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Geoscience Australia's GNSS Antenna Calibration Facility: Initial Results

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ABSTRACT

A Global Navigation Satellite System (GNSS) antenna calibration facility has been established at Geoscience Australia, for determining individual antenna calibrations as well as aiding the establishment of type mean calibrations as used by the International GNSS Service (IGS). Studies have highlighted the importance of accounting for the variation in individual antenna calibrations for high precision positioning applications. In order to use individual antenna calibrations reliably, the repeatability of the calibration needs to be well understood. In this paper, we give an overview of the repeatability of calibrations for different antenna types. We also present a case study on the application of an individual GNSS antenna calibration in Australia and its effect upon positioning.

KEYWORDS: GNSS antenna, calibration, robot, positioning.

1. INTRODUCTION

The models used to account for receiver antennas can still limit the accuracy of GNSS positioning (Gorres *et al.* 2006, Zeimetz and Kuhlmann 2008). GNSS antennas do not have an ideal point-like physical centre at which the satellite signals are received and so an electromagnetic phase centre is defined. The mean phase centre position of an antenna is defined as a phase centre correction (PCC) which is characterised by the combination of the phase centre offsets (PCO) and phase centre variations (PCV). The antenna PCC's are both elevation and azimuth dependent upon the direction of the incoming satellite signal. The phase centre position can also vary due to the frequency of the received signal.

1.1 Overview of Antenna Calibration Techniques

Since the 1980's, different antenna calibration techniques have been established and can be allocated into 'absolute' and 'relative' and into 'field' and 'laboratory' procedures (Zeimetz and Kuhlmann 2008). 'Absolute' refers to calibrations where the phase is not measured relative to a reference antenna; 'relative' phase centre corrections are referenced to PCO estimates from an anechoic chamber calibration of an antenna (typically Dorne Margolin T) where the arbitrary assumption is made that the reference antennas PCV's are zero. The 'field' procedure uses real satellite signals from satellites in view, such as the robotic calibration performed by Geo++ in Germany (Wubbena *et al.* 1997) and the National Geodetic Survey (NGS) in the United States (Bilich and Mader 2010). A 'laboratory' procedure uses simulated GNSS signals, such as in an anechoic chamber (Gorres *et al.* 2006).

Geo++ - robotic calibration process

Geo++ has developed an absolute field based GNSS antenna calibration system where a robotic arm tilts and rotates the antenna to calculate the absolute PCC. A homogeneous coverage of the antenna hemisphere is maintained, even for observations at negative elevations. The calibration uses actual satellite signals from satellites in-view where the orbit and atmospheric errors are mathematically cancelled by a near-by (<15 m) reference base station during processing. Far-field multipath is mitigated through a dynamic elevation mask of 18° which is adopted as the antenna is tilted and also eliminated by the correlation of consecutive epoch (1-2 seconds) modelling (Schmitz *et al.* 2008).

NGS - robotic calibration process

The NGS has developed a robotic GNSS antenna calibration system where the antenna is also tilted and rotated. The field calibration set up has been designed with a simplified multipath environment and a short baseline to facilitate single baseline solutions.

The main difference between the NGS and Geo++ robotic systems is the axial rotation pivot point as defined for the robot. The Geo++ system rotates around the nominated phase centre of the antenna (fixed in space) using five rotation axes, whereas the NGS robotic system is constrained to revolve about the fixed robot axis as there are only two rotation axes. The pivot point of the NGS calibration is at the base of the robot which causes a sweeping motion of the antenna phase centre in space during the calibration procedure. The pivot point of the Geo++ calibration is the nominated phase centre and is held fixed in space so that the antenna is tilted and rotated *around* this phase centre.

Anechoic chamber calibration

An anechoic chamber uses a mechanism to rotate a GNSS antenna to simulate different signal directions. The positioner mechanism rotates and tilts the test antenna by small amounts of elevation and azimuth simulating the location of a satellite-in-view as it would appear in a field calibration.

