Australian Terrestrial Reference Frame (ATRF)

Technical Implementation Plan

Version 2.2

Intergovernmental Committee on Surveying and Mapping (ICSM)
Permanent Committee on Geodesy (PCG)
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Document History

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2.0	Nicholas Brown (December 2018)	
2.1	Nicholas Brown (March 2019)	Number of small edits and additions following the PCG face to face discussion in March 2019
2.2	Nicholas Brown (November 2019)	Updates to reflect that the reference frame epoch of ATRF should be included when defining a particular realisation of the ATRF (e.g. ATRF2014).

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1. Purpose

The purpose of this document is to provide a publicly accessible resource of:

- Background information explaining the need for the Australian Terrestrial Reference Frame (ATRF);
- Definition of ATRF and its relationship to the Geocentric Datum of Australia 2020 (GDA2020);
- Description of the roles, responsibilities and actions of the Permanent Committee on Geodesy (PCG) for the technical development of ATRF.

The document addresses many of the complex, geodetic and technical issues associated with the implementation of a time-dependent reference frame and is therefore intended for those with expertise in geodesy or the geospatial industry.

2. Introduction

Australia has traditionally used a static reference frame for its national geodetic datums (e.g. Clarke, AGD66, AGD84, GDA94) to which all spatial information can be consistently georeferenced and aligned. With a static datum, the geo-referencing of positions doesn't change over time. That is, the coordinates of features appear to remain fixed despite the ongoing changes in the Earth's landscape.

Australian and International research shows (Allen 2013; European GSA, 2017), however, that there is a rapidly growing user community including Location Based Services (LBS) and Intelligent Transport Services (ITS) employing applications that require real-time, high-precision positioning solutions aligned to a global, time-dependent reference frame, such as the frames in which Global Navigation Satellite Systems (GNSS) operate. When such applications are aligned to a global, time-dependent frame, positioning and navigation is not only compatible with GNSS, but also more closely reflects the ongoing changes in the Earth's landscape over time. That is, the coordinates of features change according to the movements of those features in the real world.

In recognition of the two use cases for geo-referencing, the Intergovernmental Committee on Surveying and Mapping (ICSM) and the Spatial Information Council (ANZLIC) have endorsed a "two-frame" approach to support users who prefer to use a static datum, while also meeting the needs of those who require a reference frame that accommodates ongoing changes in the Earth. In 2020, Australia will adopt the two-frame approach, enabling users to work with a static datum, the Geocentric Datum of Australia 2020 (GDA2020), or with a time-dependent reference frame known as the Australian Terrestrial Reference Frame (ATRF).

The first realisation of ATRF will be ATRF2014; aligned to the 2014 realisation of the International Terrestrial Reference Frame (ITRF2014). Subsequent realisations of ATRF be released over time and aligned with new ITRF realisations.

GDA2020 and ATRF2014 will be equivalent at the reference epoch of 01/01/2020. Given the diverse range of user requirements in Australia, the choice of which reference frame to use (GDA2020 or ATRF2014) will remain with the user for the foreseeable future.

Time-dependent reference frames are not new – thirteen International Terrestrial Reference Frame (ITRF) versions[1] have been developed and released since the introduction of ITRF in 1988. The World Geodetic System of 1984 (WGS84), the reference frame underpinning the USA Global Positioning System (GPS), is another example which has had six realisations.

The origin of time-dependent reference frames is coincident with the Earth's centre of mass (including the oceans and atmosphere). The Z axis is coincident with the mean axis of the Earth's rotation, and the equator is coincident with the XY plane. As the tectonic plates move on the Earth (e.g. the Australian plate moves ~7 cm/yr to the north, north-east (NNE)), the coordinates of points on the Earth change over time to reflect the motion (between 1.0 - 1.4 mm per week depending on your location within Australia). With each new ITRF realisation, new and improved models, analysis strategies and geodetic techniques have been applied to improve the realisation of the size and orientation of the Earth and improve the quality of time-dependent coordinates achievable by a user.

3. Regional Reference Frames

Global time-dependent reference frames such as ITRF2014 are developed using combinations of data from a range of geodetic techniques including Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and GNSS. There is a limit on the number of sites that can be used in these global combinations and as such, not all GNSS Continuously Operating Reference Stations (CORS) feature in each combination. The resulting reference frame is a best fit on a *global* scale, but not necessarily on a regional (or local or continental) scale.

