Astronomical Calibration of the GMRT Antenna Positions

Jayaram N. Chengalur & Sanjay Bhatnagar

15/Jan/2001

Abstract

The positions of the GMRT antennas were measured via L band observations of celestial radio sources during several calibration runs in December 2000. This report describes the procedure followed and also lists the final calibrated antenna positions.

Historically, the GMRT antenna positions were first determined using theodolite measurements. These were refined using P band observations following the procedure laid down by Bhatnagar & Rao (1996). Later, dual frequency GPS measurements (Kulkarni et al. 1997) were done to independently determine the antenna co-ordinates. These GPS co-ordinates were then further refined using P band observations of celestial sources. The final set of co-ordinates were accurate to ~ 1 m for the arm antennas and ~ 0.2 m for the central square antennas. It is these positions that were then further refined using the current L band observations.

Earlier efforts at calibration using L band observations did not yield consistent results for the arm antennas. A series of sytematic observations obtained during the current session showed that the problems with the earlier observations were caused by an error in the precession routines used at GMRT. After correction of these routines, observations of several widely separated calibrator sources gave consistent solutions for the antenna positions.

Comparison of the newly determined co-ordinates with those measured using GPS show that the Y component of the baseline was measured to an accuracy of better than $\sim 0.1 - 0.2$ cm by the GPS observations. However there were errors of up to ~ 33 m in the X

and Z co-ordinates. These large errors appear to have arisen from problems with tying observations made on different days to a common reference point. The internal error for antennas measured in a given "occupation" is $\sim 0.1 - 0.2$ m even in the X and Z co-ordinates.

Even after correction of the antenna co-ordinates the phase of the distant arm antennas (although considerably more stable) still shows non negligible variation. Part of this may be due to atmospheric/ionospheric propagation effects, but it would probably be fruitful to check if there is any correlation between this residual phase variation and the round trip phase.

1 Introduction

The geometric phase, Φ_g, for a given antenna which is tracking a point source can be written as:

$$\Phi_g = \frac{2\pi}{\lambda} w = \frac{2\pi}{\lambda}[b_x \cos(h)\cos(\delta) - b_y \sin(h)\cos(\delta) + b_z \sin(\delta)] \qquad (1)$$

Where (b_x, b_y, b_z) are the antenna co-ordinates in a right handed cartesian co-ordinate system fixed on earth with Y pointing east and Z pointing towards the north pole (see eg. Thompson et al., 1986), h is the hour angle and δ the declination of the source being tracked. Note that some suitable reference position has been assumed in writing down equation (1). In the ideal case this geometric phase Φ_g is exactly compensated[1] by the instrumental phase Φ_i. In the real situation errors in compensation for Φ_g could arise for three reasons, viz.,

1. The antenna position is wrong, i.e. errors in b_x, b_y, and b_z, or
2. the time is wrong, i.e. an error in the hour angle h, or
3. the source position is wrong, i.e. errors in h and δ.

Assuming that that all of the above errors are small, we can expand equation (1) to first order to get the resulting phase error $\Delta\Phi = \Phi_g - \Phi_i$, viz.

$$\frac{\lambda}{2\pi}\Delta\Phi \quad = \quad (\Delta b_x - b_y \Delta h - b_x \tan(\delta)\Delta\delta)\cos(h)\cos(\delta)$$

[1] See Chengalur, 1998, for details on how this is achieved at the GMRT

$$-(\Delta b_y + b_x\Delta h - b_y\tan(\delta)\Delta\delta)\sin(h)\cos(\delta)$$
$$+(\Delta b_z + b_z\cot(\delta)\Delta\delta)\sin(\delta) \quad (2)$$

Note that Δh the error in the hour angle includes contributions from both an error in the time-keeping as well as an error in the source position. Procedures for solving for the error in time as well as the errors in antenna positions and source co-ordinates (assuming the time error to be constant for all sources and the other errors to be random) from observations of a large number of sources are described in, for eg. Thompson et al. (1986).

