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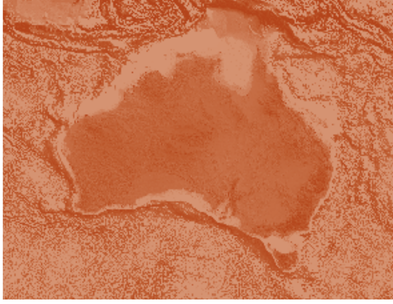

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Report on the Asia Pacific Reference Frame (APREF) Project

G. Hu, M. Jia and J. Dawson

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Geoscience Australia acknowledges the traditional custodians of the country where this work was undertaken. We also acknowledge the support provided by individuals and communities to access the country, especially in remote and rural Australia.

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Contents

Executive Summary

This report overviews the status and development of the Asia Pacific Reference Frame (APREF) project, which is a major activity of the Geodetic Reference Framework for Sustainable Development Working Group of the United Nations Global Geospatial Information Management for Asia and the Pacific (UN-GGIM-AP), and the Reference Frame Sub-Commission 1.3e (SC1.3e) of the International Association of Geodesy (IAG). In this work, the APREF Continuously Operating Reference Station (CORS) network is reviewed. This is followed by an overview of the analysis methodology and strategy adopted for processing of data from the network. Coordinate time series, velocities as well as other parameters are generated for 450 CORS sites across the Asia-Pacific region and 200 International GNSS Service (IGS) core stations located around the world. An accuracy assessment of the output and products, including the estimated position and velocity field is presented. The position solutions have an internal accuracy of 1-4 mm and 4-8 mm in horizontal and vertical components, respectively, determined from position repeatability of the weekly solutions. When compared with the published IGS14 velocities for the 173 common sites, the velocity solutions have an external accuracy of 0.02 ± 0.29 mm/yr, 0.01 ± 0.32 mm/yr, and 0.08 ± 0.54 mm/yr for north, east and vertical components, respectively. Products of the APREF Project include the daily and weekly solutions, combined weekly solutions, position time series of long-term solutions, coordinates and velocity field of the CORS network in ITRF2014.

Geoscience Australia’s contribution to the APREF Project includes maintaining the Central Bureau, data flow management, routine analysis of the whole APREF CORS network, combination of solutions from the Local Analysis Centres (LACs) and the generation of the position time series of the cumulative solutions.

Introduction

Over the past decades, with the improvement and advances of Global Navigation Satellite Systems (GNSS), receiver and antenna design, and data processing techniques, the precision and accuracy of GNSS has steadily and significantly improved. The demonstrated repeatability of horizontal position estimates obtained from GNSS is currently at the millimetre to sub-millimetre level on regional and local scales and at the millimetre level on global scales (e.g., Steigenberger et al., 2006).

Geodetic coordinates of stations on the surface of the Earth change with time due to plate motion, and thus become dependent on the epoch in which the positions are obtained. If the direction and magnitude of the change are determined, it is possible to estimate the velocity of the sites. GPS has contributed to such geodynamics applications since the 1980's because of its low equipment costs and high precision (Parkinson and Spilker, 1996). With the advent of GNSS CORS, it has become possible to determine site velocities using a multi-year position time series (Perez et al., 2003).

In the Asian and Pacific region, there has been a rapid increase in the number of GNSS CORS networks and stations over the past decade. This provides an opportunity to improve the definition, realisation and maintenance of the regional geodetic reference frame, i.e. the so-called Asia Pacific Reference Frame (APREF), in support of both scientific and regional geospatial activities by densifying the International Terrestrial Reference Frame (ITRF) (Huisman et al., 2011; Hu et al., 2011, Nardo et al., 2014). The APREF project is a collaboration of the Geodetic Reference Framework for Sustainable Development Working Group of the United Nations Global Geospatial Information Management for Asia and the Pacific (UN-GGIM-AP), and the Reference Frame Sub-Commission 1.3e (SC1.3e) of the International Association of Geodesy (IAG).

Well-sampled velocity fields of the Asia and Pacific region relies on the integration of the regional and national permanent GNSS networks. Deriving a coherent and accurate velocity field in a global reference frame (currently in ITRF2014) is the main challenge. To assist reference frame definition and to be able to link it to the ITRF, it is necessary to further extend the Asia Pacific network with globally distributed IGS sites. Previous work has demonstrated that positions obtained through global solutions are less sensitive to the reference frame definition compared to regional solutions (e.g., Wöppelmann et al., 2008; Legrand et al. 2010).

The rigorous realization of geodetic frames based on CORS networks requires constant monitoring of the coordinates and velocities defining the particular frame of the datum. APREF CORS network data analysis is a continuous effort of Local Analysis Centres (LACs) in Asia Pacific countries to realise an Asia Pacific Reference Frame in the most accurate manner. High accuracy estimation of station velocities can be obtained by the analysis of the position time series with a long term observing period. Several velocity field solutions for the Asia Pacific were published with data from different station networks, time spans and processing strategies (Tanaka et al, 2005; Huisman et al, 2011; Hu et al, 2011, Kreemer et al., 2014).

A by-product of APREF is an improved understanding of the complex tectonic setting of the region, which has numerous complicated active plate boundary zones. The resultant earthquake and volcanic processes observed in places such as Japan, New Zealand, Indonesia and the South Pacific region are of particular interest and concern given the societal impacts associated with them. In addition to this and from a scientific perspective, the Asia Pacific region is exceedingly important for understanding plate boundary deformation (Kreemer et al., 2014).

Beyond tectonics, the coordinate time series exhibits numerous signals at multiple spatial and temporal scales. Multipath of GNSS data is a very good example of path or environmental dependant signals, which can also be directly derived from the signal-to-noise ratio (SNR) or from the pseud-observations. The multipath effects, or near-field effect, has geometric and reflection characteristics of the environmental or reflecting surface. These reflection signals have been used for the analysis of soil moisture, hydro or water cycle as well as snow depth, for example, in the Antarctic region where the data are not easily accessible (Larson et al., 2008; Herring et al., 2016; Teunissen and Montenbruck, 2017). Furthermore, the coordinate time series may present offsets due to equipment (antenna and/or receiver) changes or co-seismic displacement, or non-linear deformations due to annual or semi-annual seasonal change or post-seismic deformation signals, as well as non-linear signals.

The aim of this report is to overview the analysis strategy and combination method for generating position time series as well as the estimation of velocities along with other useful parameters. Our goal is to provide millimetre to centimetre level accuracy products to the communities as well as our stakeholders.

In this document, we present the results of Asia Pacific velocity field based on GNSS CORS data with a homogeneous processing of the APREF network of 760 stations including 252 IGS core stations, spanning an 18 years period (2001.0 to 2019.3). This velocity field is generated using CATREF software (Altamimi, et al., 2016). The next section overviews the status and development of the APREF network. The data processing of routine analysis and velocity estimation strategies as well as combination products are described followed by an assessment of the estimated velocity field in terms of internal and external accuracy. A discussion on the impact of meta-data changes as well as pertinent changes of the network such as antenna and receiver updates, the offset or jump in the position time series are also detailed in terms of discontinuities detections including offsets due to post-seismic deformation. Finally, the concluding remarks are given and future work is discussed.

The status and development of APREF

As of mid-2019, APREF archives the CORS data from 28 countries and 16 national agencies that are participating in the project. Currently, there are 530 CORS stations available from the region as well as 252 IGS core stations for linking to the ITRF2014 and for improving the network geometry, see Figure 1. The number of stations in APREF has increased over recent years, see Figure 2.

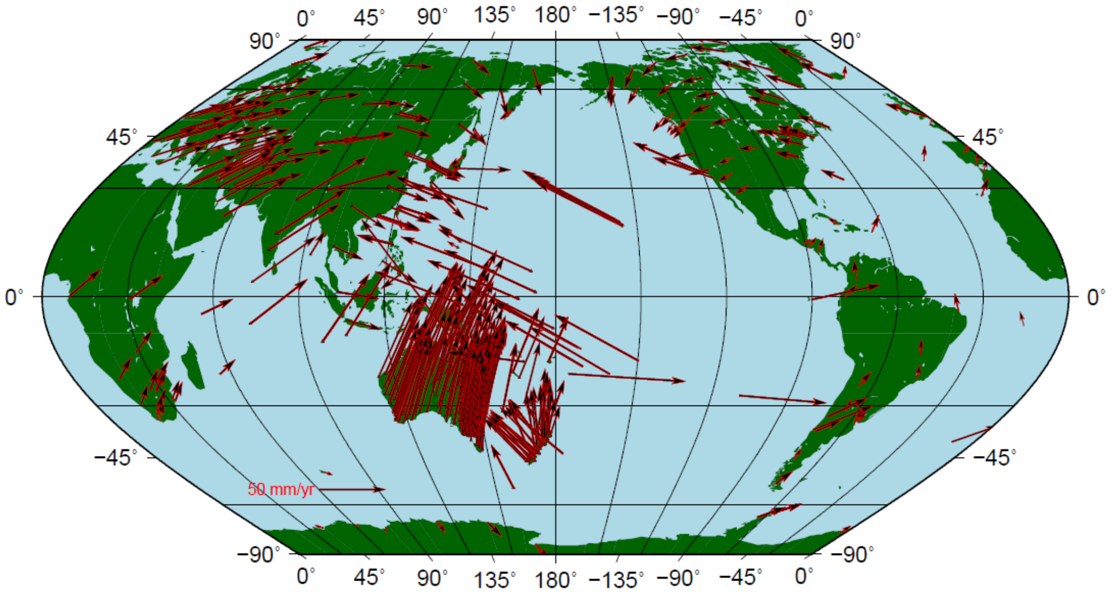


Figure 1. *The distribution of APREF CORS network along with the IGS core stations. The arrows represent the GPS-derived velocity field.*

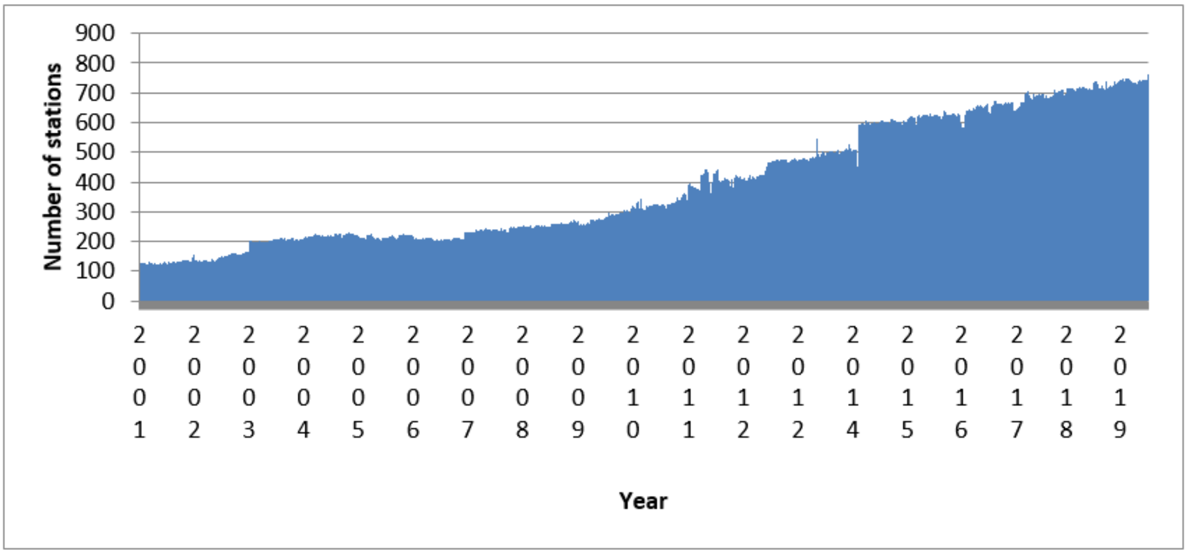


Figure 2. *Number of the APREF CORS sites since 2001, with a total of 760 stations including 252 IGS core stations.*

The Australian national networks

Geoscience Australia operates a number of high quality GNSS networks in the Australian region, see Figure 3.

