Hartebeesthoek Radio Astronomy Observatory (HartRAO) antenna axis offset determined by geodetic VLBI analysis and ground survey

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Abstract

In the Very Long Baseline Interferometry (VLBI) space geodetic technique, various station-specific error sources corrupt the observable VLBI delay. An antenna axis offset (AO) model is applied in the VLBI data analysis for antennas with non-intersecting rotational axes, such as the 26-m and 15-m antennas for the Hartebeesthoek Radio Astronomy Observatory (HartRAO). The a priori AO values recommended by the International VLBI Service for Geodesy and Astrometry (IVS) for use in geodetic VLBI data analysis are taken, where possible, from values measured in ground surveys. The a priori AO values used for the HartRAO antennas in geodetic VLBI analysis have been identified as possible sources of error. The a priori AO value of 6695.3 mm for the 26-m antenna originates from a 2003 co-locational ground survey, conducted before a major bearing repair in 2008, which could have changed the AO. The a priori AO value of 1495.0 mm for the 15-m antenna was determined in 2007 in only a preliminary GPS survey. In this study, the respective AO values of the HartRAO 26-m and 15-m antennas were estimated from a VLBI analysis using the Vienna VLBI and Satellite Software (VieVS) and compared with measurements from co-locational ground surveys. It was found that the VLBI estimated values do not agree within the formal margins of error with the ground survey values, in that they differ by up to eight millimetres (8 mm) for the 26-m antenna and up to five millimetres (5 mm) for the 15-m antenna. As the ground survey values are considered to be more accurate than the VLBI estimated values, a further investigation of the site-specific error sources that may be contaminating the accuracy of VLBI results is required.

Keywords: *antenna axis offset, geodetic VLBI, geodetic VLBI analysis, co-location survey*

1. Introduction

The Hartebeesthoek Radio Astronomy Observatory (HartRAO) station forms part of a global network of stations that monitor Earth system processes. At the HartRAO, the long-term monitoring of these processes is conducted by applying four major space geodetic techniques, namely, Very Long Baseline Interferometry (VLBI), Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) from the very same site to provide a trusted long-term data series. The co-location of the four space geodetic techniques makes the HartRAO one of only twelve fiducial geodetic sites worldwide (GGOS, 2022). It is also the only fundamental station in Africa. Located on the African continent, as well as in the Southern Hemisphere, the position of the station is of strategic importance in the worldwide space geodesy network (Combrinck and Combrink, 2004).

The 26-m and 15-m radio antennas of the HartRAO regularly participate in astrometric and geodetic VLBI sessions, and contribute to the following: (1) the realisation of the International Celestial Reference Frame (ICRF); (2) the establishment and maintenance of the International Terrestrial Reference Frame (ITRF); (3) the linking of these reference frames by observing the full set of Earth Orientation Parameters (EOP); and (4) the unique provision of directly measuring nutation parameters and variations in the Earth's rotational angle, UT1-UTC (Schuh and Böhm, 2013). Geodetic VLBI also provides the VLBI reference point for the 26-m antenna of the HartRAO which serves as the reference point for other co-located instruments, such as the 15-m antenna, as well as SLR and GNSS stations on site, and also as a reference datum (Hartebeesthoek94 datum) for South Africa's national geodetic survey system (Combrinck et al., 2015).

Astrometric VLBI allows for the determination of the precise and accurate positions of extragalactic radio sources at the sub-milliarcsecond (nanoradian) level. In its turn, Geodetic VLBI is used for determining the positions of radio antennas in the global network at an accuracy level of several millimetres and their velocities at an accuracy level of several millimetres per decade. The positions and velocities can be inferred from the difference in the arrival time of a radio signal emitted by an extragalactic radio source, such as a quasar (quasi-stellar object), at the different antennas forming the baseline. This geometric delay, together with additional contributions, which affect the propagation of the radio wave or that change its path, constitutes the primary observable ………….. of the geodetic/astrometric VLBI, namely, the group delay. In its turn, this observable delay is corrupted by various station-specific structural, instrumental and propagation error sources, degrading the accuracy of the astrometric/geodetic VLBI results (Schuh and Behrend, 2012).