In recognition of this, the International Association of Geodesy (IAG) has a number of sub-commissions responsible for the definition, realisation and maintenance of *regional* reference frames. Regional reference frames are 'densified'. That is, they include a larger number of GNSS CORS from the region, while also including the CORS used in the global reference frame determination that maintains a strong connection between the global and regional frames. Examples of regional reference frames include the European Reference Frame (EUREF), the African Reference Frame (AFREF), System Reference for Central America and South America (SIRGAS) and the Asia-Pacific Reference Frame (APREF).

3.1 Asia-Pacific Reference Frame

The Asia-Pacific Reference Frame (APREF) provides a dense, accurate and continually refined reference frame for the Asia-Pacific region. This regional frame supports scientific studies and national geodesy, leading to significant economic, environmental and societal benefits for

[1] ITRF88, ITRF89, ITRF90, ITRF91, ITRF92, ITRF93, ITRF94, ITRF96, ITRF97, ITRF2000, ITRF2005, ITRF2008 and ITRF2014. Each ITRF version is a realisation of the International Terrestrial Reference System (ITRS). See http://itrf.ensg.ign.fr/general.php

member states in the Asia-Pacific region and supporting multi-disciplinary applications including surveying, geodynamics research, sea level monitoring, and numerical weather prediction.

The APREF Permanent Network has contributions from 28 countries and includes 718 CORS sites that have been operational for more than two years (as of August 2018). Of the 718 CORS sites, 488 are on the Australian tectonic plate. In contrast, only 15 Australian sites were incorporated into ITRF2014; purely because it is not feasible to incorporate all possible sites in computations for the global reference frame. The increased number of reference sites within APREF provides a denser and more accessible reference frame and velocity field, leading to a more robust positioning capability, and ultimately an improved interoperability of spatial data in Australia.

4. Australian Terrestrial Reference Frame 2014

ATRF2014 is based on a subset of GNSS CORS contributing to APREF and is limited to CORS sites contained within Australia's maritime jurisdiction and external territories on the Australian Tectonic Plate. This limitation is to ensure authoritative Australian coordinates are only supplied for Australian sites, and not other sites from throughout the Asia-Pacific region. The extent of ATRF is the same as GDA2020, as shown in Figure 1.

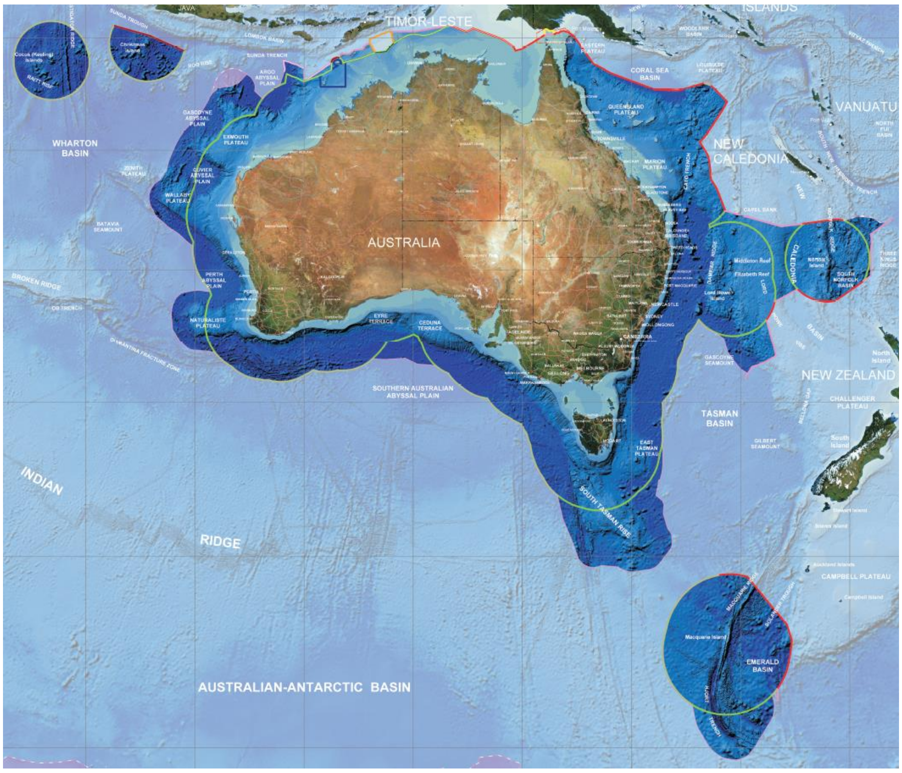

Figure 1: The area shown in dark blue is the ATRF/GDA2020 extent. The colours of the lines represent different types of jurisdictional boundaries or proposed jurisdictional boundaries. For more information, please refer to http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_70362

