation, however this deformation is localised.

The horizontal deformation components of the Australian kinematic model have been derived from the ITRF2008 Euler pole of the Australian plate (Altamimi *et al.* 2012) which has been computed by inversion of observed site velocities at a selection of geodetic monitoring stations across the Australian plate. These stations comprise of IGS Reference frame GNSS stations, SLR and VLBI stations. As the Australian plate is tectonically stable at the mm/yr level, a 1 degree apriori grid of site velocities (topocentric East and North rates) was computed for each node covering the Australian continental landmass from the ITRF2008 plate model. The 1 degree grid resolution was chosen as it is the maximum grid size where a planar assumption of an ellipsoid does not propagate error during interpolation of the grid at a significant level. While the Australian continent is sufficiently tectonically stable to support a 1 degree grid, higher resolution grids are warranted in regions of higher relative deformation, or in urban areas and mines. In the absence of any apparent widespread vertical deformation beyond the 0.05 mm/yr level within the Australian continent on geological timescales (Braun *et al*., 2009), the apriori vertical deformation model has been set to zero for all nodes.

Observed site velocities from 18 CORS comprising all of the fiducial CORS that define the Australian Datum (Geoscience Australia, 2013) on the Australian continent (Figure 1) were then selected to further refine the apriori ITRF2008 plate motion model by kriging of the residuals of observed site velocities (IERS, 2014). All CORS selected have observation spans greater than eight years. For each of the CORS locations the site velocity was estimated from the ITRF2008 plate model and compared with the observed site velocity from Geoscience Australia's APREF data analysis (Geoscience Australia, 2013).

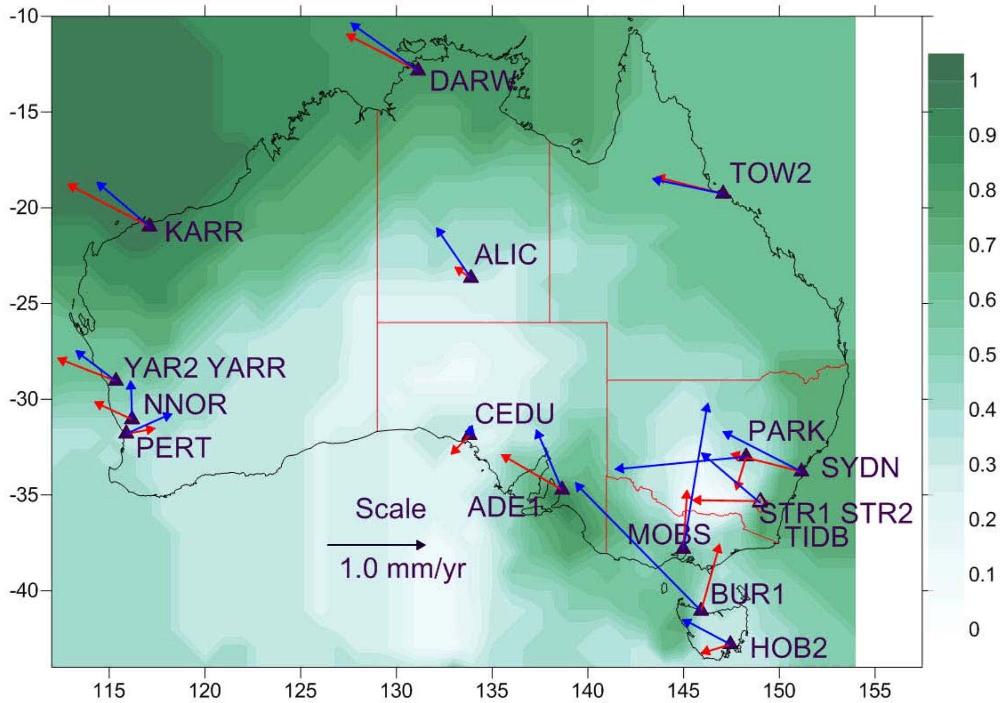

Figure 1. Differences between published APREF, ITRF2008 GPS velocities and modelled velocities estimated from the ITRF2008 Australian Plate Euler pole at Australian fiducial CORS (purple triangles). Green shading shows the site velocity differences between the kinematic model (this paper) and velocities estimated from the ITRF2008 Euler pole in mm/yr. The blue vectors show ITRF2008 GPS published velocities minus modelled velocities. The red vectors show APREF velocities minus modelled velocities.