A next generation astrometric/geodetic VLBI system, the VLBI Global Observing System (VGOS, Schuh and Behrend, 2012), is currently being introduced worldwide to form part of the Global Geodetic Observing System (GGOS), which aims to combine the major geodetic techniques into a single highly accurate observing system (Gross et al., 2009). In order for the HartRAO to contribute to VGOS and meet the accuracy requirements of one millimetre in the station position and one millimetre/decade in the station velocity (Niell et al., 2005), as well as to continue participating in the realisation of the ICRF, station-specific error sources have to be eliminated or at least minimised.

One such possible source of error is the antenna's axis offset (AO). The VLBI reference point of an antenna, to which astrometric/geodetic VLBI observables are referred, is a point within the antenna which is fixed and invariant to the antenna's rotation. It is located at the intersection of the antenna's two rotational axes. In cases where the rotational axes do not physically intersect, such as for the HartRAO 26-m and 15-m antennas, the VLBI reference point is represented by the intersection of the antenna's fixed primary axis with the plane perpendicular to it containing the moving secondary axis, i.e. the point on the primary axis closest to the secondary axis (Combrinck and Merry, 1997). The antenna AO is the distance between the VLBI reference point and the secondary axis, and if the VLBI reference point is to be determined accurately, it must be known with high accuracy. As the antenna AO contributes to the observed delay, it needs to be considered in the VLBI analysis. In order to correct for the additional delay caused by the antenna's AO, an antenna AO model is applied for antennas with non-intersecting rotational axes (Krásná et al., 2014).

An error in the value of the antenna AO would degrade the accuracy of the station's positional estimates, displacing the VLBI reference point, which defines the station's location. Nilsson et al. (2017) showed that the antenna AO and station coordinates are highly correlated, with an error of one centimetre in the AO of an azimuth-elevation mount antenna, thus causing an error of ~1.3 cm in the estimated vertical station coordinate. Although the AO is considered to be fixed, major antenna repairs, such as a bearing replacement on the 26-m antenna in 2010, could conceivably cause a change in the AO (Kurdubov and Skurikhina, 2010; Nilsson et al., 2017). The AO of the 15-m antenna has been measured in a preliminary Global Positioning System (GPS) survey only. At the HartRAO, the 26-m legacy antenna's VLBI reference point serves as the reference point for other co-located instruments (e.g. the 15-m antenna) and a soon-to-become operational VGOS antenna. For accurate astrometric/geodetic VLBI results, the VLBI reference point, i.e. the station coordinates of the co-located antennas, and thus their AOs, have to be known with high accuracy. In order to reach the GGOS/VGOS goal of a one millimetre accuracy level in the station coordinates, the AO needs to be known with sub-millimetre accuracy (Nilsson et al., 2017).

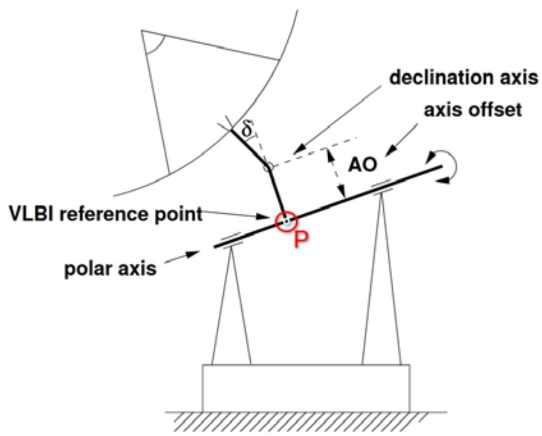
Stations are required to conduct terrestrial surveys to measure the AO accurately (IERS, 2005). The AO values obtained from VLBI analysis are usually compared with these ground survey values, which are, in general, considered to be the more accurate (Nilsson et al., 2017). Owing to the large number of measurements that can be taken over a short period, the stations performing the measurements during co-locational surveys have an accuracy at the one millimetre level, and precision at the sub-millimetre level. The IVS therefore recommends, wherever available, the use of AO values determined in ground surveys as a priori AO values in the VLBI analysis.

Such surveys are, however, knowledge- and resource-intensive and are therefore not conducted on a regular basis. It is therefore important to establish whether it is possible to estimate, with the required level of accuracy, the AO in geodetic VLBI analyses. In this study, the geodetic VLBI analysis software, VieVS (Böhm et al., 2018), was used to analyse data from global geodetic sessions in which the HartRAO 26-m and 15-m antennas participated in order to obtain estimations of the respective AO values for each of the antennas. The VieVS-estimated antenna AO values were subsequently compared with the values measured in the relevant ground surveys.