A CORS site must be in operation for more than two years before being considered for inclusion to APREF. Two years is considered the minimum length of time required to compute a statistically significant coordinate and site velocity. ATRF enables accurate, reliable and authoritative time-dependent coordinates and a dense velocity field to be derived for all Australian sites. This includes CORS that have been operating for less than two years, passive survey marks such as short term geodetic project control stations and geophysical monitoring of campaign sites.

4.1 ATRF2014 Definition

The first realisation of ATRF will be ATRF2014; aligned to the 2014 realisation of the International Terrestrial Reference Frame (ITRF2014). Subsequent realisations of ATRF be released over time and aligned with new ITRF realisations.

Table 1: ATRF2014 definition.

Reference frame	Epoch	Ellipsoid	Semi-major axis (m)	Inverse flattening
ITRF2014	Time-dependent	GRS80	6378137	298.257222101

Note: ATRF2014 has the same ellipsoid parameters as the GDA2020 and ITRF2014.

4.2 Computing ATRF2014 coordinates

GDA2020 and ATRF2014 coordinates will be maintained and updated over time in response to plate tectonics and local deformation. National adjustments will be undertaken monthly to ensure Australia has an accurate and densely realised geodetic framework based on continuous observation and analysis of Global Navigation Satellite Systems (GNSS) data. Below is a detailed description of the process to update and maintain GDA2020 and ATRF2014 coordinates and velocities.

4.2.1 APREF

4.2.1.1 Weekly APREF analysis

APREF data is processed by three Local Analysis Centres (AC): Geoscience Australia (GA) Surveyor-General Victoria, and the Institute of Geodesy and Geophysics - Chinese Academy of Sciences. Daily APREF solutions from each AC are generated in SINEX (Solution INdependent EXchange) format and combined into a weekly solution aligned to the latest GNSS reference frame adopted by the International GNSS Service (IGS) known as IGS14.

The weekly combined solutions from the three ACs are generated with Bernese software on the 'daily normal equations level'. That is, daily station solutions appearing to be inconsistent with a weekly trend are removed from the weekly combined solutions based on a comparison of the residuals of seven-parameter Helmert similarity transformations generated from daily and weekly solutions. The threshold of the residuals is 10 mm horizontally and 20 mm vertically.

The weekly SINEX files[2] from the three ACs are combined using the Combination and Analysis of Terrestrial Reference Frame (CATREF) software from Institut Géographique National (IGN) to derive site coordinates and uncertainties. The combined weekly APREF solutions are published on the APREF website and are available as Earth centred XYZ coordinates dated at an epoch of the middle of the week (UTC time).

4.2.1.2 Cumulative APREF position and velocity solutions

All historical weekly combined solutions (from 1994 onwards) are rigorously stacked using the CATREF software to obtain cumulative station coordinates and velocities as well as the station

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[2] http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame

position time series. These solutions are considered the most accurate and up-to-date coordinates for APREF stations and as such are the basis of ATRF2014 and GDA2020.

4.2.2 National Adjustment to compute ATRF2014 and GDA2020 coordinates

The process of undertaking the national adjustment will be:

- The national adjustment will be run undertaken monthly.
- The national adjustment will be maintained in GDA2020.
- Constraints for the national adjustment will be from a cumulative APREF solution from ~3 months prior. This allows enough time for any discontinuities in the APREF solution to be identified and resolved. The cumulative APREF solution will be propagated to the epoch of 2020-01-01 using the Australian Plate Motion Model (PMM; Section 4.3).
- The National Geodetic Campaign Archive (NGCA) data (i.e. >6hr GNSS data) will be subject to ongoing revision and included as baselines.
- The Jurisdictional Data Archive (JDA) (i.e. <6hr GNSS data and terrestrial data) will be subject to ongoing revision and will continue to be quality checked by jurisdictions before supplying it to GA to include in the national adjustment.
- The output of the national adjustment will be new GDA2020 coordinates and uncertainties.
- ATRF2014 coordinates will be derived at any epoch by applying the Australian PMM to the latest GDA2020 coordinates.