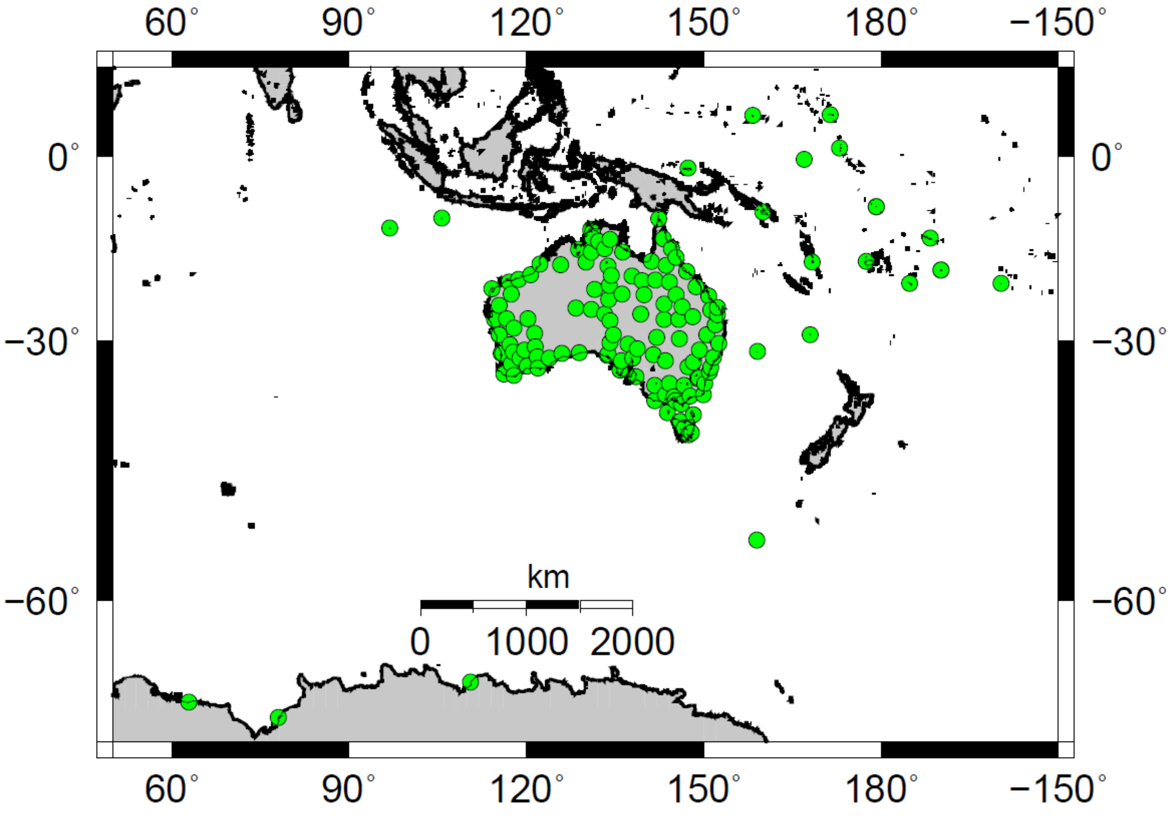


Figure 3. *CORS sites maintained and operated by Geoscience Australia, each circle represents a GNSS CORS site.*

Geoscience Australia closely adheres to the IGS site installation guidelines, where stations are installed on stable bedrock with a good sky view to meet specific geophysical research requirements based on the location as well as instrument configuration standards, including receiver and antenna types, monumentation and local communication methods. Most stations are installed on geodetic monuments with concrete pillars (Langbein et al., 1995), and equipped with Dorne-Margolin element choke-ring antennas. In recent years, most of the stations have been upgraded with multi-GNSS receivers and antennas. The networks are operated using standardized equipment configurations and quality control processes.

CORS operated by provincial Australian governments

In Australia, most CORS operated by provincial (i.e. state and territory) governments are installed on roof tops or attached to buildings with a stainless steel mast. These stations support high-accuracy GNSS service providers across areas with high density populations in Australia. Figure 4 presents a typical CORS site installation attached to the building. CORS sites from VICNET, Victoria; CORSnet, New South Wales; and PerthNet, Western Australia are presented in Figures 5, 6 and 7 respectively.

Figure 4. *A typical installation of a CORS site attached to a building via a stainless steel mast.*

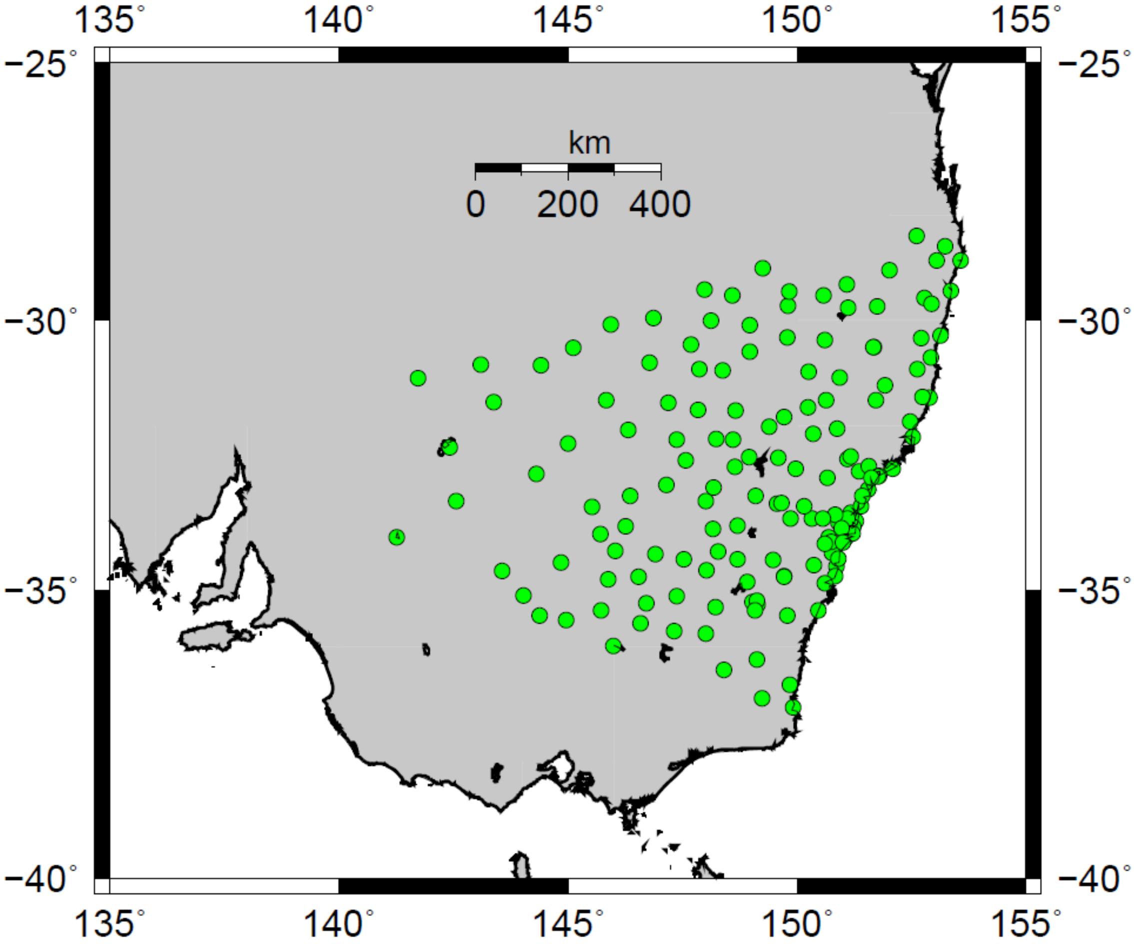


*__Figure 5.__ Stations of CORSnet, New South Wales, Australia*__.__

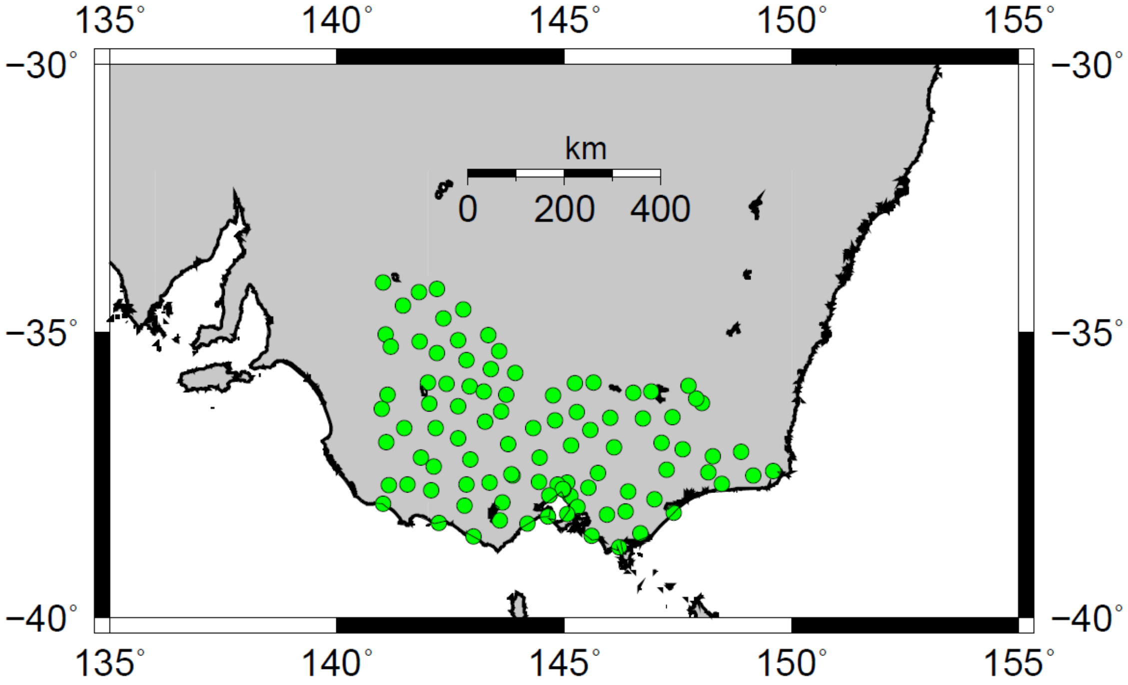


__Figure 6.__ CORS sites of VICNET, Victoria, Australia.

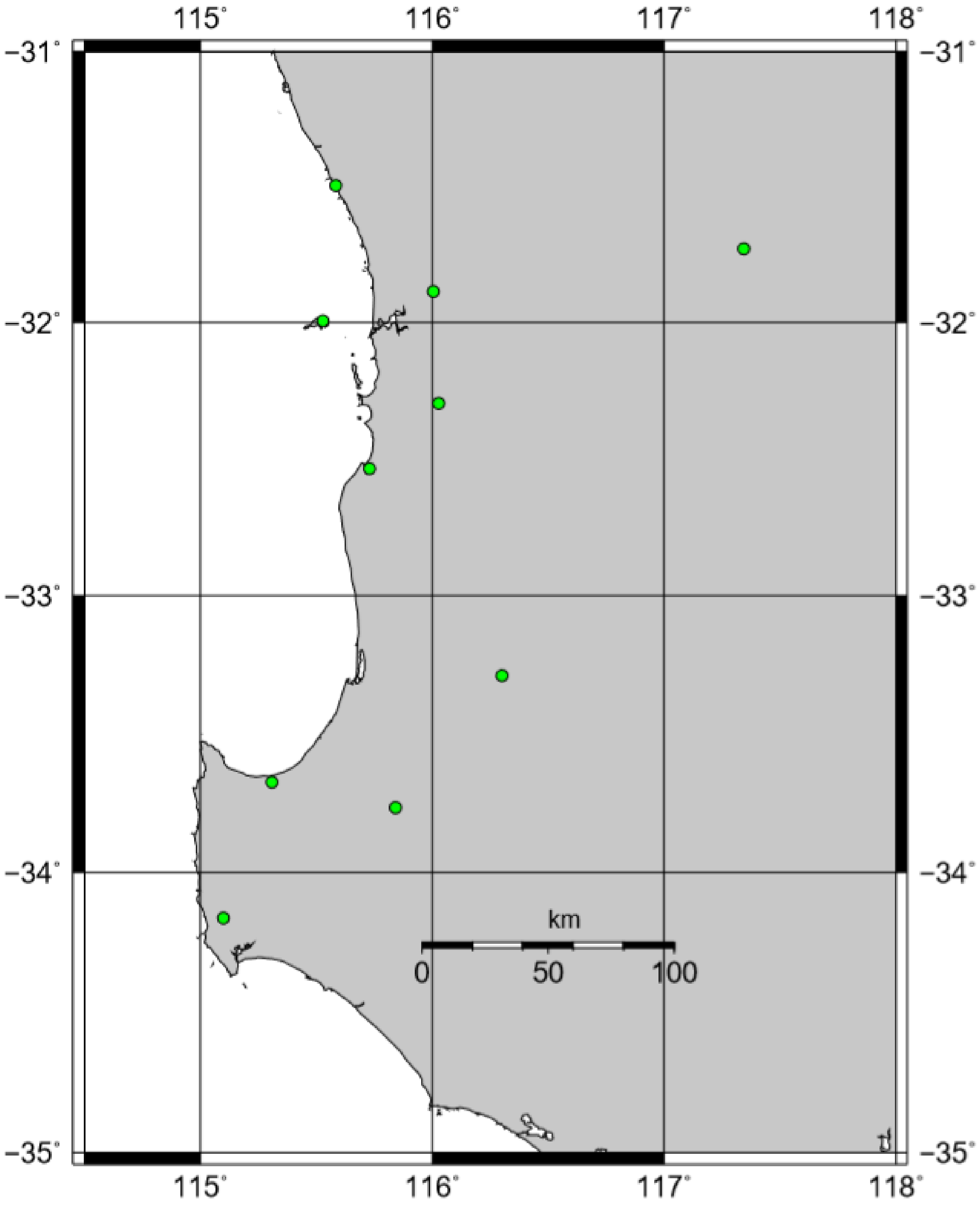


Figure 7. *CORS sites of PerthNet, Western Australia.*

South Pacific Regional GNSS network (SPRGN)

The South Pacific Regional GNSS network (SPRGN) consists of thirteen CORS sites located in close proximity to sea level monitoring stations in the South Pacific region as plotted in Figure 8. The SPRGN stations are collocated with tide gauges to facilitate monitoring sea level changing in a global reference frame for the region. These stations were installed in terms of IGS site guidelines with concrete pillars, and have heterogeneous instrumentation, monumentation and follow best practice metadata management configuration and data flow.