2. Methodology

The rotational axes of the HartRAO 26-m equatorially mounted Cassegrain antenna do not intersect and an AO of approximately 6.7 m exists. Its VLBI reference point is represented by the intersection of the fixed hour angle (HA) axis, with the perpendicular plane containing the moving declination (Dec) axis (as illustrated in Figure 1(b)). For the equatorially mounted 26-m antenna, this AO produces a time delay, $\Delta\tau_{AO}$, dependent on the declination of the radio source, δ, as follows (Nothnagel, 2019):

$$\Delta\tau_{AO} = \frac{1}{c} \cdot AO \cdot \cos\delta \qquad [1]$$

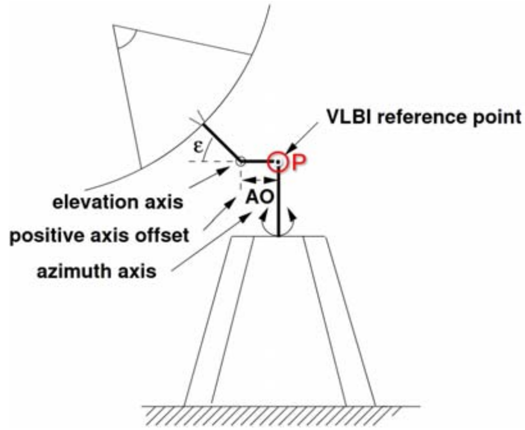


(a) (b)

Figure 1. (a) Image of the HartRAO 26-m equatorially mounted antenna with non-intersecting hour angle (HA) / polar and declination (Dec) axes. (b) Schematic drawing indicating the antenna axis offset (AO) of a polar mounted antenna to be the distance between the VLBI reference point (P) and the declination (Dec) axis. (Nothnagel, 2019)

The rotational axes of the HartRAO 15-m azimuth-elevation (az-el) mounted antenna do not intersect, and an AO of approximately 1.5 m exists. Its VLBI reference point is represented by the intersection of the fixed azimuth axis with the perpendicular plane containing the moving elevation axis (as illustrated in Figure 2(b)). For the az-el mounted 15-m antenna, this AO produces a time delay, $\Delta\tau_{AO}$, dependent on the pointing elevation angle, ε, as follows (Nothnagel, 2019):

$$\Delta\tau_{AO} = \frac{1}{c} \cdot AO \cdot \cos\varepsilon \qquad [2]$$



(a) (b)

Figure 2. (a) Image of the HartRAO 15-m azimuth-elevation (az-el) mounted antenna with non-intersecting azimuth and elevation axes. (b) Schematic drawing indicating the antenna axis offset (AO) of an az-el mounted antenna to be the distance between the VLBI reference point (P) and the elevation axis. (Nothnagel, 2019)

The geodetic VLBI analysis software, VieVS (Böhm *et al*., 2018), was used for data analysis. The software makes use of the VLBI delay observables to estimate the parameters of interest in a least-squares adjustment. Geodetic VLBI data from 1482 sessions, observed by 77 IVS network stations (Nothnagel *et al.*, 2017) over the period 1986–2017, in which the HartRAO 26-m and/or 15-m antennas participated, were used in the solutions of the combined geodetic VLBI sessions (global solutions) in VieVS. Data analysis consisted of processing sessions individually in single session analyses with VieVS to remove clock breaks, set reference clocks, exclude defective stations, baselines, observations and/or station cable calibration, and to eliminate outliers where necessary. Normal equations, which serve as inputs to the global solutions, were generated with *a priori* modelling, in general following the IERS Conventions 2010 (IERS, 2010) and parametrisation, as presented in Table 1. The normal equations of the single sessions were then combined to derive global solutions in which the antenna AO, station coordinates and velocities were estimated as global parameters for the period under investigation. The terrestrial datum was realised by applying No-Net-Translation (NNT) and No-Net-Rotation (NNR) constraints to the coordinates of the established stations. Positional discontinuities were introduced where station coordinates had changed as a result of seismic events or the relocation or the repair of an antenna.