The experimental set up consists of a fixed transmitter on one end of the test range and a remote-controlled positioner carrying the antenna under test at the other end (Zeimetz and Kuhlmann 2008). Multipath effects can be successfully avoided and dampened in an anechoic chamber by using spectral absorbers on the room surfaces (walls, floor and ceiling).
Zeimetz and Kuhlmann (2008) found that repeatability of an anechoic chamber calibration ranges from 0.17 mm to 0.34 mm between two calibrations under near identical conditions for

GPS L2. The largest discrepancies between calibrations occur at elevation angles between 0° and 10° elevation, where the maximum difference was 0.34 mm. This demonstrates that the largest effects are normally seen at the lower elevation angles, which is also a product of the constraint that the variations will be equal to zero at 90°.

The Geoscience Australia antenna calibration facility includes access to the National Measurement Institute (NMI) anechoic chamber in Sydney, where a multi-frequency antenna calibration process is currently being developed.

1.2 Inter-method Comparison

Table 1 presents a comparison of calibration techniques. Aerts (2012) provides the comment that from an antenna engineers' perspective, the anechoic chamber antenna calibration technique seems the most intuitive. But from a geodetic point of view, the robotic technique as developed by Geo++ satisfies geodetic antenna calibration specifications.

	Geo++ Robotic System	**Anechoic Chamber**
technique	field robot	anechoic chamber
signal source	real satellite	generated sine wave
signals	currently available/in-view	any (future) sequence
plane waves	perfect	approximation
equipment	GNSS receiver	vector network analyser
multipath	strong	weak
multipath suppression	adaptive sequence	absorbers
environment	variable	stable
duration (2 sequences)	approx. 6-8 hours	approx. 1h at Bonn (Germany) currently 6h at NMI (Sydney)
station mock-up	limited by max. robot payload	limited by chamber quiet-zone size

Table 1. Comparison of calibration techniques (modified from Aerts 2012).

2. ESTABLISHMENT OF A CALIBRATION FACILITY AT GEOSCIENCE AUSTRALIA

The Geoscience Australia GNSS antenna calibration facility comprises of two robotic systems and access to an anechoic chamber at NMI. The project was funded under AuScope's Australian Geophysical Observing System and it is expected that the development of antenna type mean calibrations will be provided to the IGS Antenna Working Group for antenna and dome combinations that do not currently exist in the IGS Antenna Exchange file (ANTEX). The system is also capable of providing individual antenna calibrations as used in the EUREF Permanent Network (Baire *et al.* 2012).

One of the robotic systems has been purchased from Geo++ which includes both the robotic arm hardware and pre-programmed software to complete an absolute field antenna calibration. The robotic system has been successfully used by Geo++, University of Hannover and the Berlin Senate Department for Urban Development and Environment. The majority of the type mean results published by the IGS have been derived from one of these systems.

The second robotic system is manufactured by Kuka and is in the developmental phase for programming and antenna calibration sequence.

2.1 Comparability

Establishing the comparability of antenna calibrations between different organisations, and across different calibration techniques is an important validation step. Before the Geoscience Australia robot (hereafter called GeoAus (robot # 6)) was installed in Canberra, the system (both robotic hardware and software) was tested by Geo++ in Germany. This provided validation that the calibration system was performing as expected and repeatability between the Geo++ robotic system (robot #5) and Geoscience Australia robotic system GeoAus (robot #6) matched previously published values for comparing robotic antenna calibration systems in Wubbena *et al.* (2006).

Geoscience Australia has three antennas that are primarily for the purpose of validating and benchmarking the robotic calibration system:

- Trimble chokering (TRM59800.00 NONE, sn: 4938353442);
- Javad chokering (JAVRINGANT_DM NONE, sn: 00711);
- Leica chokering (LEIAR25.R3 NONE, sn: 09330003).

Each of these antennas has been sent to at least one other facility for calibration as listed in Table 2. These particular antennas were selected as reference antennas to reflect the majority of geodetic antenna types in the Australian Continuously Operating Reference Station (CORS) network. The details of the inter-comparison results and methodologies used to perform the comparison will be further detailed in a future publication.

	TRM59800.00 NONE	**JAVRINGANT_DM NONE**	**LEIAR25.R3 NONE**
Geo++ (robot #5)	[May-2012]	[Sep-2014]	[May-2012]
Geo++ (robot #6)	[May-2012]	-	[May-2012]
GeoAus (robot #6)	[ongoing]	[ongoing]	[used as reference for base station]
Bonn chamber	-	[Sep-2014]	-
NMI chamber	-	[Feb-2015]	-

Table 2. Reference antenna calibrations at each facility, with date of calibration. Geo++ (robot #6) is GeoAus (robot #6) installed at the Geo++ facility in Germany.