The maximum differences between APREF and modelled apriori site velocities are 0.9 mm/yr. The RMS of APREF site velocity differences is 0.2 mm/yr over all of the CORS sites modelled and this provides a global level of uncertainty for site velocities estimated from the deformation model for bedrock locations. Between epochs 2013 and 1994 the site velocity model error has a global uncertainty of 6 mm at 95% CI for propagation back to the GDA94 reference epoch. Kriging using Surfer software (Golden Software, 2013) was used to model and propagate site velocity differences over the Australian continent. The standard kriging technique with a variogram slope of 1 was used due to the sparsity of the network of CORS stations used.
The velocity model corrections were then applied to the apriori ITRF2008 plate model derived grid. This approach ensures that site velocities interpolated from the model are consistent with observed velocities of the fiducial CORS network.

Vertical deformation rates over the Australian continent (Figure 2) are very poorly constrained due to the absence of long time series on a dense network of CORS stations, unmodelled seasonal deformation and other biases in vertical time series. A number of the fiducial CORS in Australia are located on clay-rich regolith or potentially unstable locations such as buildings and jetties (e.g. PERT, MOBS, ADE1, PARK and BUR1) and the vertical rates for these locations are strongly influenced by seasonal ground water and seasonal clay moisture variations. Large areas of the Australian continent are also overlain by clay-rich regolith and there are also extensive aquifers across the continental interior. Vertical deformation rates in these regions have yet to be determined with any precision and any continental scale vertical deformation model is contingent on the availability of accurate and widespread vertical deformation observations.

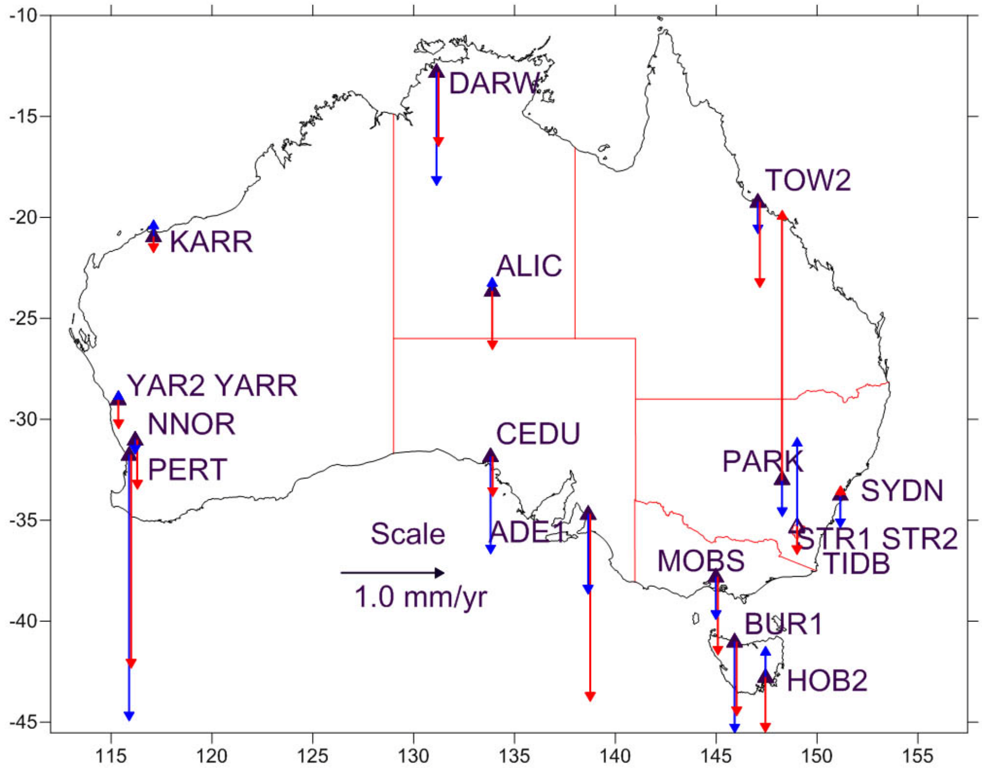

Figure 2. Observed vertical (UP) velocities at Australian fiducial CORS. The blue vectors show ITRF2008 GPS published vertical velocities. The red vectors show APREF observed vertical velocities.