For the 26-m antenna, the AO value was estimated for the following sessions: (1) from the start of the 26-m antenna's operation in 1986 until the critical bearing failure in October 2008; (2) for sessions subsequent to the bearing replacement in August 2010 to the end of 2017; and (3) for the entire period from 1986 to 2017. For the 15-m antenna, the AO value was estimated for sessions from the start of the 15-m antenna's operation in October 2010 to the end of 2017. The *a priori* AO values used in the VLBI analysis are as recommended by the IVS. For the HartRAO 26-m antenna, the *a priori* AO value of 6695.3 mm is based on the value determined in a 2003 co-locational survey (IGN, 2005). For the HartRAO 15-m antenna, the *a priori* AO value of 1495.0 mm is based on the value determined in a GPS survey in 2007 (HartRAO, n.d.). The VieVS-estimated antenna AO values from the various investigations were subsequently compared with the AO values determined in the following surveys: (1) the 2003 co-locational survey for the 26-m antenna, (2) the 2007 GPS survey for the 15-m antenna and (3) a 2014 co-locational survey (Muller *et al*., 2020) for both the HartRAO antennas. Owing to the re-processing of the 2014 co-locational survey data, the 2014 AO survey values for both the HartRAO antennas were not available for inclusion as *a priori* AO values for the VLBI analysis in the ITRF2020 computation.

Table 1. Models applied and parameters estimated in the single session analysis in VieVS

VieVS3.2 Input parameters	
Models:	
TRF	ITRF2020 (Altamimi *et al*., 2022)
CRF	ICRF3SX (Charlot *et al*., 2020)
Ephemerides	JPL 421 (Folkner *et al*., 2009)
ZHD and ZWD mapping function	VMF3 (Landskron and Böhm, 2018)
Solid Earth tides	IERS Conventions (IERS, 2010)
Tidal ocean loading	TPXO72 (Egbert and Erofeeva, 2002)
Tidal atmosphere loading	APL_VIENNA (Wijaya *et al*., 2013)
Non-tidal atmosphere loading	APL_VIENNA (Wijaya *et al*., 2013)
Pole tide	IERS Conventions (IERS, 2010)
Ocean pole tide loading	Desai (2002)
Thermal antenna deformation	Nothnagel (2009)
EOP	14C04 (IAU2000) (Bizouard *et al*., 2019)
Ocean tide loading	IERS Conventions (IERS, 2010)
Precession/nutation	IAU 2006/2000A (Captaine *et al*., 2003, Mathews *et al*., 2002)

VieVS3.2 Estimated parameters	
Estimation – Least squares:	
ZWD	interval = 0.5 h, constraints = 1.5 cm/h
Troposphere north and east gradients	interval = 3 h, relative constraints = 0.05 cm/6h, absolute constraints = 0.1 cm
Clock	interval = 1 h, constraints = 1.3 cm/h
EOP	interval = 1 day, constraints = 10^{-4} mas/day

During the co-locational surveys, an indirect method was used to determine the antenna's VLBI reference point and AO (IGN, 2005; IERS, 2005; Muller *et al*., 2020). Targets mounted on the rotational axes were measured by the total stations whilst the antenna was being moved about one rotational axis, with the other axis held fixed in a specific position, for several different positions. The targets traced an arc in a circular plane normal to the axis being measured. The axis intersects the plane in the centre of the circle. By finding the axis intersection and centre of the circle, the VLBI reference point and the antenna's AO could be determined. The circle-fitting approach was also used in the 2007 differential GNSS survey. However, in this case, baseline measurements were performed by using a fixed GNSS antenna as base station, together with a roving antenna mounted with a gimbal at the vertex of the 15-m antenna's quadripod. Whilst moving the antenna according to either the azimuth or the declination, the other axis was held fixed (Combrink, personal communication, October 2022; Combrinck and Merry, 1997). Thus, multiple baselines were computed with the 15-m antenna in different orientations to determine the circle centres, their positional differences being determined as the respective AO values.

The antenna AO values for the HartRAO 26-m and 15-m antennas, as determined by the ground survey, are displayed in Table 2. There is good agreement between the AO values determined for the 26-m antenna by the following surveys: (1) conventional and GPS surveys well before the failure and replacement of the bearing in 2008–2010 (Combrinck and Merry, 1997); (2) a co-locational survey in July and August of 2003 (IGN, 2005), five years before bearing failure; and (3) a co-locational survey in February of 2014 (Muller *et al.*, 2020), less than four years after the bearing was replaced and operations on the 26-m antenna were resumed in August of 2010. In contrast, the AO value determined for the 15-m antenna by the GPS survey in 2007 (HartRAO, n.d.), well before the start of the geodetic VLBI observations on that same antenna in 2012, and that was determined by the co-locational survey of 2014, differed by ~5 mm. The formal error pertaining to the AO value measured in the GPS survey is unknown, but it should have been at the several millimetre level (~3–5 mm; Combrink, personal communication, October 2022); therefore, the 2007 GPS survey value could ultimately be in agreement with the AO value determined from the 2014 co-locational survey and within the formal margin of error.