2.2 Repeatability of Robotic Calibrations

Calibration of a reference antenna provides confirmation that the robotic system and software are performing as expected. So as a matter of routine to check that the calibration system is performing within expectations, a reference antenna is re-calibrated every 2 weeks, or after a calibration result is significantly different from a type mean, or after a new antenna type is calibrated for the first time.

The Trimble reference antenna has been calibrated by the Geoscience Australia robot approximately 45 times and the repeatability of these calibrations is within ± 0.5 mm for GPS L1, and within ±1.0 mm for GPS L2, of the original calibration provided by Geo++.

3. VARIATION WITHIN A TYPE MODEL

The current IGS standard is to only apply type mean calibrations during processing. However there can be significant deviations of individual antenna variations with respect to the IGS type mean. This may occur due to changes in componentry during a manufacturing run, mistakes made during the manufacturing run, and/or the natural variation in performance from the different componentry used to make up the antenna.

Studies have further highlighted the importance of accounting for the variation in individual antenna calibrations for high precision positioning applications due to the electromagnetic coupling between the antenna and monument when applying absolute PCV model for the GNSS data processing. Schmid *et al.* (2005) found that individual antenna PCC could vary from the IGS type mean by over 10 mm. Baire *et al.* (2013) found that when a type mean calibration was applied during processing instead of an individual calibration for the antenna dome combination LEIAR25.R3/LEIT, the height at European Reference Frame (EUREF) stations SOFI and VALE changed by -10 mm, and by +8 mm at station HOE2.

Individual antenna calibrations are expected to vary from the IGS type mean by up to ±1 mm for GPS L1 and up to ±1.5 mm for GPS L2 for elevation dependent differences according to the IGS Antenna Working Group (i.e. azimuth variations are not taken into account). This has been demonstrated to be the case for nine TRM59800.00 antennas calibrated at Geoscience Australia as shown in Figure 1 and Figure 2 for GPS frequencies L1 and L2 respectively.