At the GMRT however the situation is considerably simpler. Time at the GMRT is kept to an accuracy of better than $\sim 100\mu$sec (see Singh, 1999), and at the highest frequency of operation (viz. L band) there are a large number of sources which are sufficiently point like and whose position is known to sufficient accuracy (Pereley & Taylor, 1999) so as to make the errors in Δh and $\Delta\delta$ negligible.

In situations like this, where the dominant source of error is in the antenna co-ordinates, equation (2) simplifies to

$$\frac{\lambda}{2\pi}\Delta\Phi = \Delta b_x\cos(h)\cos(\delta) - \Delta b_y\sin(h)\cos(\delta) + \Delta b_z\sin(\delta) \quad (3)$$

Because of this simplification, the following two stage strategy can then be used to solve for the GMRT antenna co-ordinates.

A The visibilities are measured for a sufficiently long track on a calibrator; it is important that the hour angle coverage be sufficient to distinguish between terms that vary as $\cos(h)$ and $\sin(h)$. The antenna based phases are derived from the measured visibilities by the usual self-calibration procedure. A function of the form

$$\phi = a_1\cos(h) + a_2\sin(h) + a_3 \quad (4)$$

is then fit to the antenna based phases. The constant term is meant to account for both the error in b_z as well as for the electronic and atmospheric phases (which are assumed to be constant throughout the observation). The errors in b_x and b_y are related to the fit parameters by

$$\Delta b_x = \frac{\lambda}{2\pi\cos(\delta)}a_1$$

$$\Delta b_y = \frac{\lambda}{2\pi\cos(\delta)} a_2 \qquad (5)$$

Note that as can be easily verified from equation (2), if this procedure is followed when the dominant source of error is poor time-keeping and not errors in the antenna co-ordinates, then for an antenna in the east or west arm the derived Δb_x will be proportional to b_y, i.e. will have the largest magnitude for the extreme east and extreme west antennas. For these antennas the magnitude of the derived Δb_x will also be much larger than that of derived Δb_y. This sort of error is hence very easy to identify.

B Once the b_x, b_y co-ordinates have been determined, the only remaining error is in b_z, and we hence have from eqn (3):

$$\frac{\lambda}{2\pi}\Delta\Phi = \Delta b_z \sin(\delta) \qquad (6)$$

If one observes a large number of sources with sufficiently different declinations, and fits a function of the form

$$\phi = a_4 \sin(\delta) + a_5 \qquad (7)$$

to the antenna based phases, then the error in b_z is related to a_4 by

$$\Delta b_z = \frac{\lambda}{2\pi} a_4 \qquad (8)$$

The positions of the GMRT antennas were measured using this two stage strategy.

2 Details

Astronomical determined antenna co-ordinates (using the two stage strategy as described by Bhatnagar & Rao (1996) and explained above) using the P band and L band were found to an accuracy of $\sim$ 0.1 m for the *central square antennas*. However the corrections derived for the distant arm antennas were larger and not repeatable. While it was clear that for a given source the antenna phases varied in a systematic and repeatable (at least on a time scale of a few days) way with hour angle, the derived antenna co-ordinates were not stable. It was unclear whether this was because of some systematic change in the delay produced in the fiber optic system or due to atmospheric phase or some more subtle effect. This report documents the latest attempt (which was made during the L band run during December 2000) to determine the GMRT antenna co-ordinates.