Table 2. HartRAO 26-m and 15-m antenna axis offset (AO) values determined by ground surveys (26m *a priori* AO = 6695.3 mm; 15m *a priori* AO = 1495.0 mm)

Survey method	Determined by (year of survey)	AO (mm)
<u>26m before bearing failure</u>:		
Conventional survey	M. Newling (in 1990)	6695 ± 3
HartRAO GPS	L. Combrinck (in 1995)	6695.6 ± 2.3
Local tie survey	IGN (in 2003)	6695 ± 2.5
<u>26m after bearing replacement</u>:		
Local tie survey	Muller, Pesce & Collilieux (in 2014)	6694.5 ± 0.7
<u>15m</u>:		
GPS survey	A. Combrink (in 2007)	1495
Local tie survey	Muller, Pesce & Collilieux (in 2014)	1490.1 ± 1.3

In this paper, three global solution tests were conducted in which the AO estimation was treated differently for stations other than the HartRAO to determine which of the following approaches would produce the VieVS-estimated AO results for the HartRAO antennas closest to their 2014 co-locational survey values:

i. T1: global solution in which the AO was estimated for the two HartRAO antennas only
ii. T2: global solution in which the AO was estimated for all participating stations except for those with *a priori* AO values based on ground survey values
iii. T3: global solution in which the AO was estimated for all participating stations

A further test was conducted to investigate a possible change in the AO of the 26-m antenna as a result of the bearing replacement during the 2008–2010 period. Sessions from the entire period (1986–2017) in which the 26-m antenna participated were analysed in groupings of 30 consecutive sessions to avoid the artificial separation and comparison of older data from the period prior to bearing failure and later data for the period subsequent to bearing replacement. The antenna AO was estimated in the context of a global solution for each of the session groupings. Given the limited time span of an individual session grouping, station velocities could not be estimated but were fixed to their ITRF2020 values.

3. Results and Discussion

In Table 3, the AO values estimated with VieVS for the 26-m and 15-m antennas in the current study are compared with the ground survey values. For all the investigations, the test in which the respective antenna AO values were estimated for all participating stations (T3) provides for the smallest difference between the VieVS-estimated AO values for the 26-m and 15-m antennas and the AO values determined in the ground surveys. Henceforth, results from T3 are thus used for comparisons with the ground survey values.

For the 26-m antenna, the AO values estimated in the current study for the entire period (1986–2017), as well as for the period before bearing failure and subsequent to bearing replacement, do not agree within the formal margin of error with either the 2003 co-locational survey value determined before bearing failure (the *a priori* AO value currently in use) or the 2014 co-locational survey value determined after bearing replacement. For the 15-m antenna, although the VieVS-estimated AO value agrees within the formal margin of error with the AO value determined by the GPS survey in 2007 (and thus the *a priori* AO value currently in use), it does not agree within the formal margin of error with the AO value determined in the 2014 co-locational survey and is several millimetres larger than this latest survey value.

Although the ground survey values are considered to be the more accurate, in the current study it is the VieVS-estimated AO values which display the smaller formal errors. These can be ascribed to unrealistic AO formal errors emanating from the VLBI global solutions of the three tests (T1, T2 and T3), possibly as a result of variations in the difference between the estimated and *a priori* AO values propagating into other parameters in the global solution. The induced correlations between the estimated parameters, which are not properly accounted for in the least-square analysis, have led to over-optimistic AO formal errors which are reflected by the estimated AO values for the three global solution tests and which do not agree within the formal margins of error.