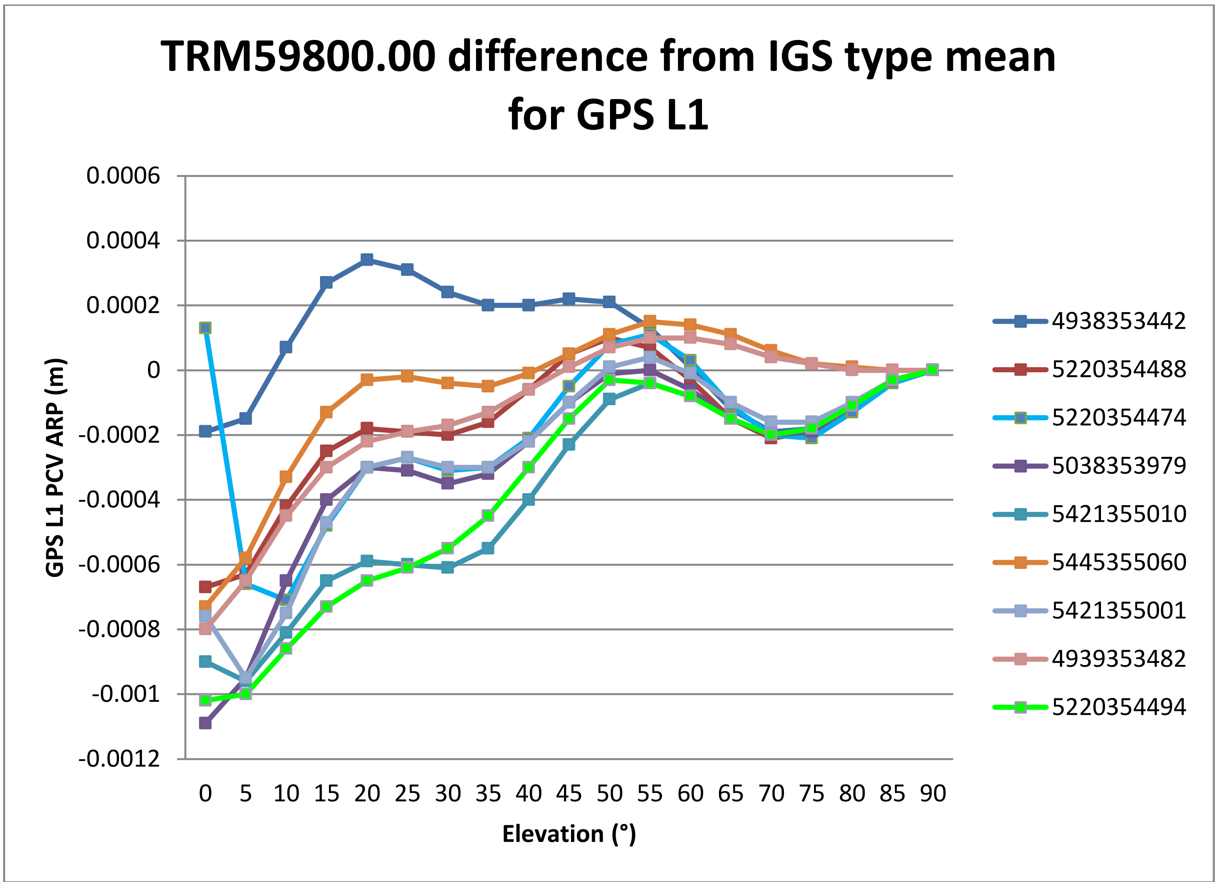

Figure 1. Individual calibration (denoted by serial number) elevation dependent differences from the IGS type mean for nine TRM59800.00 NONE antennas for GPS L1. The green line is for sn: 5220354494, which was later installed at MRO1.