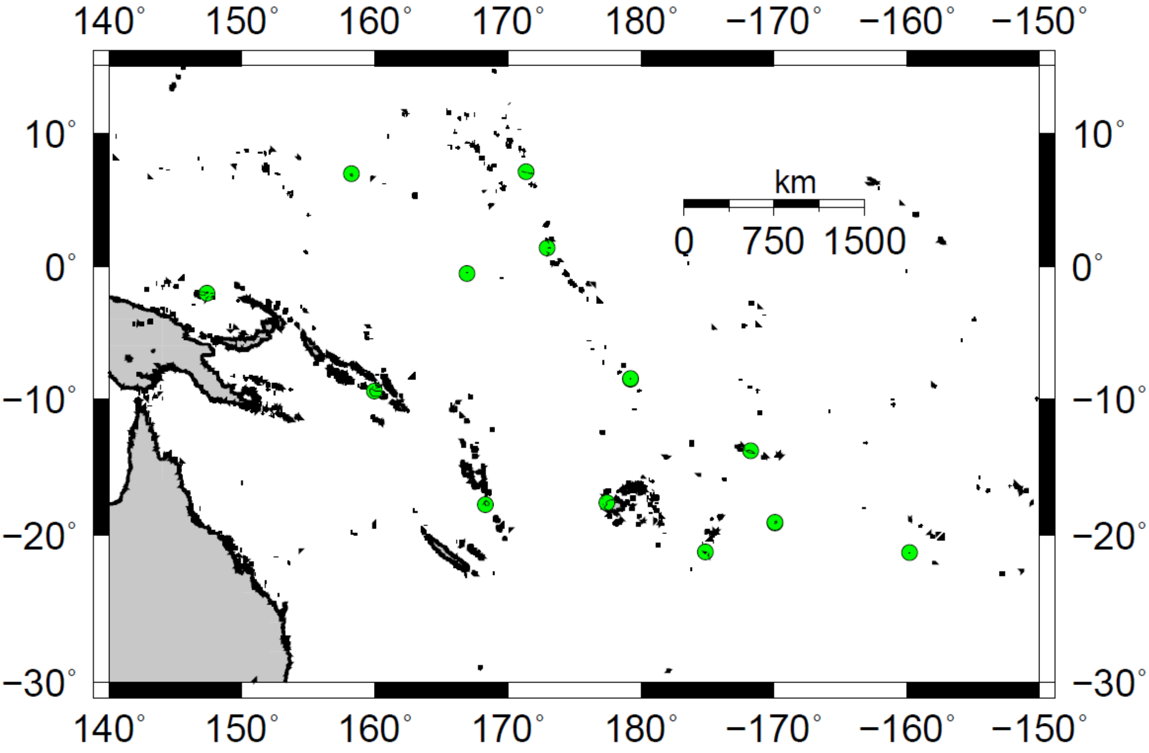


Figure 8. *CORS sites of SPRGN in the South Pacific region.*

Other GNSS CORS networks in the Asia-Pacific region

Other high quality geodetic GNSS CORS networks contributing data to the APREF project include GeoNet in New Zealand - Figure 9, the Hong Kong Satellite Positioning Reference Station Network (SatRef) - Figure 10, the Macau permanent geodetic GNSS network - Figure 10 (Chan, and Li, 2007; Iu, 2007) and PageNET in Philippines (Cayapan, 2016).

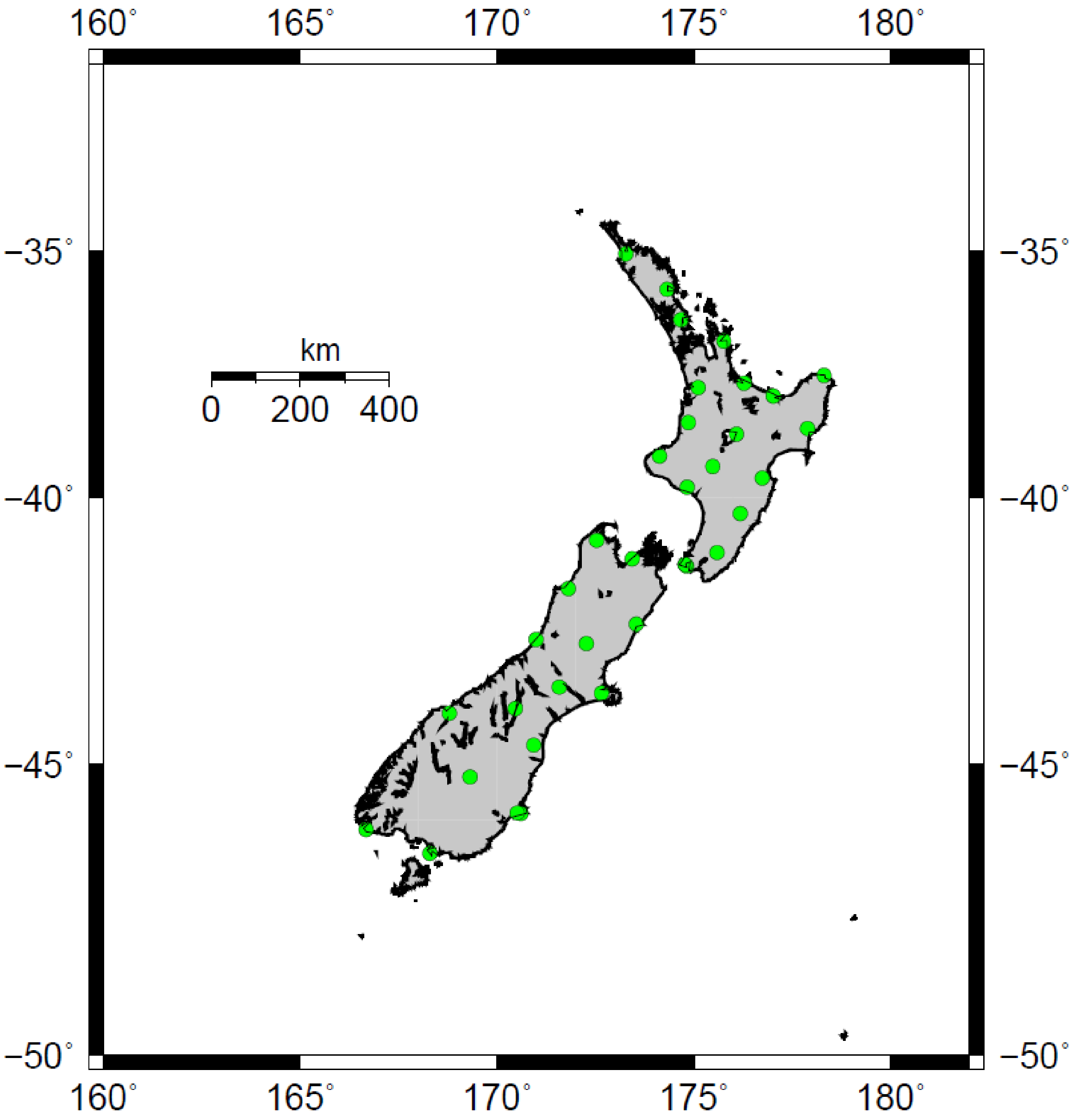


Figure 9. *CORS sites of GeoNet, New Zealand.*

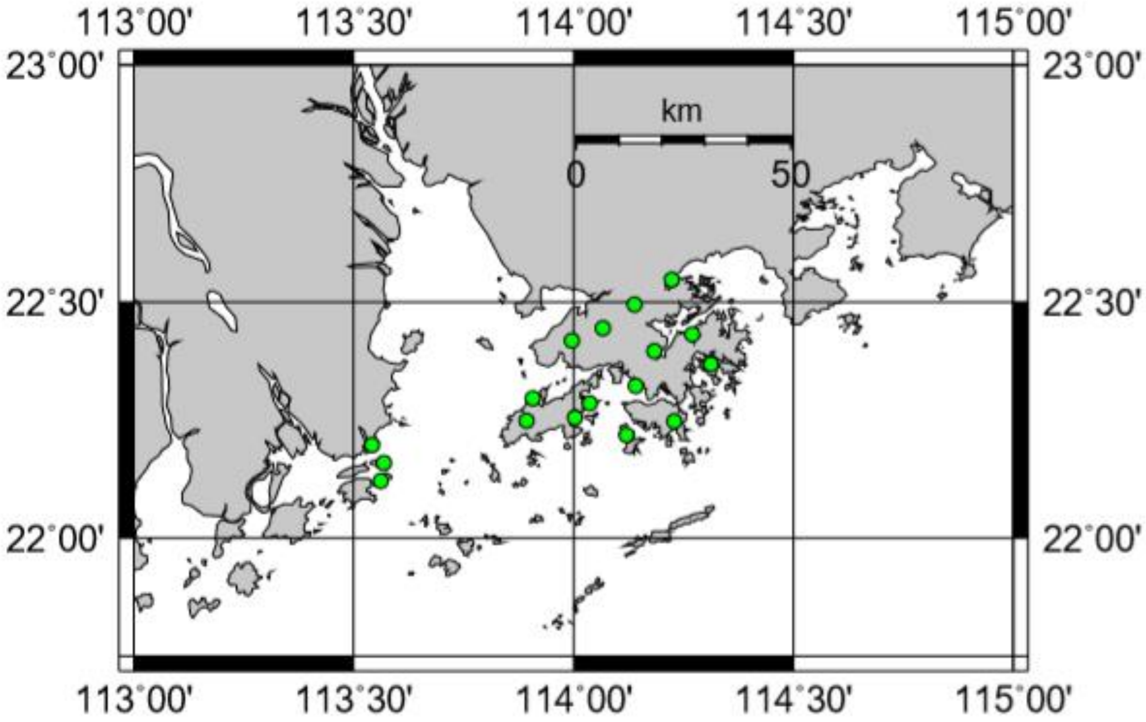


Figure 10. *CORS sites in Hong Kong and Macau, China.*

All the RINEX (Receiver INdependent Exchange format) data and products output from the APREF project are available from the ftp link (ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/) as well as the APREF website (http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame). Table 1 summarizes the number of stations for the APREF CORS network. The APREF data and product access follows the IGS policy approach and encourages applications in earthquake hazard assessment, water resource management, civil engineering, disaster preparedness and environmental monitoring (Herring et al., 2016). Furthermore, APREF has encouraged the unification of site installation standards, operation guidelines, data management, site maintenance as well as data analysis strategies (Hu et al., 2011). APREF also serves to validate the quality of individual CORS as a precursor to acceptance as a global IGS site.

Table 1. *APREF GNSS stations (as of 17 January 2019).*

Country/Locality	Agency	Number of Stations
Afghanistan	National Geodetic Survey (USA)	2
Alaska, USA	National Geodetic Survey (USA)	7
American Samoa	National Geodetic Survey (USA)	1
Australia	Geoscience Australia	139
Australia	Curtin University	1
Australia	Department of Natural Resources, Mines and Energy, Queensland	8
Australia	Department of Environment, Land, Water and Planning, Victoria	107

Country/Locality	Agency	Number of Stations
Australia	Department of Infrastructure, Planning and Logistics, Northern Territory	5
Australia	Department of Primary Industries, Parks, Water & Environment, Tasmania	2
Australia	Department of Finance, Services & Innovation, New South Wales	170
Australia	Department of Transport and Main Road, Queensland	17
Australia	IPS Radio and Space Services	3
Australia	RTK NetWest	12
Brunei	Survey Department, Negara Brunei Darussalam	1
Cook Islands	Geoscience Australia and Lands Department of Cook Islands	1
Cook Islands	Geospatial Information Authority of Japan	1
Federated States of Micronesia	Geoscience Australia and Weather Service of the Federated States of Micronesia	1
Fiji	Geoscience Australia and Lands Department of Fiji	1
French Polynesia	Geospatial Information Authority of Japan	1
Guam, USA	National Geodetic Survey (USA)	1
Hawaii, USA	National Geodetic Survey	19
Hong Kong, China	Survey and Mapping Office	14
Indonesia	Bakosurtanal	4
Iran	National Cartographic Center, Iran	6
Iraq	National Geodetic Survey (USA)	6
Japan	Geospatial Information Authority of Japan	10
Kazakhstan	Kazakhstan Gharysh Sapary	2
Kiribati	Geoscience Australia and Weather Service of Kiribati	1
Kiribati	Geospatial Information Authority of Japan	2
Macau, China	Macao Cartography and Cadastre Bureau	3
Malaysia	Department of Survey and Mapping Malaysia, JUPEM	7
Marshall Islands	Geoscience Australia and Weather Service of Marshall Islands	1
Mongolia	Administration of Land Affairs, Construction, Geodesy and Cartography (ALACGaC)	8
Nauru	Geoscience Australia and Lands Department of Nauru	1
New Zealand	Land Information New Zealand	38
Northern Mariana Islands	National Geodetic Survey (USA)	1
Papua New Guinea	National Mapping Bureau, Papua New Guinea, and Geoscience Australia	2
Philippines	Department of Environment and Natural Resources, National Mapping and Resource Information Authority	4
Samoa	Geoscience Australia and Lands Department of Samoa	1
Solomon Islands	Geoscience Australia and Weather Service of Solomon Islands	1
Tonga	Geoscience Australia and Lands Department of Tonga	1
Tuvalu	Geoscience Australia and Weather Service of Tuvalu	1

Country/Locality	Agency	Number of Stations
Vanuatu	Geoscience Australia and Lands Department of Vanuatu	1

Data flow

APREF data are archived with a sampling interval of 30 seconds and stored in RINEX format, currently in RINEX v2.11. Metadata are managed by a dedicated database, the so-called site-manager (Owen et al., 2018). The basic process of data flow includes file downloading, RINEX header information validation, metadata management, quality checks, archiving and distribution. The raw GNSS data are converted to RINEX version 2.11 and 3.x format using IGS data exchange guidelines and metadata are managed by the site-manager database with quality checking using the teqc software and gfzrnx Tools (Estey and Meertens, 1999; Nischan T., 2016). For stations not operated by GA, the RINEX data are provided directly by network or site operators via GA's ftp uploading system and/or downloaded directly from data centres including the NASA Crustal Dynamics Data Information System (CDDIS), the BKG and the Scripps Orbit and Permanent Array Centre (SOPAC). An illustration of the data flow schema are plotted in Figure 11.