Figures 3 and 4 show topocentric East and North deformation rates for the Australian continent estimated from the ITRF2008 plate motion model with corrections applied from kriging of the residuals between observed and modelled site velocities at the fiducial CORS stations.

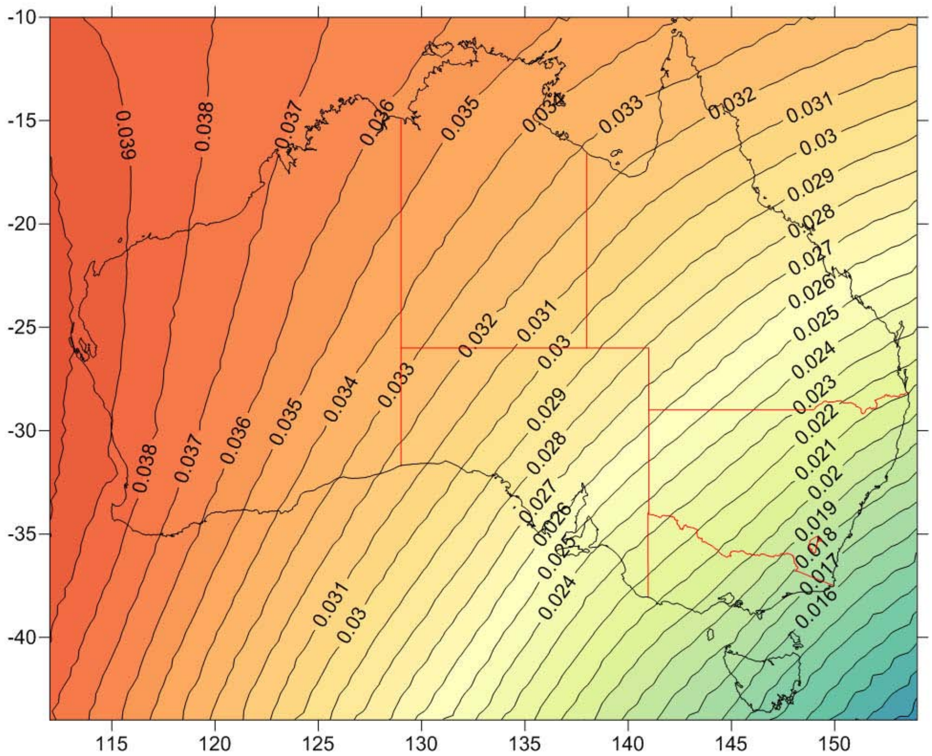

Figure 3. Australian Kinematic Model - Topocentric East velocity (m/yr)