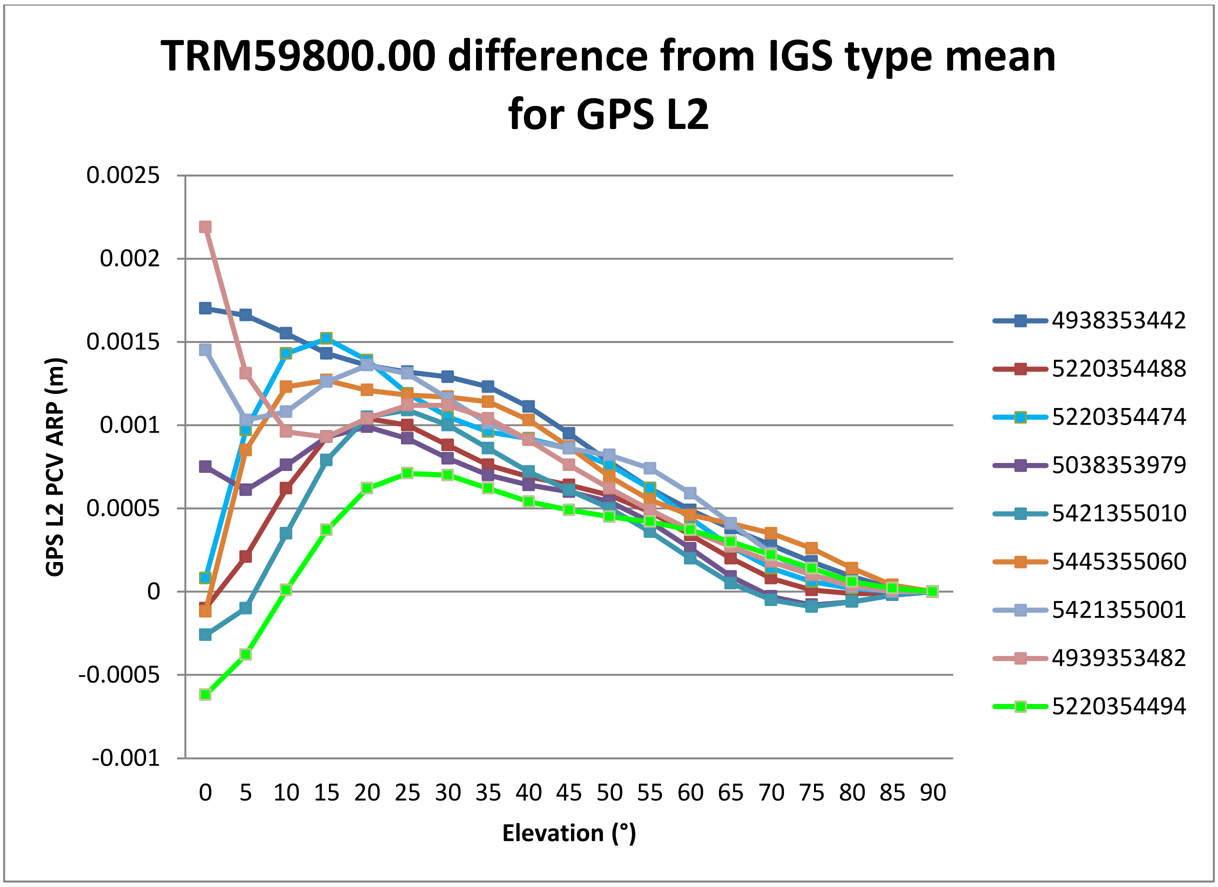

Figure 2. Individual calibration (denoted by serial number) elevation dependent differences from the IGS type mean for nine TRM59800.00 NONE antennas for GPS L2. The green line is for sn: 5220354494, which was later installed at MRO1.

Twelve individual antenna calibrations of JAVRINGANT_DM antennas, shown in Figure 3 and Figure 4 have also been completed. The JAVRINGANT_DM individual antenna calibrations in Figure 3 are within ±1 mm of the IGS type mean calibration for elevation-only dependent differences above 10° elevation for GPS L1. However, for the GPS L2 elevation dependent differences (see Figure 4) the departure is larger than the expected variability of ±1.5 mm. Despite this the calibration results are internally consistent, and are comparable to calibrations performed at Geo++. For this antenna type the IGS type mean has been based upon only five different antennas. Our results indicate a larger sample size may be required to obtain a more reliable type mean to ensure the variation with individual antenna calibrations is within ±1.5 mm.