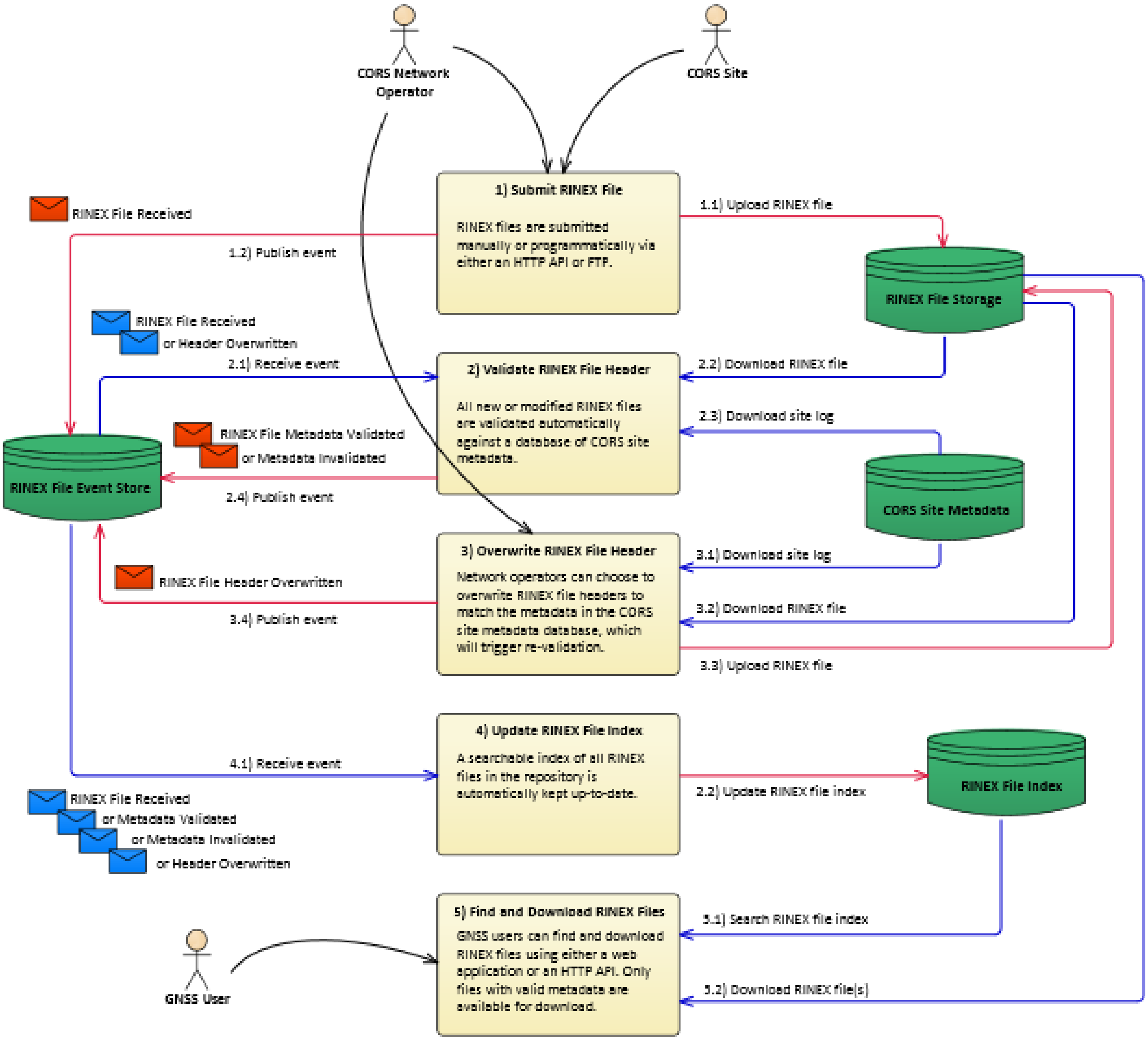


Figure 11. *APREF data flow and repository diagram (Credit: Owen et al., 2018).*

Data processing scheme

Daily and weekly position solutions

Four Local Analysis Centres (LACs) have contributed to APREF. These have included the University of Curtin, Australia (CUT), the Victorian General Surveyor office, Australia (VIC), the Institute of Geophysics and Geodesy, Chinese Academy of Science, China (IGG), and Geoscience Australia (GA). The University of Curtin concluded their contribution in September of 2018, leaving three ongoing active LACs. All LACs use the Bernese software version 5.2 (Dach et al., 2012), albeit with slightly different processing strategies, including reference frame and IGS core site selection. The independent solutions support quality control of the APREF products. Independent analysis enables the identification of meta-data errors.

All LACs provide loosely-constrained solutions following the IGS standards in the Software Independent Exchange Format (SINEX) format that contain coordinates and the associated full variance-covariance matrix. The comparison of the LACs solutions with the published IGS weekly solutions for common IGS stations is summarised in Table 2, using GPS week 1939, i.e., from 05 March to 11 March 201, as a typical example.

Table 2. *The comparison of the LACs solutions with the published IGS weekly solutions for common IGS stations for the GPS week 1939.*

Solution	Number of common IGS stations	Weighted RMS (mm)			Standard deviation (mm)		
		North	East	Up	North	East	Up
AUS	162	0.6	0.9	1.7	0.5	0.7	1.1
CUT	23	1.1	0.8	3.4	0.9	0.9	3.6
VIC	30	1.2	1.1	3.5	1.3	1.3	4.4
IGG	135	1.0	1.2	1.9	1.2	1.7	2.9

The processing scheme adopted by the LACs is based on the IERS conventions (Petit and Luzum, 2010). Carrier-phase smoothed pseudo-range measurements are used to estimate receiver clock offsets, and also used to automatically edit carrier-phase observables to detect cycle slips and to assist solving integer ambiguities. The Bernese software uses a weighted least squares algorithm to estimate station positions whilst fixing satellite orbit position using IGS final orbit and clock products. Code bias corrections are applied for the whole period using monthly tables from the University of Bern. Ocean tide loading is corrected using FES2004 model (Lyard et al., 2006). The generated daily position and covariance solutions as well as estimated tropospheric parameters for the stations are then combined into weekly solutions with the output of station positions and covariances in SINEX format.

The percentage of integer ambiguities are greater than 90% for most baselines, however when fewer integer ambiguities are fixed (50-60%) it is likely due to insufficient data quality. The FES2004 ocean tide model is used to account for ocean tide loading effects which is calculated from the ocean loading web service maintained by Chalmers University of Technology (http://holt.oso.chalmers.se/loading/). This model derives corrections for centre of mass motion including ocean and solid Earth. Tropospheric zenith wet delay is estimated using the Vienna Mapping Functions grids (VMF1) (Boehm et al., 2006). The second-order ionospheric correction effects are accounted for by modelling the Earth's ionosphere as a 600 km thin shell.

The combination of LACs was undertaken using the CATREF software in three steps (Altamimi et al., 2002): 1) each LAC solution was de-constrained using a-priori information provided in SINEX files. LACs provide constrained coordinate solutions in ITRF2014, before combining the LACs solutions, these constraints were removed; 2) the de-constrained solutions were transformed to ITRF2014 through a minimum constraint solution using a set of IGS14 core stations (Altamimi et al., 2002). For the combination, all LACs solutions were aligned to one common reference frame to avoid systematic differences between the solutions; and 3) all LAC solutions were combined into one solution. For outlier detection, the coordinate difference between the combined solution and each LAC solution is calculated, and then the RMS value corresponding to the series of coordinate differences of all LACs is computed. A station is rejected from the LAC solution if the coordinate difference exceeds a value of three sigma for any one component (Panafidina et al., 2006).

APREF Central Bureau's (CB) daily and weekly solutions

The APREF Central Bureau (CB, currently Geoscience Australia) have processed the data set of the APREF network over an 18 years span from 2001.0 to 2019.3 using the Bernese Software version 5.2 (Dach et al., 2012). All data were processed following the same processing strategy. There are a total of approximately 1028 GB of CORS data with more than 6500 days of RINEX files processed. Analysis effort was focused on the manual checking of metadata as well as the validation of results. A state-of-the-art GPS processing strategy was applied, and was based on the IERS Conventions 2010 and the IGS guidelines (Petit and Luzum, 2010), with the satellite orbits and clocks as well as the Earth orientation parameters fixed to the final IGS products. The absolute antenna phase centre variation (PCV) corrections for satellites and receivers were used (Schmid et al., 2007).

GPS processing time increases exponentially with the number of stations. In order to improve the computational efficiency, the whole APREF network of 750 stations is divided into four subnetworks, each with about 200 stations and using IGS core stations and/or ARGN/AuScope stations to link the subnetworks solutions together into one solution after subnetwork processing finalisation, which means there are some overlaps between subnetworks. The sub-networks are chosen based on the geographic location of stations to minimise the length between station baselines, which can also help to improve the resolution of integer ambiguities. The processing of subnetworks speeds up the whole network analysis, which can also be run in parallel across different machines and then undertaking normal equation stacking. We assign weights to some stations in accordance to the long term data quality of the stations. Usually equal weights are added to each station assuming that they have same data quality.

The daily solutions are generated in SINEX format. Data cleaning was also applied by rejecting solutions with incorrect metadata. The phase ambiguities are fixed where possible to improve the position in east-west direction. We focus on the Asia Pacific region, but also process global data with the available IGS core stations to link the solutions to the ITRF2014, currently IGS14 which is the recent IGS realization of ITRF2014 based on GPS observations, plus others for improved distribution and geometry with approximately 165 sites per day. The IGS14 consists of 252 IGS stations based on station performance, track record, monumentation, co-location and geographical distribution selected by the IGS reference frame Working Group for the IGS realization of the ITRF2014 (Altamimi, et al., 2016; Rebischung and Altamimi, 2017).

The daily final solutions are then combined into a weekly solution that is aligned to the IGS14 (Altamimi, et al., 2016). The weekly combined solutions are generated with Bernese software on the daily normal equations level. The stations are removed from the weekly combined solutions based on the residuals of the seven-parameter (Helmert) similarity transformation between daily and weekly solutions. The threshold of the residuals are set to be below 10 mm and 20 mm for horizontal and vertical components, respectively.

At the writing time of this report, there were 940 weekly solutions. The overall repeatability statistics of each weekly combination solution is an estimate of the day-to-day scatter of coordinate components about a weighted weekly epoch mean, and can be used as an indicator of data quality and daily position solutions. This can also be taken as a measure of internal precision of position. In general, the daily coordinate repeatabilities are between 1 and 4 mm for the north and east horizontal components, respectively, and between 4 and 8 mm for the vertical component, as shown in Figure 12. As expected, the repeatability for the height component is 1-2 times worse than the horizontal components. It also can be seen from the Figure 12 that the quality of the solutions has improved over time, as a result of the improvement of data processing techniques and GPS modernisation as well as advances in the IGS products. The repeatabilities are thought to represent the true uncertainties of position better than the smaller formal errors output from the Bernese software (Dixon, 1991; Weber, et al., 1998). Some stations with large repeatabilities are associated with poor data quality caused by poor sky view such as obstructions from vegetation, land forms and structures, but can also be caused by hardware failures such as the antenna receiving incomplete raw GNSS observations.