A long track on 3C286 was used as the starting point. The visibilities were decomposed into antenna based phases using `rantsol` (Bhatnagar, 1999) (see Appendix A for details). Each antenna based phase was then fit by a function of the form given in equation (4), and the corrections to b_x, b_y were derived from equation (5). The fits were done using the program `antpos`. This program (see Appendix B for details) directly reads the gain solutions generated by `rantsol`, allows interactive control of the windows to be used for fitting etc., and finally generates as output an *antsys.hdr* file. This *antsys.hdr* file is in the correct format as required by the data acquisition program[2] `acq30` for calculating the instrumental phase to be applied to each antenna. A subsequent observation of 3C286 using these corrected co-ordinates showed a considerable improvement in the phase stability; however observations of 3C48 using these corrected co-ordinates showed that the phases were once again winding very rapidly. From eqn (2) one sees that the phase can vary in a different way for different sources for two reasons:

1. The source co-ordinates are wrong (most likely because of some error in precession, since the sources being used for baseline calibration have well determined catalog positions), or,

2. There is an error in time keeping which is different for different sources.

Since it seemed unlikely that there was a variable time keeping error at the GMRT the remaining alternative was that the source position that was being used for computing the instrumental phase Φ_i was erroneous. Observations of a sequence of sources with declinations close to that of 3C286 but with right ascensions uniformly spaced between that of 3C48 and 3C286 showed that the phase grew more and more stable as one approached 3C286 (i.e. the source for which the baseline corrections were made). It seemed highly likely therefore that there was an error in the precession. After considerable discussions involving A. P. Rao, it was determined that the ONLINE system computes

[2] See Chengalur (1998) & Chengalur (2000) for more details.

the mean and not the apparent position of a given source. The mean position takes into account precession/nutation terms, while the apparent position additionally takes into account annual aberration (i.e. aberration caused by the motion of the earth around the sun). ONLINE was hence modified by A. P. Rao to compute the apparent position of the source. This error in precession corresponds to a maximum error of ~ 2 s of time which translates to an error of a maximum of ~ 0.1cm for central square antennas and ~ 1 m for the farthest arm antennas. This explains the residual errors in earlier co-ordinate measurements. The corrections found now for most of the antennas are also comparable to these numbers.

Corrections to the antenna (X, Y) co-ordinates were then derived using the source $0555 + 398$, which is listed in the VLA calibrator manual (Perley R. & Taylor G., 1999) as "P" for all arrays and as having no UV limits at L band . Subsequent observations of the sources $0022 + 002$, $1125 + 261$ and $0744 - 064$, (all of which are also "ideal" calibrators in the above sense[3]) all showed considerable improvement in the phase stability (see Figure 2).

It was found that the central square antennas and the inner arm antennas have fairly stable phase after this b_x, b_y correction (see Figure 1). However, the phase on the outer arm antennas, while improved, is not as stable as that on the closer antennas. The residual phase variation with hour angle is however not well fit with a sinusoidal function, (see Figure 2) and the derived baseline corrections are not stable from day to day (see Table 1). This residual phase[4] is hence unlikely to be due to a position error and could be either due to phase variations caused by atmospheric propagation or due to length changes in the optical fiber.

In principle length changes of the fiber can be detected using the program `fdelay` (which determines the instrumental delay by measuring the phase slope across the spectral band – see Appendix C for details). The scatter in the fixed delay measured by `fdelay` using a single lta record (i.e. an integration of ~ 30 s) `fdelay` is ~ 0.05 m. Should the accuracy be limited only by random noise, then increasing the averaging time should improve the accuracy and allow measurement of slowly varying systematic changes in the

[3]Note that both 3C48 and 3C286 have faint arc-second scale structure and hence are not the best sources for baseline calibration.

[4]Note that the residual phase is in general slowly varying, i.e. does not go through multiple 2π wraps during a single source track. One could hence monitor it by looking at the phase during the scans on phase calibrators done during regular interferometric observations.

fiber length. The fixed delay does appear to change in the course of a few hours (see Figure 3), however this change does not appear to be correlated with the length of the fiber, i.e. the extreme arm antennas do not in general show a greater variability in fixed delay than the central square antennas. The most extreme variation is for antenna E02, with magnitude ~ 2.5 m, and several antennas show variations of the order of $0.2 - 0.5$ m. If the fiber length truly changed by such large amounts, then one would expect to see many 2π phase wraps in the antenna phase, which one does not. It may hence be more appropriate hence to try and correlate the residual phase on the distant arm antennas with the round-trip phase measurements.