Geoscience Australia will maintain the national adjustment results in a database. The decision as to whether jurisdictions choose to update the coordinates and velocities for their products and services will be left to the individual jurisdictions.

4.2.3 ATRF2014 coordinates in real-time services

Geoscience Australia intends to make ATRF2014 coordinates available via its real-time positioning service. To do this, Geoscience Australia will create a new data stream for each CORS site with ATRF2014 coordinates used as the reference. Providing ATRF2014 coordinates as opposed to ITRF2014 coordinates enables a legally traceable solution.

Satellite Based Augmentation System (SBAS) corrections, which are to be supplied via internet / satellite, will be generated from CORS throughout Australia and will therefore also be in ATRF2014.

4.3 Plate motion model

A key requirement to ensure the successful implementation of a time-dependent reference frame is that software is able to transform / propagate data from the epoch it is natively captured or stored in, to a user-defined epoch. This will primarily be achieved through application of an Australian PMM and in some areas a deformation model may be applied.

Australia's PMM accounts for the horizontal plate tectonic motion about the Euler pole of the Australian plate. This motion is a slight clockwise rotation of the Australian plate about an Euler pole that is responsible for the ~7 cm / year movement to the NNE. The Australian PMM can be used to propagate GDA2020 coordinates to ATRF2014 coordinates. For example, to align real-time vehicle positions with published road maps.

NOTE: The Australian PMM is only a 2D model. It does not change the height component of the data. Changes to the height component are being considered in the form of a deformation model (see Section 4.4).

Australia's PMM was derived to propagate coordinates between ITRF2014@epoch (YYYY-MM-DD) and GDA2020 based on the time series of GPS data at the 109 RVS Determination sites. Analysis undertaken by GA has shown that the Australian Plate is stable at the 0.2 to 0.3 mm/yr level at the RVS Determination sites. This analysis also showed that Tier 3 GNSS sites and other sites with a short time series show less consistent stability, some over 1 mm/yr (Dawson pers. comm.). In order to achieve a more statistically reliable PMM solution, these sites were removed from the Australian PMM computation.

In accordance with the RVS Determination (see Section 5), the Australian PMM can be used to propagate coordinates over time between GDA2020 and ATRF2014 (Figure 2). This 3-parameter model can be expressed as a 14-parameter Helmert transformation, whereby the only non-zero values being the rates of change relating to each axis (Table 2).

Table 2: Transformation parameters for ATRF2014 / ITRF2014 to GDA2020 along with their one sigma uncertainties (1σ). Units are in metres (m) and m/yr for the translations and their rates, respectively, parts-per-million (ppm) and ppm/yr for scale and its rate, respectively, and arcseconds and arcseconds/yr for rotations and their rates, respectively. The reference epoch t_0 is 2020.0.

	$t_x, \dot{t}_x$	$t_y, \dot{t}_y$	$t_z, \dot{t}_z$	$s_c, \dot{s}_c$	$r_x, \dot{r}_x$	$r_y, \dot{r}_y$	$r_z, \dot{r}_z$
parameters	0.00	0.00	0.00	0.00	0.00	0.00	0.00
uncertainty	0.00	0.00	0.00	0.00	0.00	0.00	0.00
rates	0.00	0.00	0.00	0.00	0.00150379	0.00118346	0.00120716
uncertainty	0.00	0.00	0.00	0.00	0.00000417	0.00000401	0.00000370

NOTE: This refers to coordinates that are in the same reference frame (i.e. GDA2020, ITRF2014, ATRF2014), not coordinates from different reference frames. Transformation coordinates between different frames will require a transformation to GDA2020 (or ITRF2014) using the appropriate parameters (see GDA2020 Technical Manual).