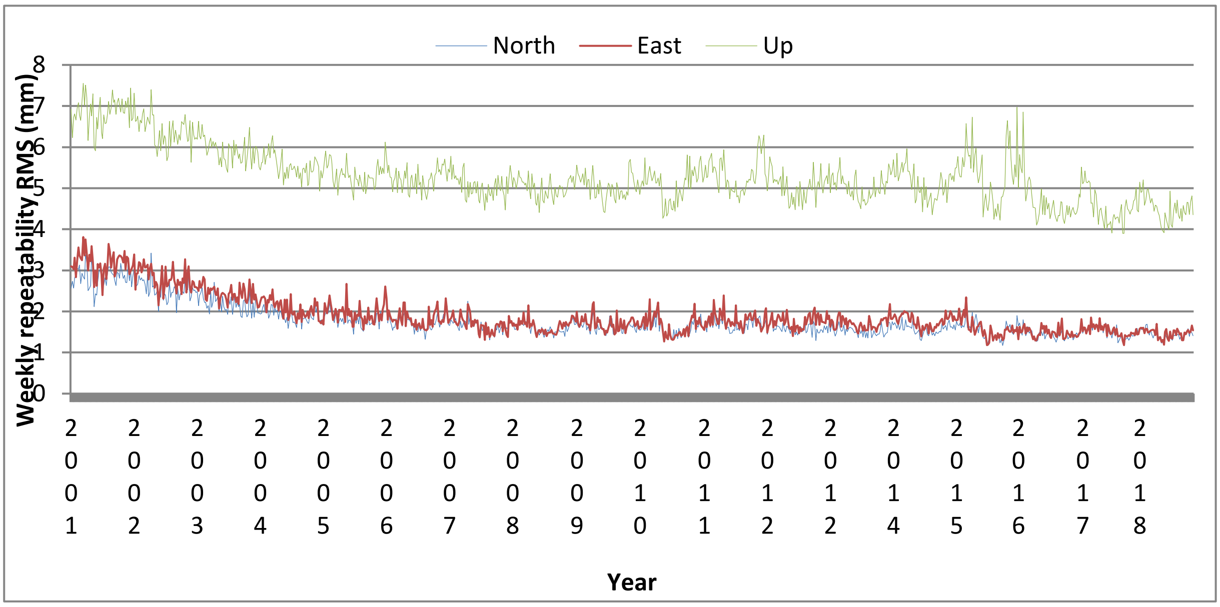


Figure 12. *Weekly repeatability RMS of position solutions versus time.*

The generation of position time series

The APREF CB provides the overall management of the LACs and combinations as well as the provision of data and products to the community. All the products are based on GPS L1 and L2 observations while most of the receivers are logging multi-GNSS data and publishing to the communities, they are not currently analysed by the APREF LACs. Therefore, the products are mentioned below as GPS output except discussing multi-GNSS data flow.

The weekly combined solutions are rigorously stacked using the CATREF software package from Institut Géographique National (IGN) to obtain the new regularized station coordinates and secular velocities as well as station position time series for the APREF CORS network (Altamimi, et al., 2002, 2011, 2016). The CATREF software allows estimating both the coordinates and the reference frame parameters. In order to align the estimated station position and velocity field to the ITRF2014, the CATREF software uses the minimum constraints approach over a set of qualified reference stations selected from IGS core stations. These IGS core stations were selected on the basis of: (1) having well-determined IGS14 coordinates and velocities; (2) coordinate time series are of high quality with no or few offsets; and (3) data available for 80% of the timespan used in this study.

To obtain reliable velocity field, quality control of weekly solutions and homogeneity tests including site naming conventions, site stability such as offset, discontinuities and outliers, have been taken if possible before generating the integrated multi-year solutions. In particular, the offsets were iteratively flagged and estimated during the stacking procedure. A new station position is estimated after each discontinuity and the velocities are usually constrained to be equal before and after a discontinuity (Altamimi, et al., 2002).

For outlier detection, the coordinate differences between the combined solution and each individual weekly solution were calculated, and then the RMS value i.e., so-called sigma, corresponding to the series of coordinate differences of all weekly solutions was computed. A station was rejected from an individual weekly solution if the coordinate difference of any one component exceeded three sigma.

The CATREF software, which was used to derive the ITRF2014, also considers post-seismic deformation (PSD) models for the stations. We run CATREF on the super-computer i.e. Australia’s National Computer Infrastructure (NCI) in order to speed up the estimation process and use parallel algorithm to plot the position time series.

At the time of writing, the position time series of the APREF project contain more than 6570 days. The velocity estimation for stations with time span less than 2.5 years are not considered reliable based on Blewitt and Lavallée (2002) due to the inability to reliably estimate the annual signal within the data. For most of the APREF CORS sites the time span is longer than 2.5 years, and the correlation between the annual signal and the velocity estimate can be neglected (Blewitt and Lavallée, 2002).

The output of CATREF are the residuals of the weekly ITRF2014-aligned coordinates computed with respect to the combined solution for each station and expressed in the North, East and Up frame (NEU) (Altamimi, et al., 2002, 2016; Nardo et al., 2014). To illustrate the robustness and precision of the analysis approach, the time series for the station ALIC in central Australia is shown in Figure 13. It is clear from the vertical component in Figure 13 that a data anomaly occurred in late 2010, which was caused by the antenna cable with small amounts of corrosion at the antenna end. Like time series of site ALIC, we observe that most GPS position time series exhibit an annual signal with an amplitude of a few millimetres (e.g., Bos et al., 2010). Other GPS position time series demonstrate strange behaviour, taking site BIRC in Victoria Australia as example as shown in Figure 14. Although the causes are not yet completely understood, it may be caused by hydrological instabilities related to the periodic circulation of underground water or thermal expansion of the GPS monumentation (e.g., van Dam et al., 2001; Caporali, 2003; Romagnoli et al., 2003). There are several sites in Victoria, Australia that exhibit similar behaviour, and we note that these sites are within 60-80 km distance at similar heights and with very similar climatic conditions, and mounted on masts on the roof of buildings. It is quite likely that the horizontal oscillations of the stations are temperature effects affecting the antenna mast or response a to local hydrogeological instabilities.

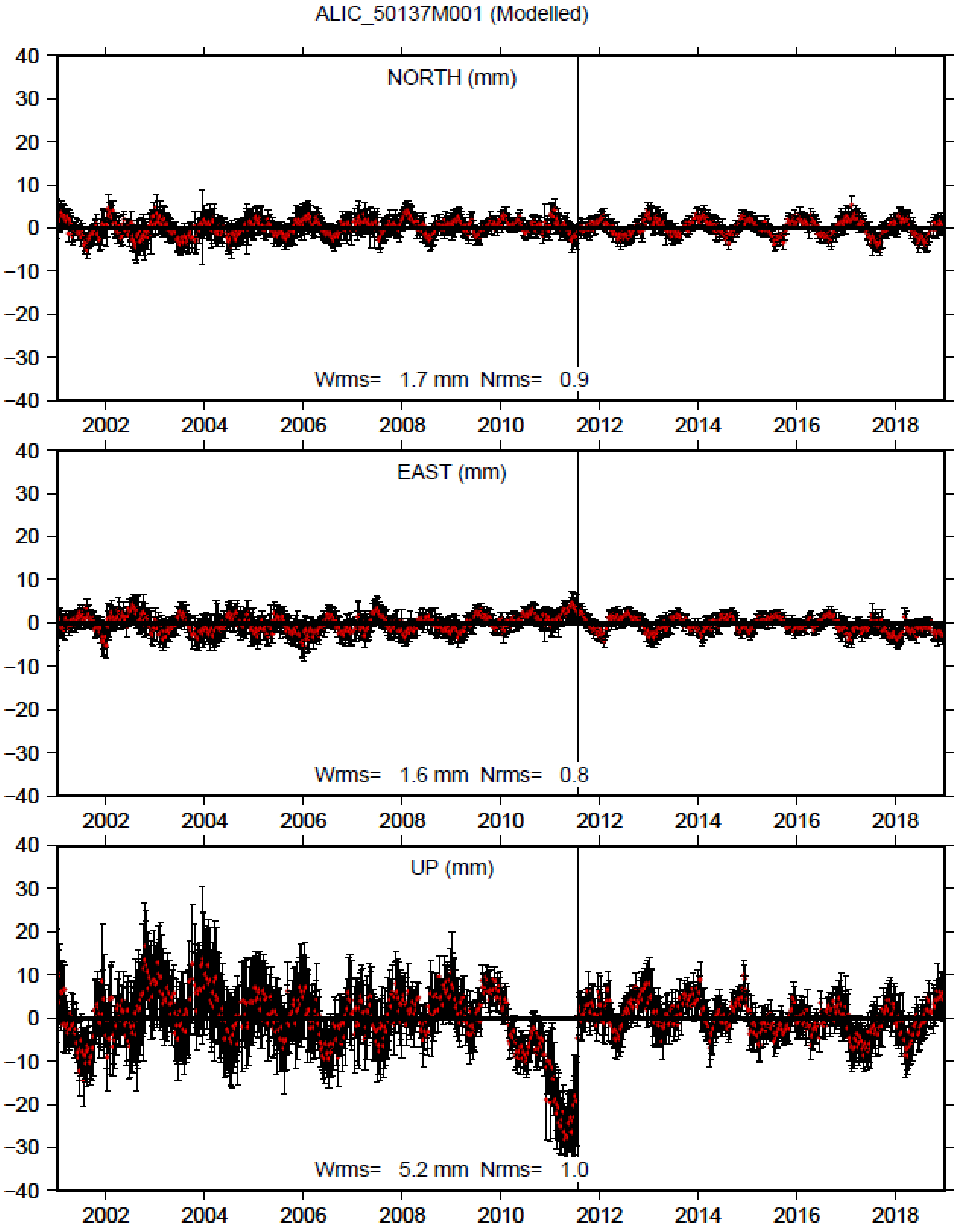


Figure 13. *Antenna anomaly behaviour detected by the time-series analysis of ALIC station. The vertical line in the middle indicates the time of the anomaly event.*

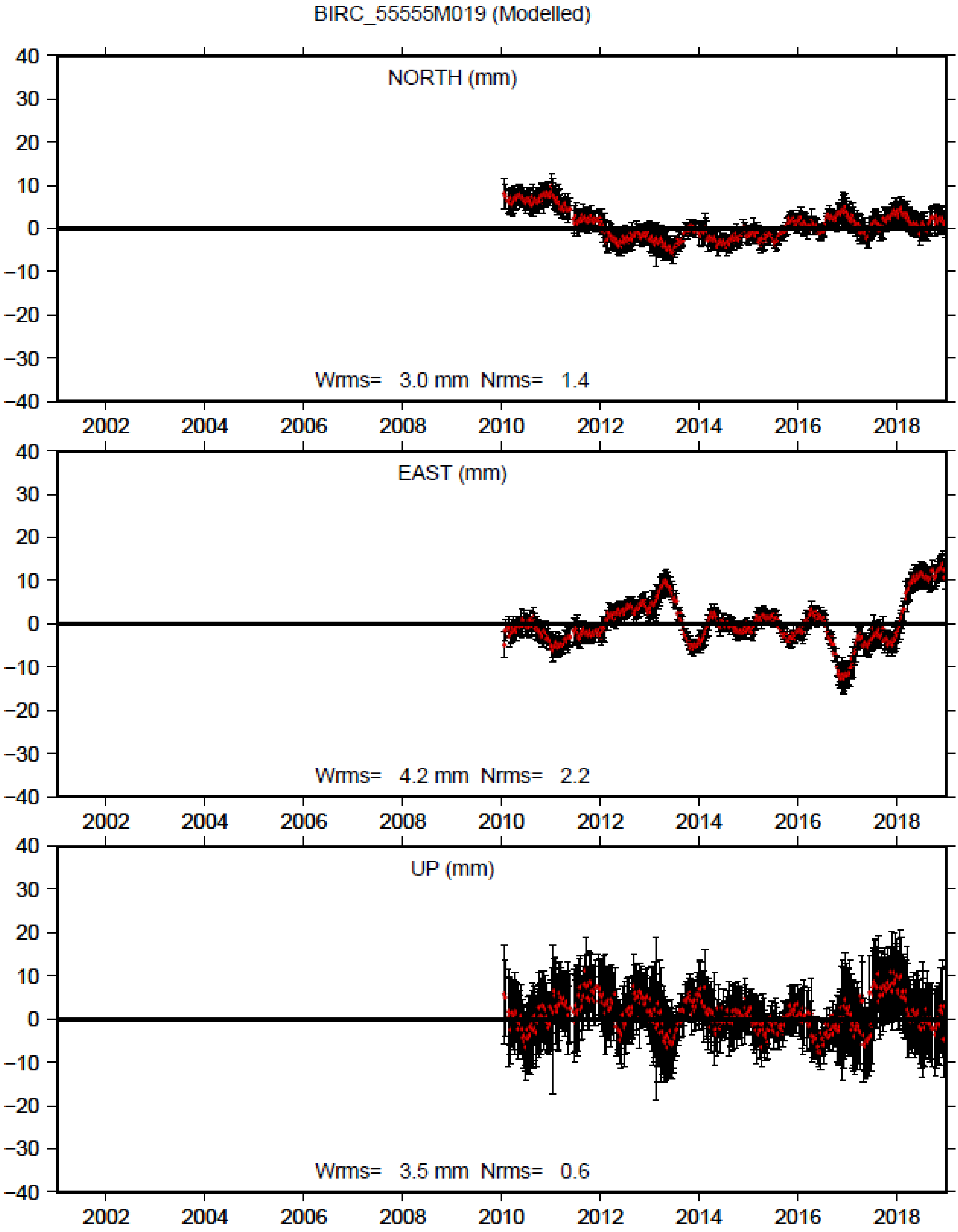


Figure 14. *Anomaly behaviour in horizontal components of the time-series at station BIRC.*

Position time series for all sites were generated. Almost all position time series exhibit periodic changes of horizontal coordinates except a linear drift. These can be explained in most cases as site monument motion due to seasonal temperature effects, hydrological loading and draconic period orbit modelling (Caporali, 2003).

The above time-series analysis of weekly solutions has become a routine operation for the APREF project. As output of the above procedure, we generated multi-year combined solutions of the APREF CORS network. The solutions include positions and velocities as well as their variance-covariance (VCV) matrix for all APREF stations referring to IGS14 at epoch 2010.0. The velocity field for the Asia-Pacific region along with the IGS core stations is plotted in Figure 5. Some stations show very irregular post-seismic movements, like LYTT (Lyttelton) and MQZQ (McQueens Valley) in New Zealand, and are excluded because constant velocities (linear coordinate changes) are insufficient to model their behaviour (Hu et al., 2011). We also do not include IGS core sites in our analyses, for instance, ANTC (Antuco) and CONZ (Concepcion) in Chile, and TSKB (Tsukuba) in Japan, because time series of site position for these stations are clearly not well modelled by a linear velocity. They are impacted by great earthquakes, in other words, post-seismic motion is typically non-linear in time (e.g., Tregoning et al., 2013).