Once the first order correction to b_x, b_y was made the correction to the b_z co-ordinate was obtained by measuring the antenna based phase as a function of source declination (see equation (6)). Two sets of sources were used for this purpose, one with right ascensions around 07h and the other with right ascensions around 20h. The sources used are listed in Table 2. Each set was observed for several hours with the telescope cycling between the sources in that set. Once cycle consisted of a 5m scan on each source in the set. The derivation of the correction to b_z from the fit to the phase as a function of declination was again done using the program `antpos` (see Appendix B for details on how the program derives the b_z correction).

Antenna	Δb_x (m)			Δb_y (m)		
	0022+002	1125+261	0744-064	0022+002	1125+261	0744-064
S03	0.15	-0.08	0.08	-0.16	-0.10	-0.06
S04	0.18	-0.08	0.12	-0.21	-0.13	-0.07
E05	0.16		0.08	0.02		-0.01
E06	0.13	-0.02	0.09	0.09	-0.03	-0.01
W05	-0.25	-0.06	-0.11	0.18	0.11	0.03
W06	-0.36	-0.11	-0.13	0.15	0.13	0.02

Table 1: Residual b_x, b_y corrections on the arm antennas for different sources. The corrections are not stable from source to source, and are hence probably not due to an antenna positional error.

The central square antennas as well as the inner arm antennas showed a systematic linear variation of phase with $\sin(\delta)$. The derived Δb_z correction

Source	RA (J2000)	Dec (J2000)	Source	RA (J2000)	Dec (J2000)
$0828-375$	$08^h28^m04.8^s$	$-37^o31'06.3''$	$2022+616$	$20^h22^m06.68^s$	$+61^o36'58.8''$
$0735-175$	$07^h35^m45.8^s$	$-17^o35'48.4''$	$2023+544$	$20^h23^m55.84^s$	$+54^o27'35.8''$
$0820-129$	$08^h20^m57.5^s$	$-12^o58'59.2''$	$2052+365$	$20^h52^m52.05^s$	$+36^o35'35.3''$
$0725-009$	$07^h25^m50.7^s$	$-00^o54'56.5''$	$2025+337$	$20^h25^m10.84^s$	$+33^o43'00.2''$
$0739+016$	$07^h39^m18.0^s$	$01^o37'04.6''$	$2035+189$	$20^h35^m33.98^s$	$+18^o57'05.4''$
$0825+031$	$08^h25^m50.3^s$	$03^o09'24.5''$	$2148+069$	$21^h48^m05.46^s$	$+06^o57'38.6''$
$0745+101$	$07^h45^m33.1^s$	$10^o11'12.7''$	$2130+050$	$21^h30^m32.88^s$	$+05^o02'17.5''$
$0738+177$	$07^h38^m07.4^s$	$17^o42'19.0''$	$2136+006$	$21^h36^m38.59^s$	$+00^o41'54.2''$
$0842+185$	$08^h42^m05.1^s$	$18^o35'41.0''$	$2011-067$	$20^h11^m14.22^s$	$-06^o44'03.6''$
$0741+312$	$07^h41^m10.7^s$	$31^o12'00.2''$	$2146-154$	$21^h46^m22.98^s$	$-15^o25'43.9''$
$0713+438$	$07^h13^m38.2^s$	$43^o49'17.0''$	$2206-185$	$22^h06^m10.41^s$	$-18^o35'38.8''$
			$2214-385$	$22^h14^m38.57^s$	$-38^o35'45.0''$

Table 2: List of L band VLA calibrators used for b_z calibration

(see eqn (7)), was in good agreement for both sets of sources and the phase stability after correcting for this error is considerably improved (see Figure 4). The outer arm antennas however did not show any clear linear trend of phase with $\sin(\delta)$ and hence no b_z correction could be derived for these antennas.