The parameters from Table 2 can be used in Eqn.1, a 14 parameter similarity transformation to transform coordinates from one geodetic reference frame (A) to another (B) where t_x t_y t_z are the translations r_x r_y r_z are the rotations s_c is the scale. The other 7 parameters describe the rates of change of the translation $\dot{t}_x$ $\dot{t}_y$ $\dot{t}_z$, rotation $\dot{r}_x$ $\dot{r}_y$ $\dot{r}_z$ and scale $\dot{s}_c$. This allows for transformation between datums with data sets at any given epoch t where t_0 is the reference epoch.

$$\begin{pmatrix} X'_B \\ Y'_B \\ Z'_B \end{pmatrix} = \begin{pmatrix} t_x + \dot{t}_x(t - t_0) \\ t_y + \dot{t}_y(t - t_0) \\ t_z + \dot{t}_z(t - t_0) \end{pmatrix} + \left(1 + s_c + \dot{s}_c(t - t_0)\right)$$

$$\begin{pmatrix} 1 & r_z + \dot{r}_z(t - t_0) & -r_y - \dot{r}_y(t - t_0) \\ -r_z - \dot{r}_z(t - t_0) & 1 & r_x + \dot{r}_x(t - t_0) \\ r_y + \dot{r}_y(t - t_0) & -r_x - \dot{r}_x(t - t_0) & 1 \end{pmatrix} \begin{pmatrix} X_A \\ Y_A \\ Z_A \end{pmatrix} \qquad (1)$$

4.4 Deformation model

Surface deformation caused by natural events (e.g. earthquakes) or anthropogenic activities (e.g. groundwater extraction) can be significant over small areas and is often non-linear. This complex deformation cannot be adequately represented by static datums or monitored using the tools traditionally used in the geodetic surveying community. For example, even though GNSS data has high temporal resolution, it has low spatial resolution. In an attempt to overcome these problems, Geoscience Australia is planning to include Interferometric Synthetic Aperture Radar (InSAR) data in the development of a 4D national scale deformation model to describe motion of the crust over time (Figure 2).

InSAR is a geodetic remote sensing technique that can identify relative movements of the Earth's surface over large areas (100s of km) with millimetre precision, spatial resolution at the metre level and multiple observations per month. Complementary GNSS and InSAR observations can be combined in a least squares adjustment to create displacement estimates in a 3D velocity field with high spatial resolution and accuracy (Fuhrmann, 2016). When combined with the Australian PMM to describe the secular motion of the continent, the deformation model will enable the alignment of GDA2020 and ATRF2014 coordinates for high-accuracy positioning applications. While the Australian PMM would cover the entire continent, a deformation model would only need to cover the area impacted by the deformation.