For the 26-m antenna, the VieVS-estimated AO values are larger by several millimetres than both ground survey values for the entire period (1986–2017) and subsequent to bearing replacement, and by a few millimetres for the period prior to bearing failure. The VieVS-estimated AO values for the 26-m antennafrom the period before bearing failure and the period after bearing replacement differ by ~5 mm from each other. The particularly large difference in the AO value for the 26-m antenna between the VieVS-estimated AO value after bearing replacement and the 2003 co-location survey value before bearing failure (~7 mm) could be ascribed to a change in the position of the station arising from the failure of the bearing and its replacement that contributed to the AO estimation. The 2003 co-locational survey value is, however, corroborated by the 2014 co-locational survey value determined after bearing replacement. The measurements of the AO during the co-locational surveys before bearing failure in July and August of 2003 and after bearing replacement in February of 2014 indicate that no significant change occurred in the AO that could be attributed to the failed bearing and its replacement.

Table 3. HartRAO 26-m and 15-m antenna axis offset (AO) estimated with VieVS compared with ground survey values (26m *a priori* AO = 6695.3; 15m *a priori* AO = 1495.0 mm)

	VieVS-estimated AO values and formal errors (mm)					
	T1		**T2**		**T3**	
26m:						
1986-2017	6700.22	± 0.34	6700.82	± 0.34	6699.11	± 0.35
1986-2008	6698.59	± 0.41	6699.66	± 0.41	6697.12	± 0.43
2010-2017	6703.10	± 0.51	6703.07	± 0.52	6702.47	± 0.52
15m:						
2012-2017	1495.40	± 0.46	1495.48	± 0.46	1495.34	± 0.46

	AO determined by ground survey		
	Survey type	**AO survey value (mm)**	
26m:			
2003 (*a priori*)	Co-location	6695.3	
2014	Co-location	6694.5	± 0.7
15m:			
2007 (*a priori*)	GPS	1495.0	
2014	Co-location	1490.1	± 1.3

The differences between the VieVS-estimated and *a priori* AO values of the 26-m antenna for 35 groupings in 30 sessions for the entire period (1986–2017) - for the purpose of investigating the possibility of a change in the AO value of the antenna as a result of the bearing replacement - are displayed in Figure 3. The variation in the differences between the groupings for the 30 sessions is a good indicator for a more realistic margin-of-error measure compared to the over-optimistic formal errors from the global solutions of the three tests as mentioned above (e.g., the standard deviation for the differences (dAO) over the 26 groupings for 30 sessions prior to bearing repair is 4.77 mm). The data point indicated in blue represents the result for the session grouping which incorporates nine sessions from August 2008, just before the bearing failure, as well as 21 sessions from August 2010 (when the 26-m antenna resumed operations after bearing replacement) until February 2011. This result —dAO = 5.72 mm ± 1.16 —, as well as those for session groupings just before and after —, appears similar to the results for other session groupings and indeed shows less of a deviation from the *a priori* AO value than do the results for some of the other session groupings. This would seemingly confirm the agreement between the AO values for the 26-m antenna determined in the 2003 and 2014 co-locational surveys, before and after bearing replacement, respectively.