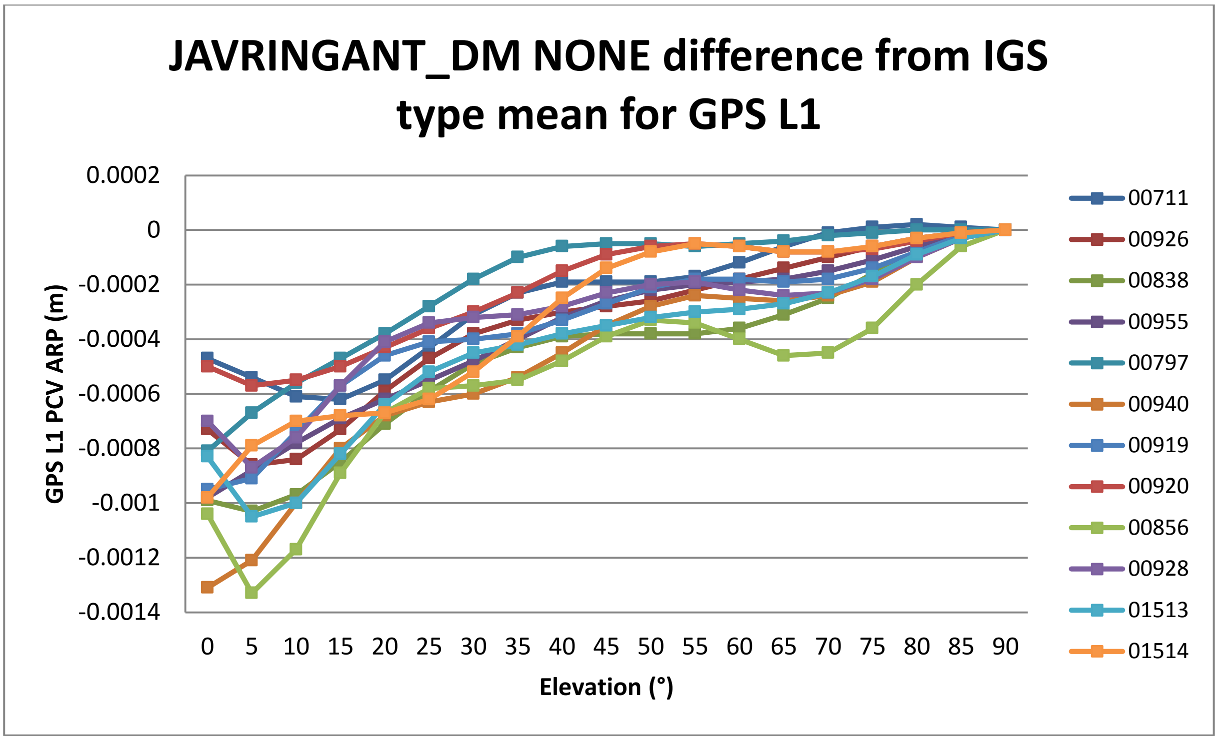

Figure 3. Individual calibration (denoted by serial number) elevation dependent differences from the IGS type mean for 12 JAVRINGANT_DM NONE antennas for GPS L1.

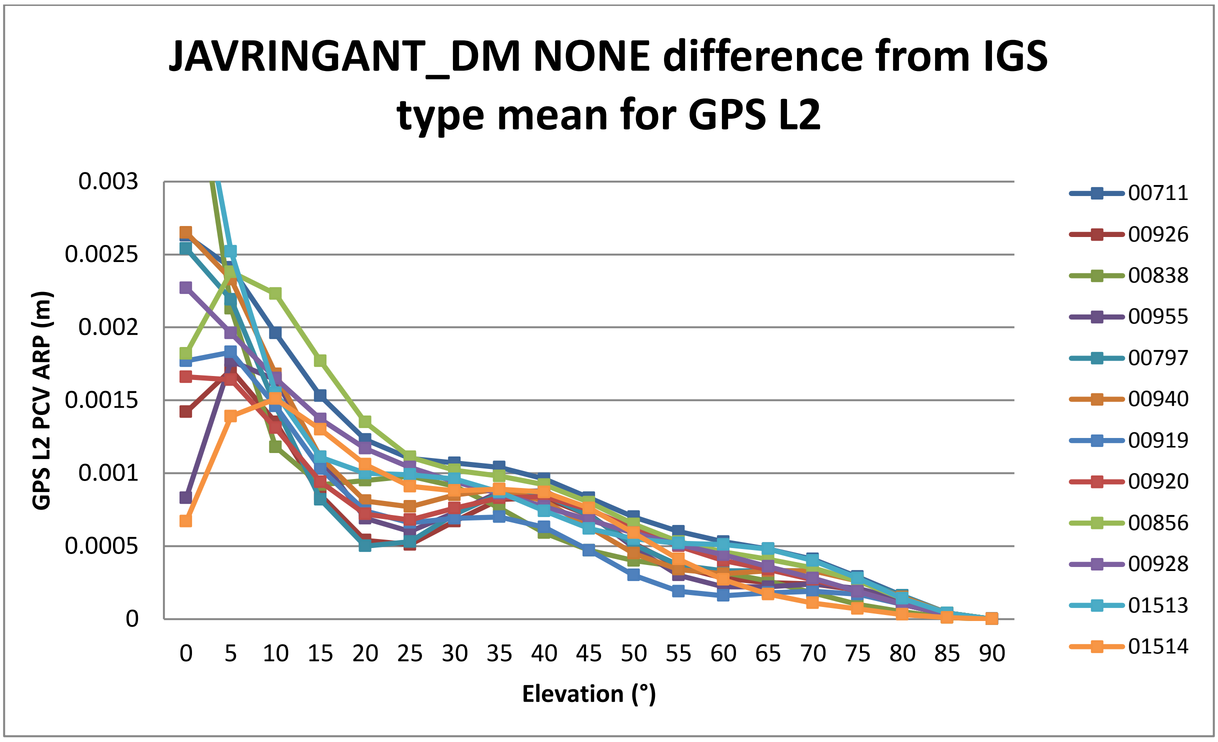

Figure 4. Individual calibration (denoted by serial number) elevation dependent differences from the IGS type mean for 12 JAVRINGANT_DM antennas for GPS L2.

To independently define the differences in phase centre corrections (PCC) between the IGS type mean and an individual calibration: the range (max and min) of the PCC differences and the root mean square (RMS) of the difference pattern, as described by Schon and Kersten (2014) are used. Figure 5 shows that the repeatability degrades with elevation angle for a Javad chokering antenna (JAVRINGANT_DM) and that the GPS L2 RMS is double the noise of GPS L1 where GPS L1 has a maximum of 0.18 mm and GPS L2 has a maximum of 0.4 mm. It was also found that there was no discernible difference between the repeatability of a calibration with or without a radome [NONE or SCIS] (results not shown here).