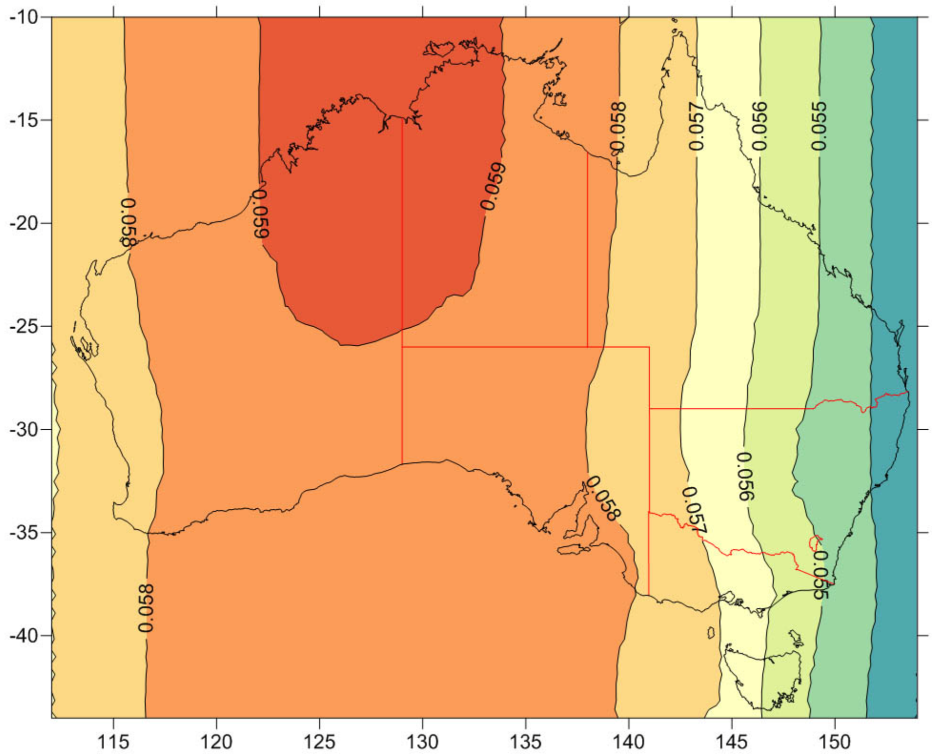

Figure 4. Australian Kinematic Model - Topocentric North velocity (m/yr)

The computed site velocity model was then used to propagate the ITRF2008 APREF solution at epoch 2012.3 to epoch 1994.0 (consistent with the GDA94 reference epoch). The propagated coordinates were then compared with the latest published GDA94 coordinates for the fiducial network. The residuals between ITRF2008 at epoch 1994.0 and published GDA94 coordinates were then used to develop a continental displacement model, also using the kriging technique. The displacement model represents a coordinate shift to be applied to ITRF2008 coordinates at Epoch 1994.0 in order to estimate the equivalent GDA94 coordinates. The model essentially combines distortions and uncertainty in the original realisation of GDA94 with any episodic deformation that has occurred between 1994 and 2012, for example deformation arising from subsidence and regional earthquakes. The RMS of the displacement estimation (for bedrock sites) is 3 mm from the kriging analysis. Figures 5 to 7 show the coordinate shift component of the deformation model for ITRF2008 (epoch 2012.3) propagation to published GDA94.