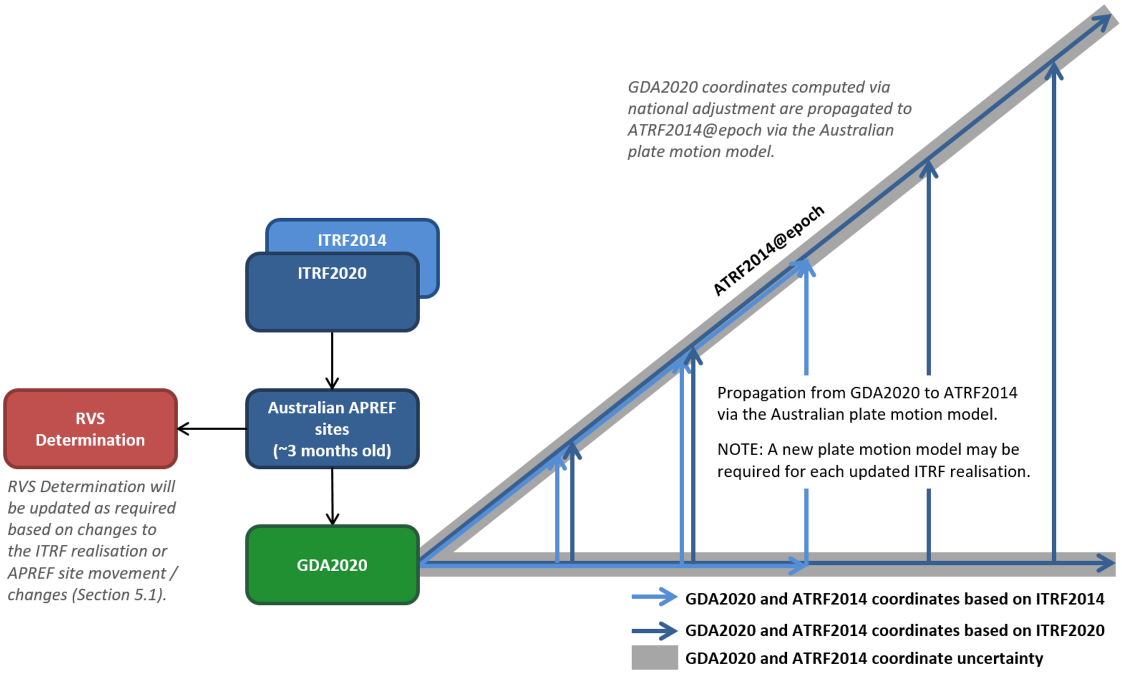

Figure 2: Summary of the workflow to compute GDA2020 and ATRF2014 coordinates.

5. Legal Traceability of ATRF

Historically, RVS Determinations have only included coordinates (X, Y, Z), however, the 2017 Determination also included coordinate uncertainty (Type A and Type B), coordinate velocity and coordinate velocity uncertainty. Eqn. 2 enables the coordinates from the RVS Determination sites (shown in GDA2020) to be propagated to ATRF2014 and expressed at any epoch t (years) in a legally traceable manner through the application of the following linear model using the coordinates (X, Y, Z) and velocities (V_x, V_y, V_z):

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_t = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{2020} + (t - 2020) \begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix} \qquad (2)$$

Eqn. 2 is valid for 15 years either side of 2020: $|\mathrm{t} - 2020| \leq 15$. This limitation is required because the velocities become increasingly unreliable as the time gap increases.

The GDA2020 coordinates in the 2017 RVS Determination were taken from the cumulative APREF solution of October 2016 and propagated to 2020 using the Australian PMM. The velocities of the sites in the RVS Determination were computed using the Australian PMM. The Australian PMM or the linear model (Eqn.2) can therefore be used to propagate coordinates in time. Both techniques are legally traceable and produce identical results, however, Eqn. 2 only applies where you have velocities and therefore only at the RVS sites, while the Australian PMM can be used anywhere.

5.1 Quality checking of RVS Determination

Regular checks (at least yearly) will be undertaken to ensure the RVS Determination coordinates, velocities and uncertainties remain valid (coordinates and velocities are within the bounds of uncertainty). If site coordinates and velocities are found to have deviated from the RVS Determination, GA will work with the National Measurement Institute (NMI) to update the RVS Determination as required.

5.1.1 Testing procedure

- Cumulative APREF solutions provide updated GDA2020 (and ATRF2014) site coordinates, velocities and uncertainties.
- Compare updated site coordinates, velocities and uncertainties to the RVS Determination values.
- If updated site coordinates, velocities and uncertainties exceed the RVS Determination values (beyond the 95% CI), advise NMI, and update the RVS Determination.

5.2 Quality checking of Regulation 13 Certificates

NOTE: Coordinates for Regulation 13 Certificates are currently derived using the GA weekly APREF solution (i.e. seven days of data; not the cumulative solution). This process is under review and may be updated in the near future to use the cumulative APREF solution and align with the process as used to update GDA2020 and ATRF.

Weekly checks are undertaken to ensure the coordinates provided in Regulation 13 Certificates remain valid. If Regulation 13 coordinates are found to have deviated from the cumulative APREF solution (over more than four weeks), GA will work with the site owner to update the Regulation 13 Certificate. This may be to update the coordinates, the coordinate uncertainties, or both.

References

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Appendix A: Q & A

Why can't we just use ITRF2014 instead of ATRF2014?

ITRF2014 is defined using only 15 sites from Australia. ATRF2014 uses the 109 Recognized-value Standard of Measurement sites from the 2017 Determination. ATRF2014 therefore provides a link to the RVS Determination and is legally traceable

How often will new solutions of GDA2020 and ATRF2014 be available?

The computation of national adjustments occurs every month by Geoscience Australia. The release of updated GDA2020 and ATRF2014 coordinates by states and territories are yet to be determined. NOTE: The computation of a national adjustment may cause only minor changes to the coordinates and will not always warrant a change to coordinates provided to the user.

Which solution is used as constraint in the national adjustment?