The increase in noise for the GPS L2 results can be due to a traditional bias by antenna designers to optimise the design for the GPS L1 frequency, and then to adapt the design for other frequencies. The tracking of GPS L1 carrier phase is inherently more precise than GPS L2, due to the wavelength of the observations. During the robotic calibration the robot has to force the loss-of-lock of observations between each manoeuvre. The time to regain phase lock is faster on GPS L1 than GPS L2, allowing for more observations to be collected on GPS L1 than GPS L2, which will usually decrease the standard deviation of the L1 observations.

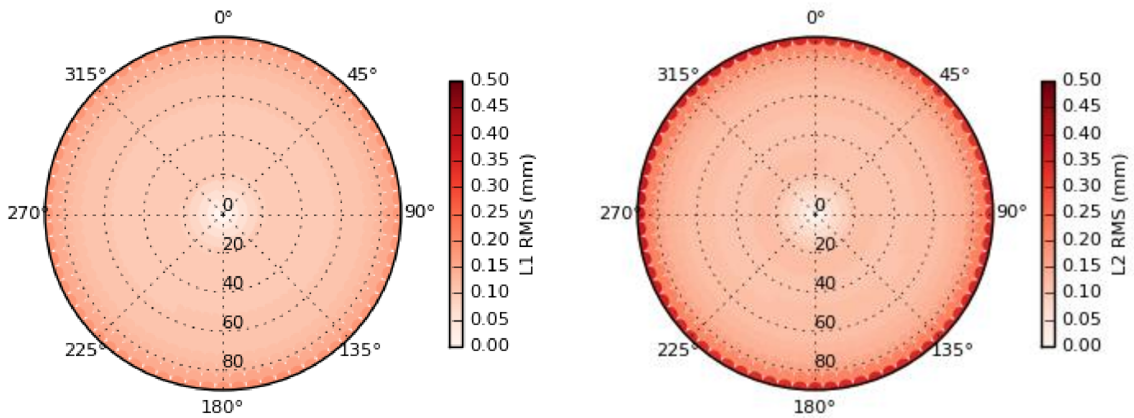

Figure 5. Root mean square error for the difference between the calibration-mean and individual calibrations of JAVRINANT_DM NONE for GPS L1 (left) and L2 (right).

3. EFFECT AND APPLICATION OF ANTENNA CALIBRATIONS

There is an Australian GNSS CORS (4 character ID: MRO1) located at the Murchison Radio Observatory in Western Australia. The CORS was established in October 2013 and has a 1.6 m concrete monument attached to bedrock with a stainless steel pillar plate, as shown in Figure 6. The TRM59800.00 [sn: 5220354494] was calibrated at Geoscience Australia before being installed at the site. The site log and RINEX files for MRO1 are available on the Geoscience Australia Public FTP: ftp://ftp.ga.gov.au/geodesy-outgoing/gnss.

Figure 6. MRO1 CORS, Western Australia.

Two separate processing runs have been analysed in which all processing options are identical except for the receiver antenna calibration. Daily solutions were processed using Bernese GPS Processing Software version 5.0 over a 12 month period [27/10/2013 - 25/10/2014 (GPS weeks 1764 - 1815)] for a small network of Australian sites, listed in Table 3. IGS final GPS satellite ephemerides and earth orientation parameters were used in the analysis. The double-differenced carrier phase observables at 30-second epoch intervals were used for GPS data processing. Other measurement modelling and parameter estimation included:

- Receiver clock corrections;
- Absolute antenna phase centre corrections;
- Solid earth tide displacements;
- Ocean tide loading displacements;
- Elevation cut-off of 10° for all observations;
- QIF integer ambiguity resolution strategy;
- Elevation dependent observation weighting; and

- Troposphere zenith delays estimated at 1-hour intervals for all stations.