Discontinuities in position

The residual position time series of each station were visually examined. More than 50% of the stations exhibit discontinuities (i.e. coordinate jumps/offsets in time), therefore the reliable detection of these breaks becomes a crucial problem and time consuming task. The detrended position time series were formed while setting up discontinuities through the original position time series. All discontinuities including significant offsets and velocity changes were detected, identified if possible, and removed using ITRF2014 discontinuities as a-priori (Altamimi et al., 2016). There are two typical causes of discontinuities in position time series: 1) equipment changes or metadata changes, such as antenna change or damage to a radome; receiver firmware changes; and 2) surface deformation due to abrupt geophysical events, such as earthquakes, post-seismic or underground water withdrawal or hydrology condition changes.

Discontinuities due to earthquakes are introduced when the site distance from the epicentre sufficiently close or the earthquake magnitude is great (>M_w8.0). There are some apparent discontinuities and anomalous position estimate in the APREF time series which may result from log file errors. In these cases, these anomalous points were removed from the time series estimation, sometimes after manual examination of the time series. Some discontinuities may also be caused by the effects of vegetation growing near the antenna, taking site BEE2 as an example, as shown in Figure 15 and 16. All discontinuities are logged in one SINEX like file and available for the community. The CATREF software can estimate the discontinuity offsets along with the position and velocity estimation (Altamimi et al., 2002, 2016).

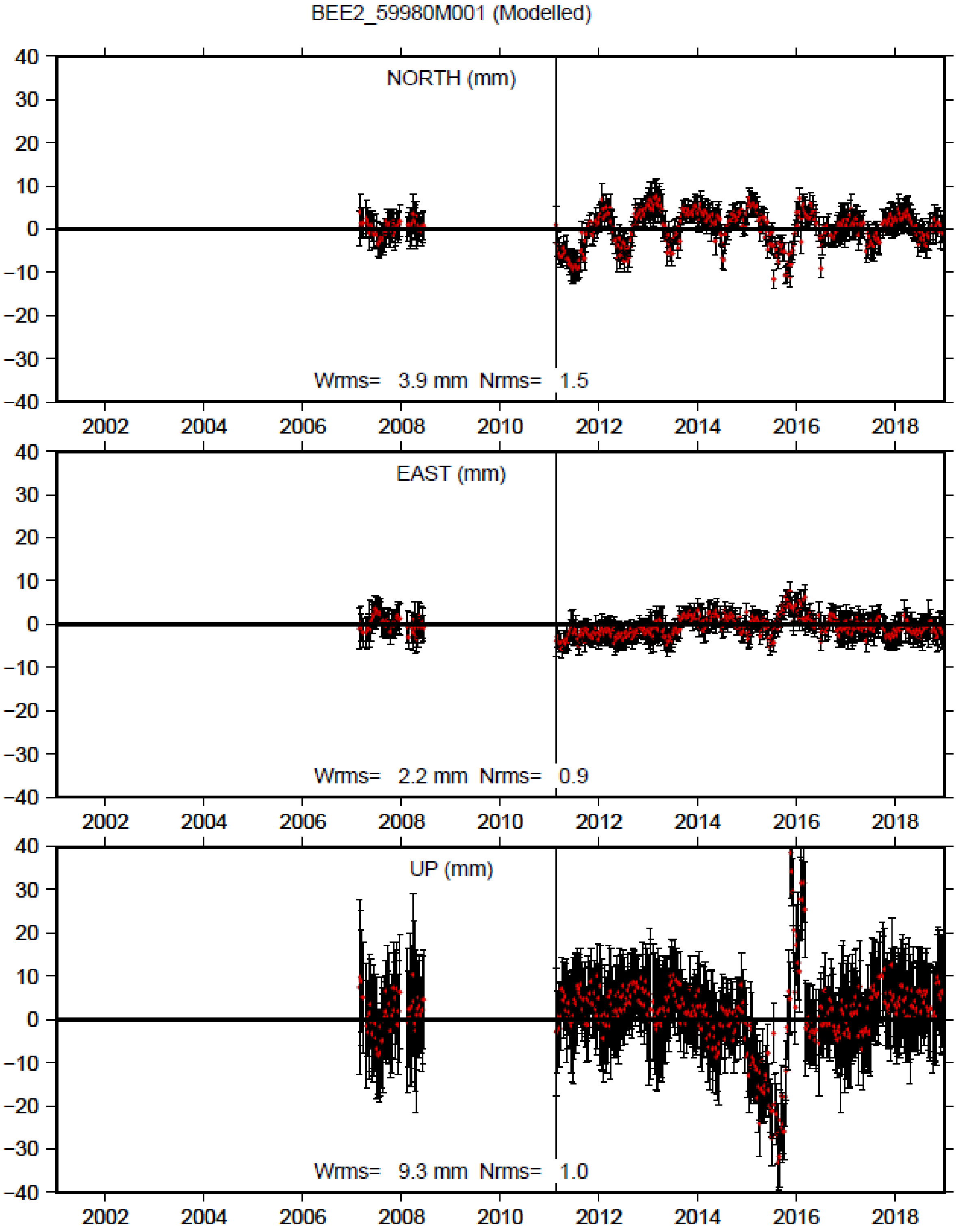


Figure 15. *Discontinuity in position time series caused by antenna covered by vegetation at site BEE2 in Queensland, Australia at the end of year 2015.*

Figure 16. *Antenna covered by vegetation at site BEE2 in Queensland, Australia.*

In all these cases a new set of coordinates were introduced for the corresponding station. In some cases effort was directed at distinguishing between discontinuities caused by hardware and by geophysical effects. While the station velocity arenot expected to change after a hardware change, it can differ after a tectonic event. In the case of a hardware change event, we constrained the station coordinate parameters in such a way that the estimated station velocities before and after the event are equal, taking station ALIC as shown in Figure 13. In the case of a tectonic event, however, the station velocities were estimated independently.

Some stations have less smooth time series, particularly in the high seismicity regions such as Indonesia, Japan and New Zealand. Some sites may have experienced monument motion or aseismic events, as neither large quakes nor data problems occurred (Hu et al., 2011; Tregoning et al., 2013). Elsewhere in the APREF CORS network, solutions clearly affected by seismicity were excluded and position jumps were estimated.

We note that within the APREF CORS network, most of the offsets in the height component are related to antenna changes. Similar case was reported in Kenyeres and Bruyninx (2004), where the replacement of the TRM22020.00+GP antenna with radome to a TRM29659.00 without radome at the station KARL caused a height offset of 4 cm. The use of in-situ calibration values (Park et al., 2004) would hopefully reduce this problem in the future. The APREF PCV models are identical with the models used by the IGS and contain a unique set of values for each antenna type. These global models cannot correctly describe the environmental dependency of the PCVs, however there are still many stations antenna without absolute PCV models or fully calibrated, necessitating the use of relative PCV models.

As the extent of the APREF CORS network grows, the detection and interpretation of position time series irregularities is becoming more and more time consuming and challenging. Estimation of the position offsets is challenging work for the routine analysis of the APREF project. If a discontinuity was detected, an independent position solutions and identical velocities before and after the offset were estimated along with the offset using CATREF software.

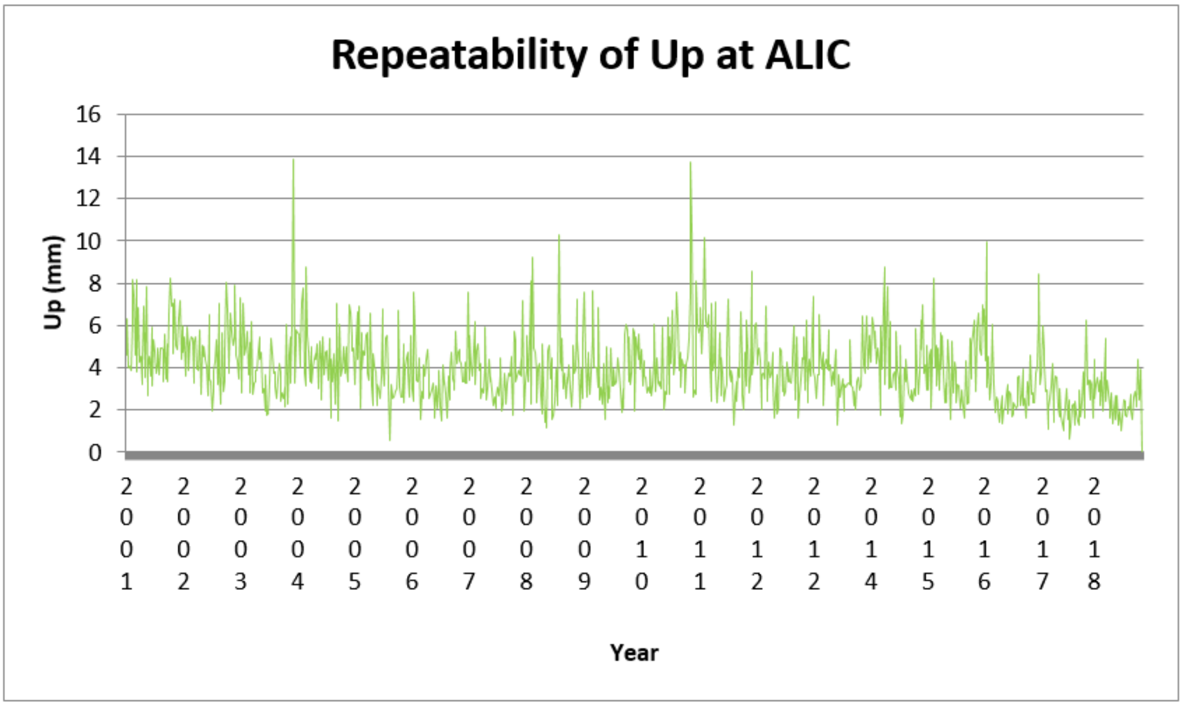
Accuracy assessment of the estimated position

The quality of position estimates of the stations not only depends on the data quality of the station but also depends on where the station is located (Herring et al., 2016; Mao et al., 1999). The accuracy assessment of the estimated position can be based on two criteria: 1) the formal standard deviations of the coordinates; and 2) the repeatability of the estimated coordinates. The daily repeatability provides a more realistic measure of precision for station coordinates, which is the weighted quadratic averaged error given by the following equation (Blewitt, 1989)

$$REP = \left[\frac{\frac{n}{n-1}\sum_{i=1}^{n}\frac{(C_i - C_m)^2}{\sigma_i^2}}{\sum_{i=1}^{n}\frac{1}{\sigma_i^2}}\right]^{1/2} \tag{1}$$

Where *n* is the number of days, here n=7; C_i is the estimated coordinate and σ_i is the standard deviation of the coordinates for day i, and C_m is the weighted mean of the coordinates of the station.

We assess the internal quality of the position estimates by analysing the repeatability of the weekly position solutions. Overall, there are smaller repeatability statistics for those sites in regions with less vegetation and more arid, e.g. station ALIC located inland of Australia in Alice Spring with drier seasons, than those sites located near coastlines with large amount of vegetation and high humidity e.g., station HOB2 located in Hobart of Tasmania, Australia. This is especially visible in vertical component, as shown in Figure 17 and summarized in Table 3. For completeness, we present the time series of HOB2 station in Figure 18.