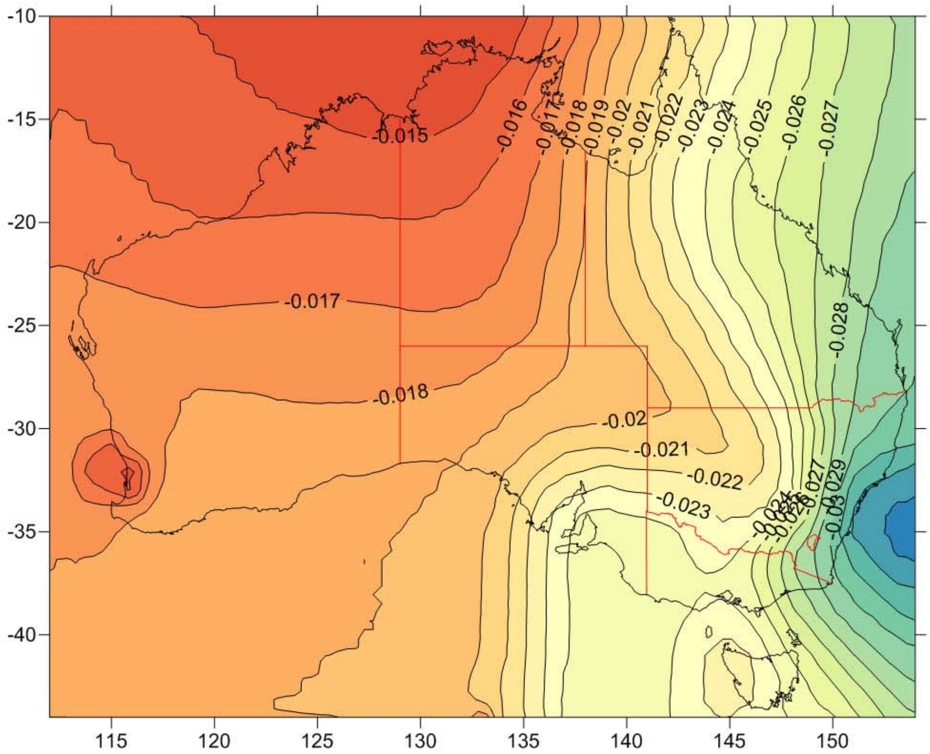

Figure 5. GDA94 to ITRF2008(1994.0) Coordinate Shift East (m)

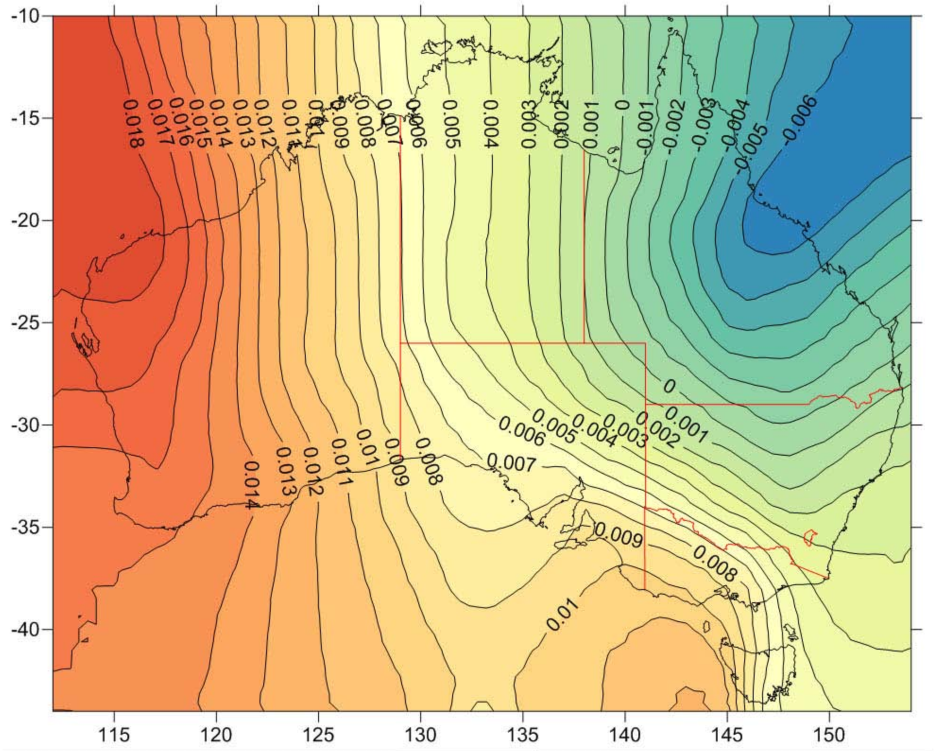

Figure 6. GDA94 to ITRF2008(1994.0) Coordinate Shift North (m)