Station	DOMES number	GPS receiver type	GPS antenna type
MRO1	59913M001	TRIMBLE NETR9	TRM59800.00 NONE
ALIC	50137M001	LEICA GRX1200GGPRO	LEIAR25.R3 NONE
CEDU	50138M001	TRIMBLE NETR8	AOAD/M_T AUST
COCO	50127M001	TRIMBLE NETR8	AOAD/M_T NONE
DARW	50134M001	LEICA GRX1200GGPRO	ASH700936D_M NONE
HOB2	50116M004	LEICA GRX1200GGPRO	AOAD/M_T NONE
KARR	50139M001	TRIMBLE NETR9	TRM59800.00 NONE
KAT1	59968M001	LEICA GRX1200+GNSS	LEIAR25.R3 LEIT
NNOR	50181M001	SEPT POLARX4	SEPCHOKE_MC NONE
PARK	50108M001	JPS E_GGD	ASH701945C_M NONE
PERT	50133M001	TRIMBLE NETR9	TRM59800.00 NONE
STR2	50119M001	TRIMBLE NETR9	TRM59800.00 NONE
SYDN	50124M003	JPS E_GGD	ASH701945C_M NONE
TID1	50103M108	TRIMBLE NETR8	AOAD/M_T JPLA
TOW2	50140M001	LEICA GRX1200GGPRO	LEIAR25.R3 NONE
YAR2	50107M004	ASHTECH UZ-12	AOAD/M_T NONE

Table 3. List of stations and equipment installed at each site at the time of processing.

Final position offsets of MRO1 were obtained by taking the mean of the daily estimates over the specified time period. The mean difference between the two processing runs for ENU position estimates are given in Table 4. These results demonstrate a clear effect of the application of an individual antenna calibration on position estimates when compared with results of a processing run where the IGS type mean antenna calibration was applied.

	ΔE (mm)	**ΔN (mm)**	**ΔU (mm)**
Mean	4.56	2.72	-6.02
Standard Deviation	1.32	0.92	2.33
Minimum	-3.68	-4.32	-18.07
Maximum	12.28	8.61	8.27
Range	15.96	12.93	26.34

Table 4. Statistics of the position component differences for site MRO1. Where the differences relate to the application of individual calibration compared against the application of the IGS type mean calibration during processing.

As expected, the Up component demonstrates a larger variation than the horizontal components. The mean score for the East component where the individual calibration was used (μ=463937.5114, σ=20.41, N=361) was significantly larger than the scores for the East component where the type mean calibrations were used (μ=463937.5071, σ=20.36, N=362), using the two-sample t-test for equal variances, $t(721)=2.88$, $p<=0.004$. The mean score for the North component where the individual calibration was used (μ=7047112.9411, σ=15.54, N=361) was significantly larger than the scores for North component where the type mean calibrations were used (μ=7047112.9386, σ=15.84, N=362), using the two-sample t-test for equal variances, $t(721)=2.14$, $p<=0.03$. The mean score for the Up component where the individual calibration was used (μ=353.9909, σ=34.97, N=361) was significantly smaller than the scores for the Up component where the type mean calibrations were used (μ=353.9971, σ=35.03, N=362), using the two-sample t-test for equal variances, $t(721)=2.37$, $p<=0.017$.

4. CONCLUSIONS

Antenna calibrations are a method of providing an estimation of the characteristics of an antenna phase centre with a three-component offset as well as elevation and azimuth dependent variation corrections. The majority of calibrations in the IGS network are performed either by a field robotic system or in an anechoic chamber. The GNSS antenna calibration facility using the Geo++ system at Geoscience Australia is capable of providing results that are comparable with the IGS standard type mean calibration in addition to Geo++ individual calibrations.

Although it is common practice within the IGS network to use the IGS type mean antenna calibration, the MRO1 example highlights the importance of applying individual antenna calibrations wherever possible as already adopted in the European Permanent Network. A significant difference in East, North and Up position estimates has been observed between two processing runs where the only difference was the application of an individual antenna calibration at one site. Individual antennas can deviate from the IGS type mean due to manufacturing differences as well as effects due to electromagnetic coupling between the antenna and the monument which can cause a bias in position estimates if not accounted for.
Antennas for installation in the Australian CORS network managed by Geoscience Australia will be calibrated prior to installation and antennas will also be retroactively calibrated where they have been replaced and returned to Canberra (provided the antennas are still operational). This provides an opportunity to post-process position time series with an individual antenna calibration.

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