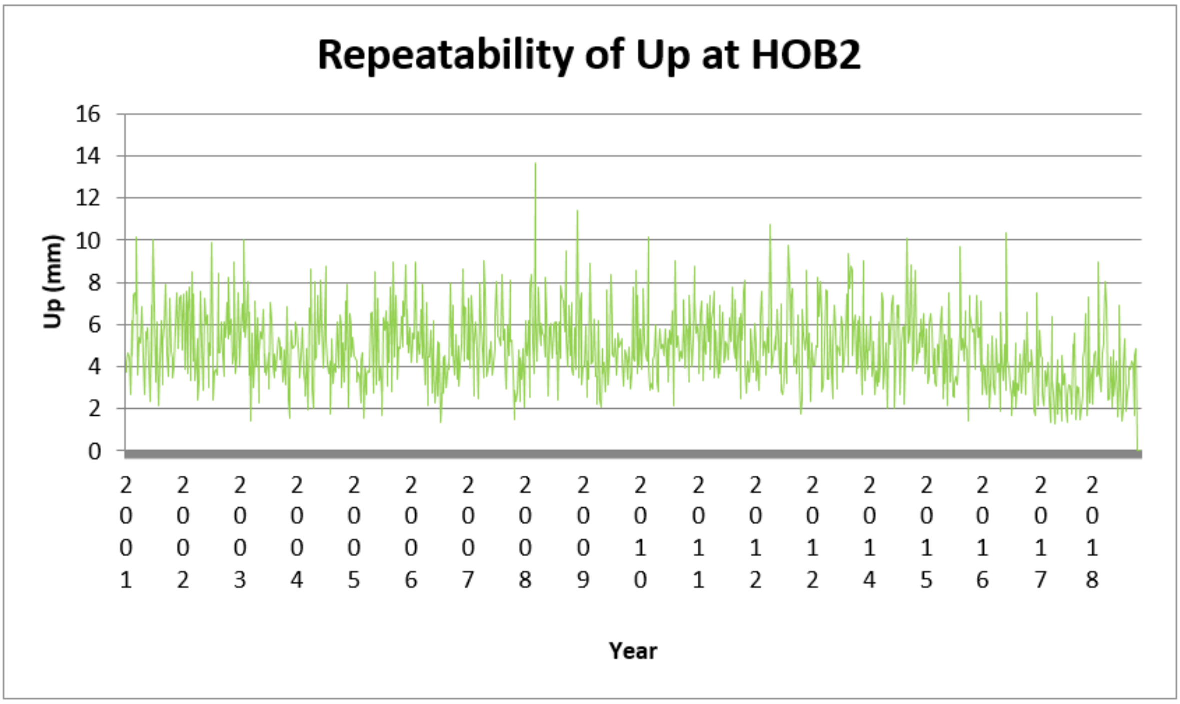


Figure 17*. RMS repeatability of weekly solutions in vertical component over 18 years (2001 – 2019) at stations ALIC and HOB2.*

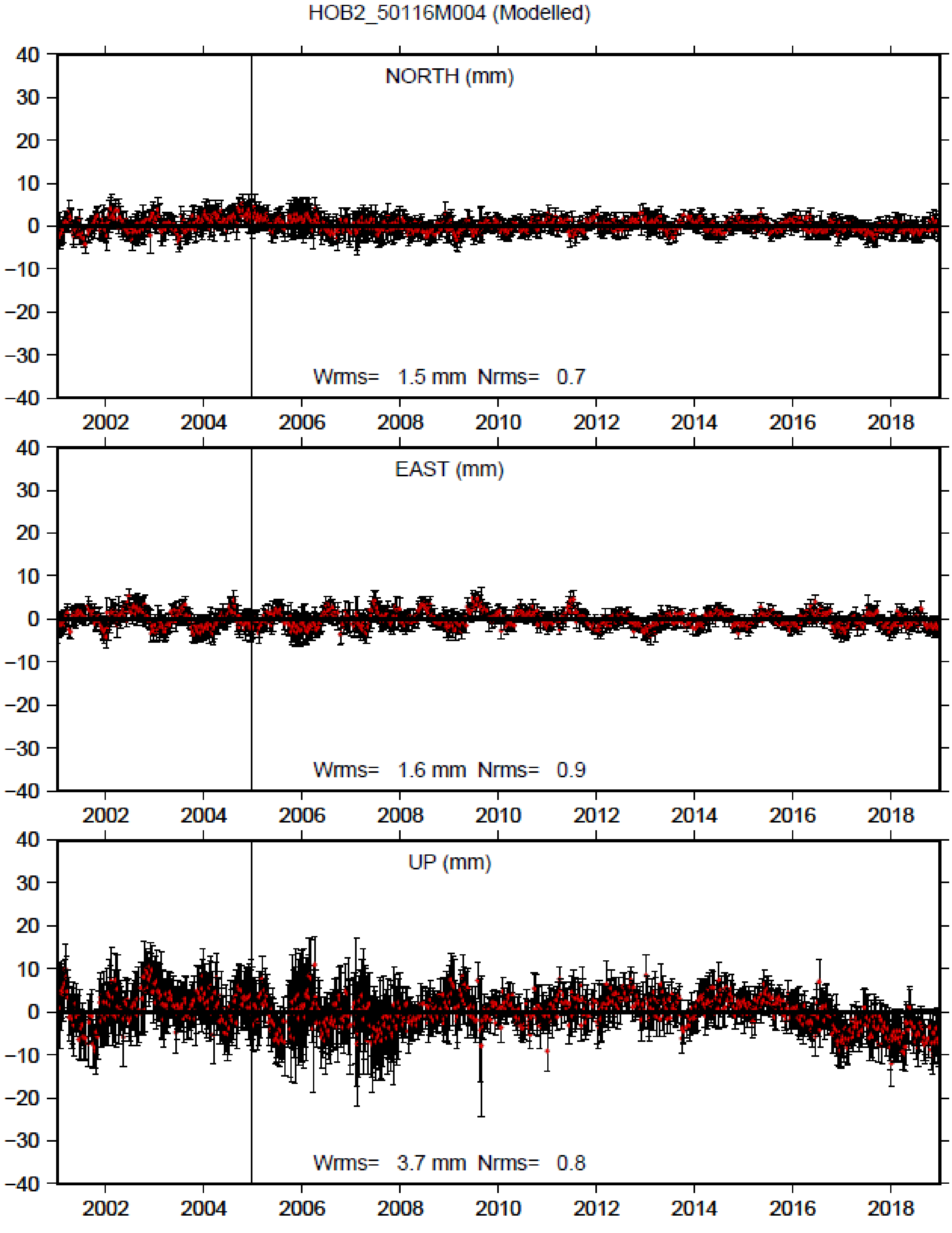


Figure 18. *Position time series for the station HOB2.*

Table 3. *Average RMS repeatability of weekly solutions over 18 years (2001 – 2019) at stations ALIC and HOB2.*

Station	North	East	Up
ALIC	1.1	1.4	4.0
HOB2	1.6	1.8	4.9

Sites with geodetic quality monuments have better repeatability than the stations attached to building or pole monuments (Beavan, 2005; Herring et al., 2016).

The variable multipath environment of the site also impacts the accuracy and repeatability RMS of position. The multipath can vary with time due to several causes, including vegetation growth, snow and soil moisture effects, or man-made alterations to the site such as adding new buildings or temporarily parking a vehicle near the antenna (Larson et al., 2008). This can also explain the variations of position repeatability as shown in Figure 15. In terms of position, Feissel-Vernier et al. (2007) found that the site-specific noise level is in the range of 0.5-3.5 mm in horizontal components and 1.0-4.5 mm in height for most sites.

We also note that variations in station position can be found in stations at higher latitudes which may experience large atmospheric loading variations from migrating high and low pressure weather systems, which were also reported in Herring et al. (2016), and Williams and Penna (2011). This can be reflected in the height component changing with the atmosphere pressure loading variation. These possible GNSS systematic errors or unexplained signals can be detected even after loading contributions from oceans and hydrology are taking consideration into the analysis. As shown in Table 4, it is interesting to note that the average RMS repeatability of weekly solutions for the stations in the South Pacific regional GNSS network (SPRGN) are larger than the average RMS repeatability of weekly solutions for the stations of the whole APRREF CORS network, in particular for the height component. This may be explained by SPRGN stations being close to the coastline or near to the tide gauge stations and the general tropospheric model may not good enough for the stations of SPRGN.

Table 4. *Average Root-Mean-Square (RMS) repeatability of weekly solutions over 18 years (2001 – 2019) for APREF stations and SPRGN stations.*

Station	North	East	Up
APREF	1.8	1.9	5.3
SPRGN	1.8	2.3	6.7

Overall, when comparing our solutions with published IGS weekly solutions, the transformation parameters between each weekly solutions and combined solutions in the ITRF2014 show that our solutions are at the 1-2 mm accuracy level for horizontal components and 5-6 mm for the vertical component on a weekly basis in terms of the translations and scale factor.

Accuracy assessment of the velocity field

The quality assessment of the above derived velocity field is a key point in the analysis. Unless the uncertainties are well understood, the estimated velocity may appear unduly significant. Over the past decades, a significant amount of research has been conducted on the accuracy assessment methods for the CORS derived velocity field in order to separate the geophysical signal from the measurement noise (e.g., Dixon, 1991; Zhang et al., 1997; Langbein & Johnson, 1997; Mao et al., 1999; Dong et al., 2002; Williams et al., 2004). Analytical expressions for the velocity uncertainty due to white noise and random walk noise were derived by Zhang et al. (1997). These works demonstrated that formal errors on the GPS-derived velocity field are grossly underestimated by factors of 5 to 11 if correlations are not properly accounted for, including spatial and temporal correlation noise. The maximum likelihood estimation (MLE) method seems to be the most appropriate technique to examine more realistic uncertainties on the GPS velocities (e.g., Mao et al., 1999; Williams et al., 2004).

However, there is no evidence and generally accepted methods to assess the absolute accuracy of the velocity estimation. Both precision and accuracy of the velocity estimates directly depend on the accuracy of site positions used during the CORS data processing. There is no external absolutely accurate reference that may be used for comparison. Different space geodetic agencies are computing position time series for the same stations but using different software packages and processing strategy, and in some cases even independent techniques. A direct comparison of the agreement of the solutions from the different analysis groups, i.e., so-called external accuracy or cross checking, provides a basis for the assessment of the accuracy of the solution.

Comparison with the IGS published velocity field was performed to verify the accuracy of the APREF CORS network velocity estimates. The estimated station velocities are compared with the IGS published combined solutions, i.e., IGS14.snx as shown in Figures 19 and 20. A statistics for this comparison was computed by using a set of 173 stations that are common in both solutions after excluding those stations with larger differences than 2.0 mm/yr due to unknown reasons. The statistics of the velocity difference is listed in Table 5. It can be seen that our results are quite close to the IGS14 results. The overall differences between the GA solutions and IGS published velocities were found to be 0.02 ± 0.29 mm/yr, 0.01 ± 0.32 mm/yr, and 0.08 ± 0.54 mm/yr for north, east and vertical components, respectively. These values are in agreement with the accuracy of the IGS14 solution. There are two main reasons for these differences: a) the different data time span; and b) the different data processing settings and strategy.

Table 5: *The statistics of the velocity differences between GA and IGS solutions for the common 173 stations.*

Velocity Component	Minimum (mm/yr)	Maximum (mm/yr)	Mean (mm/yr)	STD (mm/yr)
North	-1.10	1.17	0.02	0.29
East	-0.15	2.00	0.01	0.32
Vertical	-1.78	1.85	0.08	0.54

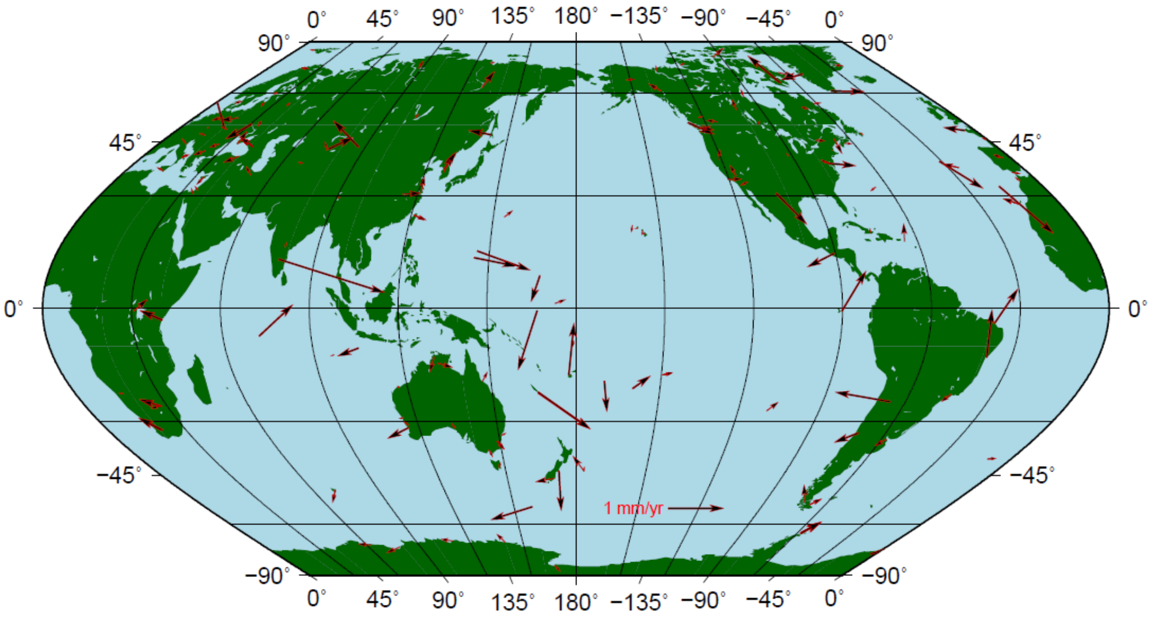


__Figure 19.__ Difference between IGS14 and APREF horizontal velocity field for the 173 common sites (mm/yr).

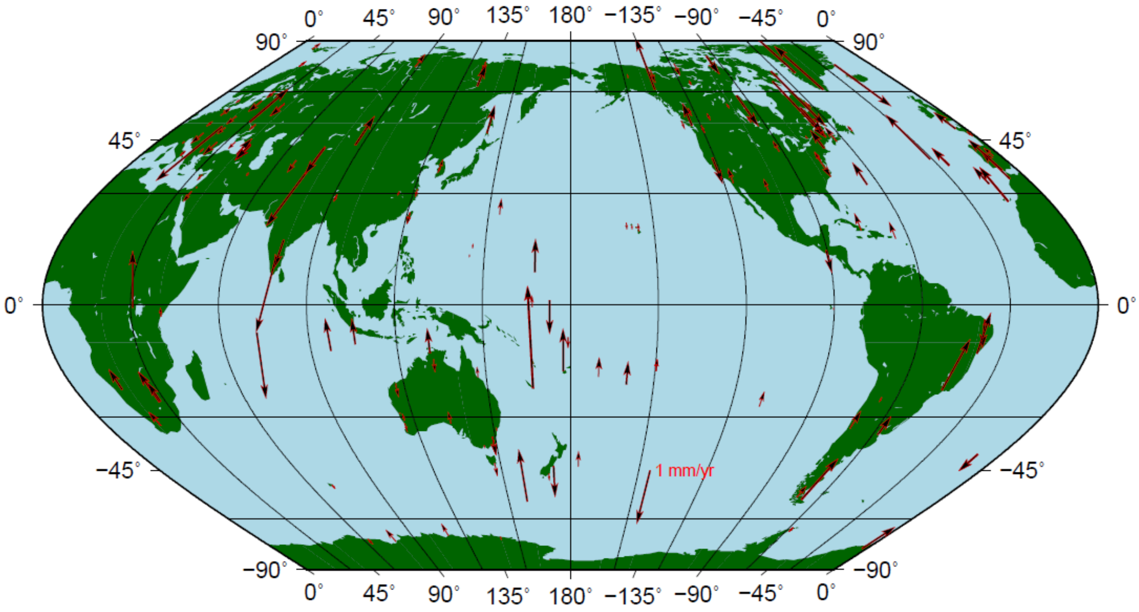


__Figure 20.__ Difference between IGS14 and APREF vertical velocity field for the common 173 sites (mm/yr).

Other effects on the estimated velocity field

In addition to the observation noise effect on the accuracy of estimated velocity field, there are other factors which impact on the velocity accuracy. For instance, a different velocity field could be derived from different time series lengths and data sampling rate as well as different data span. In theory, Langbein and Johnson (1995), Mao et al.(1999) and Williams (2003) discussed the effects of sampling rate and time series length on the velocity estimates and their error.