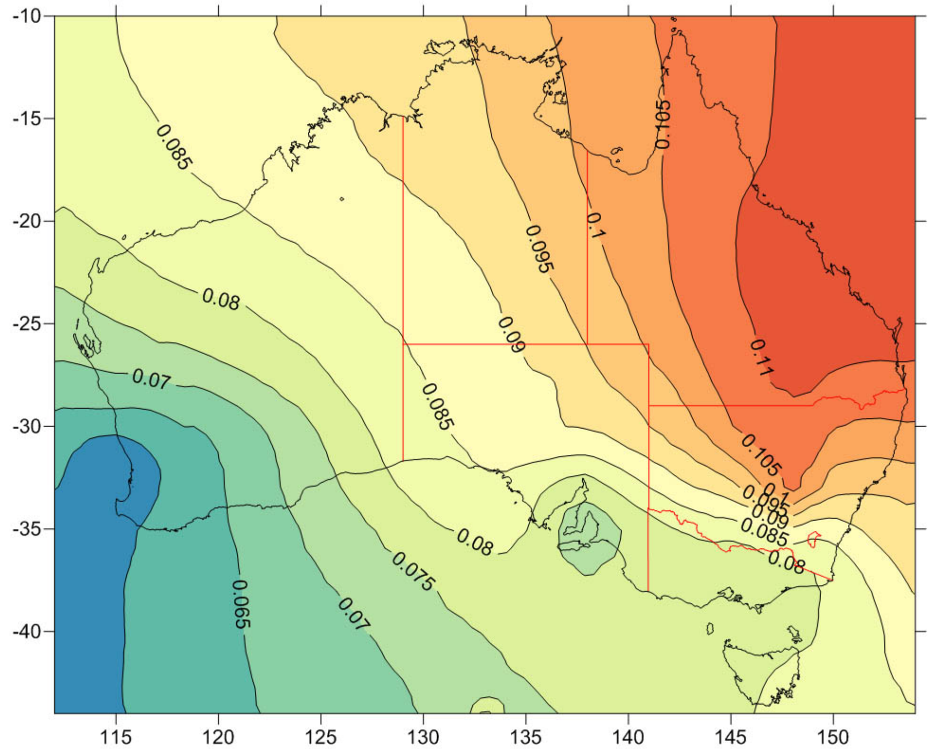

Figure 7. GDA94 to ITRF2008(1994.0) ellipsoid height correction (Up) (m)

Format and application of the Model

The model is presented in a standard ASCII text format to enable conversion to other text or binary grid formats.

The header of the site velocity deformation grid file contains metadata shown in Table 1.

Model Name	Australian site velocity model	GDA94 to ITFR2008(1994.0) displacement model
Model Datum (Start)	ITRF2008	ITRF2008
Model Datum (End)	ITRF2008	GDA94(2012 gazettal)
Model Datum Epoch (Start)	1994.0	1994.0
Model Datum Epoch (End)	not defined	1994.0
Grid size	1	1
Grid Latitude (degrees) max	-10	-10
Grid Latitude (degrees) min	-44	-44
Grid Longitude (degrees) max	154	154
Grid Longitude (degrees) min	112	112
Coordinate units	decimal degrees	decimal degrees
Velocity format	topocentric	topocentric
Velocity units	metres	metres
Interpolation Method	bi-linear	bi-linear
Version	Version 201310101	Version 201310101
Release Date	10th October 2013	10th October 2013
Model uncertainty at 95% CI	0.0004 m/yr	0.005 m

Table 1: Metadata format of the kinematic and displacement components of the model.

For each degree node of latitude and longitude, the following deformation data are provided: Latitude, Longitude, East velocity, North velocity, Up velocity (for the site velocity model component) or Latitude, Longitude, East translation, North translation, Up translation (for the displacement model component).

Propagation of ITRF coordinates at a specific epoch to GDA94 is accomplished as follows:
1. ITRF coordinates are converted to decimal degree format
2. The site velocity grid is interpolated (using bi-linear method) to extract the topocentric site velocities for that location
3. The topocentric rates are converted to ellipsoidal (latitude and longitude) coordinate rates
4. The coordinates at epoch 1994 are estimated by applying the computed deformation
5. The patch model grid is interpolated (using bi-linear method) to extract the topocentric shifts
6. The shifts are converted to ellipsoidal (latitude and longitude) format
7. The shift is applied to the 1994 epoch propagation to derive coordinates consistent with GDA94.

Propagation of ITRF coordinates to other epochs can also be accomplished using the site velocity model and other patch models that include net episodic deformation between specified epochs. These patch models would be of a similar format to the one presented here for ITRF to GDA94 propagation.

Comparison with existing models

The gridded deformation model described was compared with both the ITRF2008 Euler Pole and the latest 14 parameter models (Dawson and Woods, 2010). Figure 8 shows the magnitude of site velocity differences between this deformation model and the 14 parameter model.