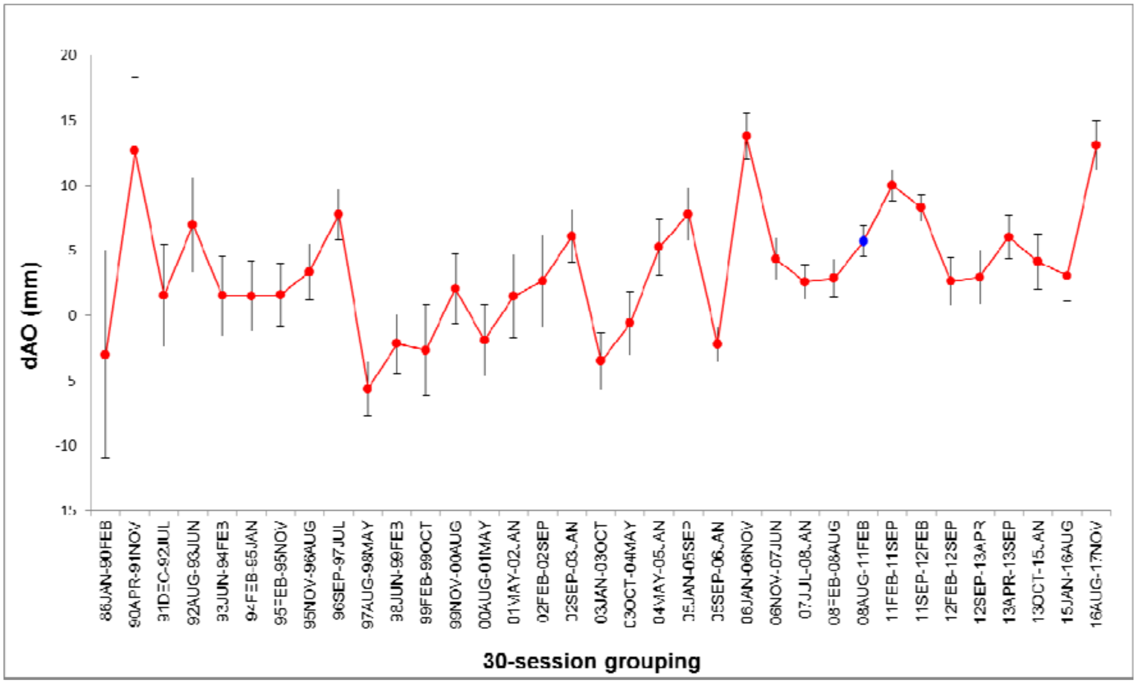


Figure 3. Differences (dAO) between the estimated AO and the *a priori* AO value (6695.3 mm) in respect of

the VieVS-estimated antenna axis offset (AO) for the 26-m HartRAO antenna for the 30 session groupings for the period 1986 – 2017

4. Conclusion

The antenna AO values estimated with VieVS in the case of the HartRAO 26-m and 15-m antennas do not agree within the formal margin of error with the values determined in a 2014 co-locational survey; they also disagree at the several millimetre level. However, it should be noted that the formal errors in respect of the estimated values are probably unrealistically small.

For the 26-m antenna, the AO estimated for the period prior to the bearing failure in 2008 differs by only 1.8 mm and 2.6 mm from the values determined in a 2003 co-locational survey before bearing failure and from a 2014 co-locational survey after bearing replacement, respectively. However, for the period subsequent to bearing replacement, from 2010 onwards, the estimated AO value differs by as much as 7.2 mm and 8 mm from the 2003 and 2014 co-locational survey values, respectively, and by ~5 mm from the value estimated for the period prior to bearing failure, which would indicate a possible change in AO as a result of bearing replacement. The displacement of Antenna AO as a result of the bearing replacement can, however, not be corroborated in terms of the estimated AO values for the 30-session groupings just before bearing failure and after bearing replacement; furthermore, it is also not reflected in the close agreement of the AO values determined in the 2003 co-locational survey before bearing failure and the 2014 co-locational survey after bearing replacement.

For the 15-m antenna, although the estimated AO value agrees within the formal margin of error with the value determined in a 2007 GPS survey, it differs by ~5 mm from the value determined in the 2014 co-locational survey. The formal margin of error of the AO value measured in the GPS survey is not available but should be ~3–5 mm. The 2007 GPS survey value could therefore concur with the 2014 co-locational survey AO value within the formal margin of error rather than with the AO value for the 15-m antenna that was estimated with the VieVS.

Typically, co-locational ground surveys are not conducted on a yearly basis and measurements are taken over a short period of time, usually over less than a month, and also at a specific time of the year when conditions are favourable. More than a decade separates the two most recent such surveys at the HartRAO with more than eight years having passed since the 2014 co-locational survey. Ground surveys are therefore not able to capture any variations over a continuous period of time.

An automated total station is currently being implemented at the HartRAO. It will support the continuous measurement of the AOs and VLBI reference points of the HartRAO antennas and should contribute significantly to investigations into the possible correlation of antenna AOs with station position, tropospheric delay, clock parameters, structural deformation, hydrology loading, etc. In a synthesis network, containing both VLBI and continuous automated total station measurements, one should be able to identify technique-dependent parameters that adversely affect the accuracy of either VLBI or total station measurements.

It is clear that the VLBI technique has the potential to solve for AO to a high degree of accuracy. However, it is also clear that there is room for improvement, and further work should therefore be done on improving AO modelling within the VieVS. The operation of the automated total station, together with ground surveys, meteorological monitoring and VLBI solutions, will continue at the HartRAO in order to build up a time series of data that will allow site-specific errors to be minimised or eliminated over time. Temporal studies of site-specific error sources, such as ground subsidence, antenna deformation, tropospheric and ionospheric delays and station clock bias, will contribute to more accurate VLBI results that would be able to meet the demand for GGOS accuracy.

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