A GDA2020 aligned cumulative APREF solution from ~3 months prior should be used to constrain the national adjustment. This allows enough time for any discontinuities in the APREF solution to be identified and resolved. The cumulative APREF solution will be propagated to the epoch of 2020.0 using the Australian PMM.

What happens if one or more of the RVS Determination sites exceeds its positional uncertainty?

Regular checks will be undertaken by GA to ensure the GDA2020 coordinates and velocities at the RVS sites are within the uncertainty of the RVS Determination. If changes exceed the uncertainties, GA will work with the National Measurement Institute (NMI) to update the RVS Determination as required. See Section 5.1.1 for the testing procedure.

After the national adjustment is run, how are ATRF2014 coordinates propagated to a given epoch?

The national adjustment will be run in GDA2020. Output coordinates will be propagated to ATRF2014 at any epoch using the Australian PMM (and potentially a deformation model if required).

Is the Australian PMM a 2D or 3D model?

The Australian PMM is only a 2D model. It does not change the height component of the data. Changes to the height component are being considered in the form of a deformation model (see Section 4.4).

What solution will be used in real-time services?

Geoscience Australia proposes to make two streams of data available: one in GDA2020 and one in ATRF2014.

Will GDA2020 coordinates be updated with time?

Yes. With each new national adjustment, new GDA2020 coordinates will be computed and stored in the GA database with access only by jurisdictions. The choice of whether / when to update GDA2020 coordinates in jurisdictional databases will be the decision of jurisdictional representatives. Jurisdictions are encouraged to closely coordinate any such updates to minimise any potential distortion issues along state/territory borders.

Why are we maintaining (e.g. storing data, reference epoch for adjustments) the geodetic data in GDA2020?

It is easier to work with, and less risk of error / mistakes, when working with data in a static datum.

How is the Australian PMM different to the ITRF2014 PMM?

ATRF2014 uses the Australian PMM based on the site velocities of 109 sites, whereas the ITRF2014 PMM is only based on the velocities of 15 sites. ICSM recommend the use of the Australian PMM.

What happens when a new realisation of ITRF is released?

Differences between ITRF realisations are expected to be minor. When the ITRF is updated, this will result in a new ATRF realisation, and the RVS Determination will be updated.

How will ATRF2014 coordinates be provided to users?

- **Real-time GNSS data streams delivered by GA:** Most recent ATRF2014 coordinates by real-time GNSS caster.
- **Static files by GA:** GDA2020 and ATRF2014 coordinates and refined velocities made available in GA database following each national adjustment.
- **Transfer to jurisdictional databases:** Establish GeodesyML web service workflows

Legal traceability of GDA2020 and ATRF2014?

The RVS Determination, through the site-specific velocities Eqn. 2, or the Australian PMM applied through Eqn. 1 provide legally traceable methods of propagating coordinates between GDA2020 and ATRF2014.

What is the ATRF2014 naming convention?

ATRF2014 coordinates will be able to be differentiated by metadata that will include three discrete pieces of information

1. ITRF reference frame year (e.g. 2014)
2. Cumulative APREF solution week (e.g. GPS week xxxx)
3. Epoch of coordinates

along with the coordinate propagation technique/s applied (e.g. Australian PMM, deformation model, site velocity).

What is the reference frame of corrections from for the NPI SBAS?

ATRF2014. Satellite Based Augmentation System (SBAS) corrections which are to be supplied via internet / satellite will be generated from CORS throughout Australia, not just from IGS / ITRF sites and will therefore be in ATRF2014.

Why is only a subset of APREF solutions provided with an ATRF2014 solution?

This restriction is to ensure authoritative Australian-derived coordinates are supplied for Australian sites.

What does 'time-dependent' actually mean?

Time-dependent reference frame means an Earth centred, Earth fixed reference frame in which coordinates vary over time, reflecting temporal changes in the earth's crust. That is, the physical location of a feature expressed by coordinates relative to a time-dependent reference frame will be dependent on time.

Does each new ATRF2014 solution need a new set of transformation parameters to transform between them?

No. Transformation parameters are required when there is a change in the reference frame. There is no change in the reference frame. The ATRF realisation only changes when there is a change to the ellipsoid or realisation of ITRF. Each new solution from the national adjustment is just a new solution in the ATRF2014 time series.