However, there are several concerns about the time span of CORS station positon time series where annual signals might significantly affect velocity estimates. After systematically analysing the effect of annual signals on geodetic velocity estimation from position time series based on theoretical derivation and experimental verification, Blewitt and Lavallée (2002) concluded that, at least 2.5 years data span is required for precise geophysical applications such as tectonics. Santamaría-Gómez et al. (2011) also showed that the data span and quality of data should be taken into account when assessing velocity uncertainty.

The accuracy and reliability of the derived velocity field is also correlated to the site monument stability (e.g., Beavan, 2005; William et al., 2004). We compare stations with different monument types in terms of uncertainties of velocities which is output from the CATREF software. There are two main types of stations in the APREF CORS network: 1) class A: concrete pillars installed with IGS site guidelines, Figure 21 presents a typical installation of class A; and 2) class B: a steel mast on the top of a building as shown in Figure 21. The statistical information of the correlation between the monument types of the APREF stations and uncertainties of estimated velocities is listed in Table 3 (only stations with reliable velocity estimation are taking account). There have been some work by other researchers for examining the character of position time series associated with different monument types (e.g., Beavan, 2005; Williams et al., 2004). They concluded that deep-drilled braced monuments are more stable than other monuments types. Our findings are supporting the above conclusion as shown in Table 6.

Table 6. *Statistics of repeatability RMS of position in terms of monument types.*

	Monument types					
	Class A			Class B		
Number of stations	206			377		
Average uncertainty of the estimated velocity (mm/yr)	North	East	Up	North	East	Up
	0.04	0.03	0.19	0.07	0.06	0.29

It is worth noting that we cannot interpret the above values to be only caused by the monument stability, there are other contributions to the noise in the velocity solutions, such as atmospheric effects. Stability of the site also depends on the geologic conditions including sediment type or bedrock. Santamaria et al. (2011) showed that the uncertainty of velocity is mainly related to data processing and data quality and quantity.

Figure 21. *Typical installations of station monument types class A (left) and B (right).*

Furthermore, the reference frame definition of the derived velocity field could also be an error source of the velocity (e.g., Mazzotti et al., 2003; Legrand et al., 2010; Firuzabadi and King, 2011). Using a different set of datum stations for the alignment to the ITRF2014 can lead to different velocities. A slight datum network distortion could be induced during the processing especially by the reference station that has a large velocity in the ITRF reference frame (frame used for the definition of the GNSS satellite orbits). This distortion increases linearly with the distance to the reference station, from ~0.1 mm/yr at 500 km to ~0.3 mm/yr at 1000 km in the horizontal components, and from ~0.6 mm/yr to ~1.2 mm/yr for similar distances in the vertical component (Mazzotti et al., 2003). Legrand et al. (2010) also confirmed the velocity differences reaching up to 1.3 mm/yr in horizontal and 2.9 mm/yr in the vertical component which were caused by the chosen different reference frame definition. They concluded that a more reliable GNSS-based velocity field could be achieved using a global reference frame definition as we have done for the APREF velocity field estimation.

On the other hand, in terms of global velocity field, the instability in centre of mass of the Earth in different realization of the ITRF would map at a 1:1 ratio into derived stations velocities, e.g., a possible instability in scale at the 0.1 ppb/yr could impact the derived vertical velocity by about 0.6 mm/yr (Lidberg et al., 2007). Riddell et al., (2017) were able to identify coloured noise in the reference frame origin of ITRF2014 that increased the uncertainty in the rates five-fold (upper bound) compared to a white noise only solution. Watson et al. (2006) also discussed how the choice of tide model may influence derived station velocities. Other factors impacting the velocity estimation include higher order ionospheric terms (Kedar, et al., 2003), GPS satellite and receiver antenna offsets (Ge et al., 2005), and atmospheric loading (Tregoning and van Dam, 2005).

APREF products available to the community

The weekly solutions from LACs are submitted to the Centre Bureau at Geoscience Australia in SINEX format with station position and variance-covariance estimation information. These files are combined using the CATREF software in a common reference frame with a weighted least square approach. Except Geoscience Australia's solutions, the LACs SINEX files only contain a selection of stations in the APREF network, but the combined SINEX files from the LACs contain all of APREF stations processed up to the time of the combination. The combined solution named following the convention" "APR(gpsweek)7.SNX", are published on the ftp link: ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/solutions/apref/.

We align the reference frame between LACs in the combination step to allow the position estimates be rotated and translated. During combination, outlier detection and validation are performed for any stations whose position differs by more than 10 mm for horizontal and 20 mm for vertical components. We use 252 IGS core stations as the common reference frame through the estimation of the rotations and translations to minimize the position residuals at the specified set of reference frame stations. Since we fix IGS orbits and clock products when we processing the data, it means that the reference frame of GNSS is well determined and that the estimated weekly translation parameters and the estimated positions are not sensitive to the translation of the reference frame (Herring et al., 2016).

The weekly solution of the APREF project from GA is computed with about two weeks' latency, as it relies on the availability of the IGS final orbits and other products which have a two week production time. The weekly APREF combination of the final solutions have a three week production time, due to the data transfer and combination time, which is significant given the long term time series and quality control process. Currently, only Geoscience Australia's final solutions are combined into position time series and estimation of velocities, the final solutions of APREF LACs combination is only for the quality checking of solutions. When necessary, we may re-process the whole data set, especially if the reference frame is updated or there are significant updates to the models or software, so that our solutions are aligned to the latest International Terrestrial Reference Frame, currently ITRF2014.

Different processing strategies, such as sample rates and noise models as well as weighting the phase and pseudo range observations, impact the output of variance-covariance matrices in the output SINEX file, which requires re-scaling of the variance-covariance matrices when using CATREF to combine the LACs solutions. Scale factors are determined such that the values of the squares of coordinate differences divided by the number of degrees of freedom at the reference frame stations are near to 1 (Herring et al., 2016). The combined weekly solutions are aligned to IGS14, the IGS realisation of the ITRF2014 by using typically 252 IGS core stations.

In practice, daily solutions are also aligned to the IGS14 using as many as possible IGS core sites where data is available. During frame alignment, reference stations are removed if the coordinate differences between a-priori and the estimated value are larger than 10 mm in horizontal and 20 mm in vertical. Similar for weekly solutions of normal equation stacking, the sites with coordinate differences between a-priori and the estimated value are larger than 10 mm in horizontal and 20 mm in vertical are removed as outliers sites, the sites with less than two days solutions in one week are also removed as outliers. In the loosely constrained solutions, the reference frame is not realized, while the solutions are rotated and translated to align to the ITRF2014. For each day, Geoscience Australia delivers five SINEX files with four for each subnetwork daily solutions and one for combined daily solution for the whole APREF network. Daily solutions are loosely constrained using a value of 100 m to the coordinates and are considered to be fiducial-free solutions.

All data and products resulting from the LACs are archived and distributed by the APREF Central Bureau made available on ftp and free open access to the community. For more details, please refer to the webpage of the APREF and related ftp link (http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame).

Since APREF products are operational analysis results, users should be cautious of possible systematic errors that might be in the position and velocity estimates, in particular, when new satellites are launched only nominal satellite transmission antenna calibrations are available for routine analysis until new ITRFs are generated to be updated for the estimates of the positions of satellite phase centre offset (PCO) for individual satellites (Schmid et al., 2007; Cardellach et al., 2007). Such systematic errors may cause geographically correlated errors in height component (Herring et al., 2016).

Concluding remarks

The APREF project is a collaboration of the UN-GGIM-AP and the IAG. The APREF CORS network is a voluntary network consisting of more than 450 permanent tracking stations which covers the Asia and Pacific region and its surroundings. APREF potentially supports multi-disciplinary applications ranging from surveying, geodynamics research, sea level monitoring to numerical weather prediction (Hu et al., 2011).

The APREF CORS network is based on contributions from more than 15 institutes distributed acorss 29 Asian and Pacific countries. Its way of operation are similar to those of the IGS with the same conflicting goals of inclusiveness and selectivity. This means that although guidelines exist for monumentation design and equipment changes, different institutes use different practices and for example some equipment changes are not always communicated to the APREF CB. In addition, when the APREF CB detects an erroneous behaviour at one of the sites, it cannot do more than inform the site operator and hope proper action would be taken.

This report details the determination of a set of homogeneous coordinates and velocities that includes the complete link from the APREF CORS sites to the ITRF2014 in the Asia and Pacific region. The output of the products from the APREF project include daily station position estimates in SINEX format, weekly station position and velocity estimates in SINEX format, long term position time series, velocity estimates, discontinuities as well as post-seismic and co-seismic offsets.

The use of the long term position time series allows a better geophysical interpretation of the observed site motion, in particular to understand the residual signal or non-linear motion which may be related to local geophysical phenomena or site stability. For classical geodetic and geophysical applications, the residual position time series provide useful information like site motion related to the events of nearby earthquakes or equipment changes. The horizontal component is primarily related to tectonic plate motion, while the height component is associated with local or regional uplift or subsidence (Feissel-Vernier et al., 2007).

The raw data as well as weekly SINEX files, and updated ITRF coordinate and velocity solutions are published on the Geoscience Australia’s ftp link ftp://ftp.ga.gov.au/geodesy-outgoing/gnss/. These solutions are considered as the most accurate and up-to-date source of the APREF coordinates and velocities for the APREF stations. These results are critical for use in geodynamic research for the monitoring of the active tectonic structures in the Asia-Pacific regions as well as verifying geodynamic models for the particular areas.

The estimated station positions and velocities are the basis of the ITRF component of the APREF products. However, it is evidenced that there are still systematic errors in the APREF products that need to be understood. The analysis of the velocity field based on the APREF CORS network shows that the high geodetic quality achieved in terms of homogeneity, precision and consistency with respect to other top-level geodetic solutions. Furthermore, the APREF project provides site specific velocities of a network at higher densities than those provided by the IGS network which is benefiting to long term geodynamic studies and reference frame maintenance.

We assess velocity uncertainty in terms of external accuracy, which is different from the above conventional so-called realistic uncertainty, by analysing the type and amplitude of the noise content in the residual position time series. The comparison to the published IGS velocities shows that the derived velocity field in the Asia-Pacific region is generally consistent with mean differences of 0.02

mm/yr, 0.01 mm/yr and 0.08 mm/yr for north, east and vertical components, respectively. Other impact factors on the GPS derived velocity field were also discussed including potential error sources associated with the reference frame definition.

The analysis of the derived velocity field and related by-products, including vertical velocities and repeatability of position, demonstrates the quality of the APREF solutions. The state-of-art GPS analysis strategy for the APREF GNSS network fulfils the IGS requirements and guidelines. The products and output of the APREF project have been used as a reference standard for other nations and regions in the Asia-Pacific.

While thorough geodetic and geophysical modelling, analysis and interpretation and discussion of the above scientific output are beyond of the scope of this contribution, we highlight the important raw data quality issues, in particular metadata management policy, which are the basis of all kinds of further analysis of the products.

We are continuing to pursue improved models, better approaches, and improving the process of detection of discontinuities of the position time series, to maintain and improve APREF products and vision, and provide an up-to-date set of coordinates and velocities in the ITRF2014 for the Asia and Pacific region.

Last but not least, we are contributing our solutions to the Working Group on Regional Dense Velocity Fields of the International Association of Geodesy Sub-commission 1.3. Through their invaluable feedback and cross-checking our results have been improved further.

Acknowledgments: Thanks go to the LACs, and to all GNSS data owners and operators contributing data to APREF. As the coordinator of the APREF project, the first author would like to thank all for the community’s efforts in producing high quality geodetic products and data, notably for those Asia-Pacific countries with cultural and policy constraints. Also thanks Anna Riddell for reviewing the document and improving the quality of the report.

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