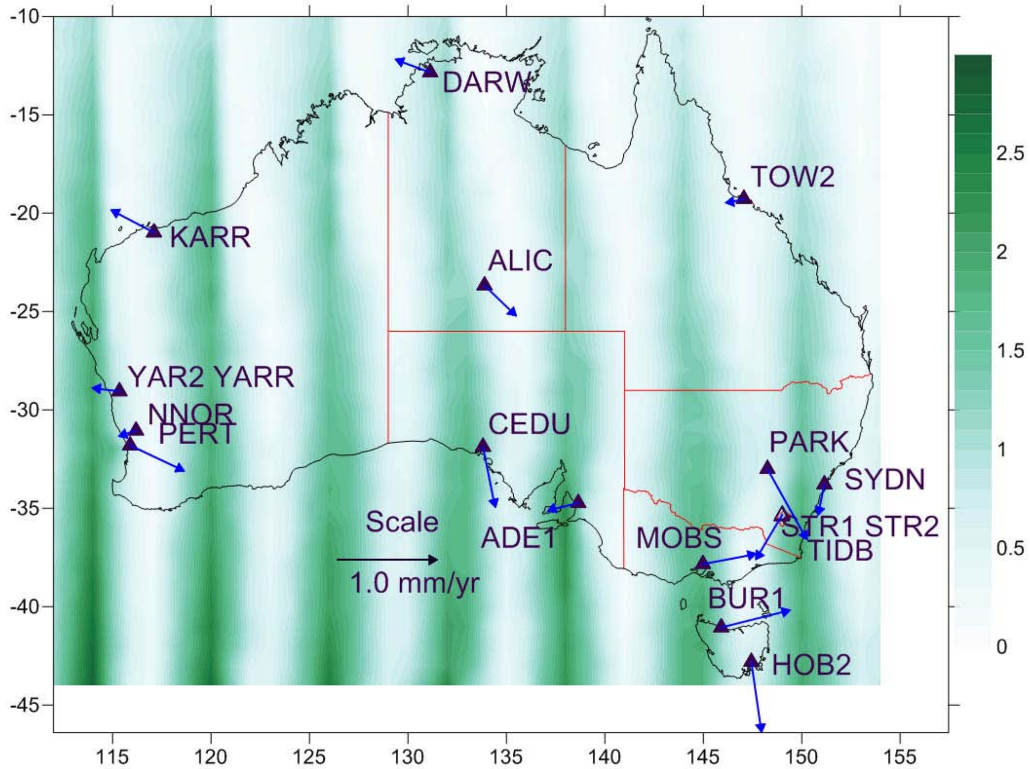

Figure 8. Comparison of Australian kinematic model with the current 14 parameter model (Dawson and Woods, 2010). Site velocity differences are shown by green shading (mm/yr). Blue vectors show APREF site velocities minus velocities estimated from the 14 parameter model.

Conclusion

The Australian kinematic model described here enables propagation of ITRF coordinates from any specified epoch to GDA94, which is a realisation of ITRF92 at Epoch 1994.0. Two modes of deformation are represented by the model, secular interseismic motion via a site velocity model, and episodic deformation combined with modelled distortion via a displacement model. The gridded deformation model approach has potential advantages over classical conformal transformation strategies such as the 14-parameter model in that localised deformation can be isolated within the model. The grid approach allows for denser nested grids than the model presented (where sufficient sites with site velocities are available) to better model deformation where there is a greater requirement for precision, or where deformation is more spatially variable. The gridded approach is also well suited to incorporation in personal navigation devices, GIS and surveying software.

One of the main advantages of a two component deformation model is that it can enable ITRF positioning to be related with centimetre precision to a digital map base or spatial data base fixed at a specified reference epoch. A disadvantage of the 14-parameter model is that localised or non-linear deformation at any sites used in the inversion of the parameter estimation will propagate into the model. In this paper, the stability of the Australian plate can support a fixed reference epoch for a number of decades before the most stringent positioning tolerances are exceeded.

The models can be improved as more quality geodetic data become available. Integrity monitoring at CORS can be achieved by comparing deformation model predictions with the latest ITRF coordinate solutions for the monitoring stations.

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