3 Current Status

The current status of the baseline calibration is summarized in Table 3, the co-ordinates themselves are given in Table 4. The status is codified as follows:

'o': The co-ordinate has been updated and the phase stability is now ok.

'r': The co-ordinate has been updated and but there is still a non negligible residual phase variation.

'u': The co-ordinate has been updated and but the phase stability could not been verified because of antenna availability constraints.

'-': The co-ordinate could not be checked because of antenna availability constraints.

Antenna	b_x, b_y	b_z	Antenna	b_x, b_y	b_z
C00	o	o	E03	-	-
C01	o	o	E04	r	r
C02	o	o	E05	r	r
C03	u	-	E06	r	r
C04	o	o	S01	-	-
C05	o	o	S02	u	-
C06	o	o	S03	r	r
C08	o	o	S04	r	r
C09	o	o	S06	-	-
C10	o	o	W01	u	-
C11	o	o	W02	o	o
C12	o	o	W03	o	o
C13	o	o	W04	r	r
C14	o	o	W05	r	r
E02	o	o	W06	r	r

Table 3: Status of the antenna co-ordinate calibration. Please see the text for the meaning of the status codes.

4 Comparison with GPS measurements

The positions of the GMRT antennas were measured using dual frequency GPS measurements by Kulkarni et al. (1997). Their final co-ordinates are presented[5] in the ITRF reference frame in the form of a (ϕ, λ, h) (i.e. latitude, longitude, height) set for each antenna. These were converted to ECEF (earth centered earth fixed) co-ordinates using the usual transformation (see eg. Hofmann-Wellenhof 1992) from ellipsoid to Cartesian co-ordinates viz.

$$\begin{aligned} X &= (N+h)\cos\phi\cos\lambda \\ Y &= (N+h)\cos\phi\sin\lambda \\ Z &= (\frac{b^2}{a^2}N+h)\sin\phi \end{aligned} \tag{9}$$

[5] In Appendix 4 of Kulkarni et al. (1997)

where a, b ($a = 6378137$ m, $b = 6356752.31$ m see[6] Hofmann-Wellenhof et al. (1992) pp 31) are the ellipsoid parameters and

$$N = \frac{a^2}{\sqrt{a^2 \cos^2 \phi + b^2 \sin^2 \phi}}$$

To convert to the same reference system as used at the GMRT, these ECEF co-ordinates were rotated by 74.05 degrees about the Z axis, and then the position of C02 was taken as the reference. That is, in the GMRT reference system, the b_x, b_y, b_z co-ordinates are:

$$\begin{aligned} b_x &= (X - X0)\cos(l) + (Y - Y0)\sin(l) \\ b_y &= (Y - Y0)\cos(l) - (X - X0)\sin(l) \\ b_z &= (Z - Z0) \end{aligned} \qquad (10)$$

where $l = 74.05^o$, i.e. the reference longitude at the GMRT, and $(X0, Y0, Z0)$ are the ECEF co-ordinates of C02. These "GPS" co-ordinates are given in Table 5

On comparing the values in Table 5, to those in Table 4, one finds that the b_y co-ordinates are in good agreement (i.e. better than ~ 0.2 m) while the b_x and b_z co-ordinates show differences of up to ~ 30 m. The differences between the co-ordinates for the different antennas are shown in Figure 5. As can be seen, the errors are not random, but several groups of antennas have very similar errors. The grouping of the errors is identical to the grouping done at the time the GPS observations were made, (i.e. the antennas which form a particular "occupation" in Kulkarni et al. 1997 have very similar errors). It appears likely that the GPS co-ordinates have an error caused by an improper conversion to the reference position.

Acknowledgments: Extremely fruitful discussions with A. P. Rao & V. K. Kulkarni are gratefully acknowledged.

[6]This reference lists the ellipsoid parameters for the WGS-84 system, but these are the as the ITRF parameters, see eg. Seidelmann (1992) pp 223.

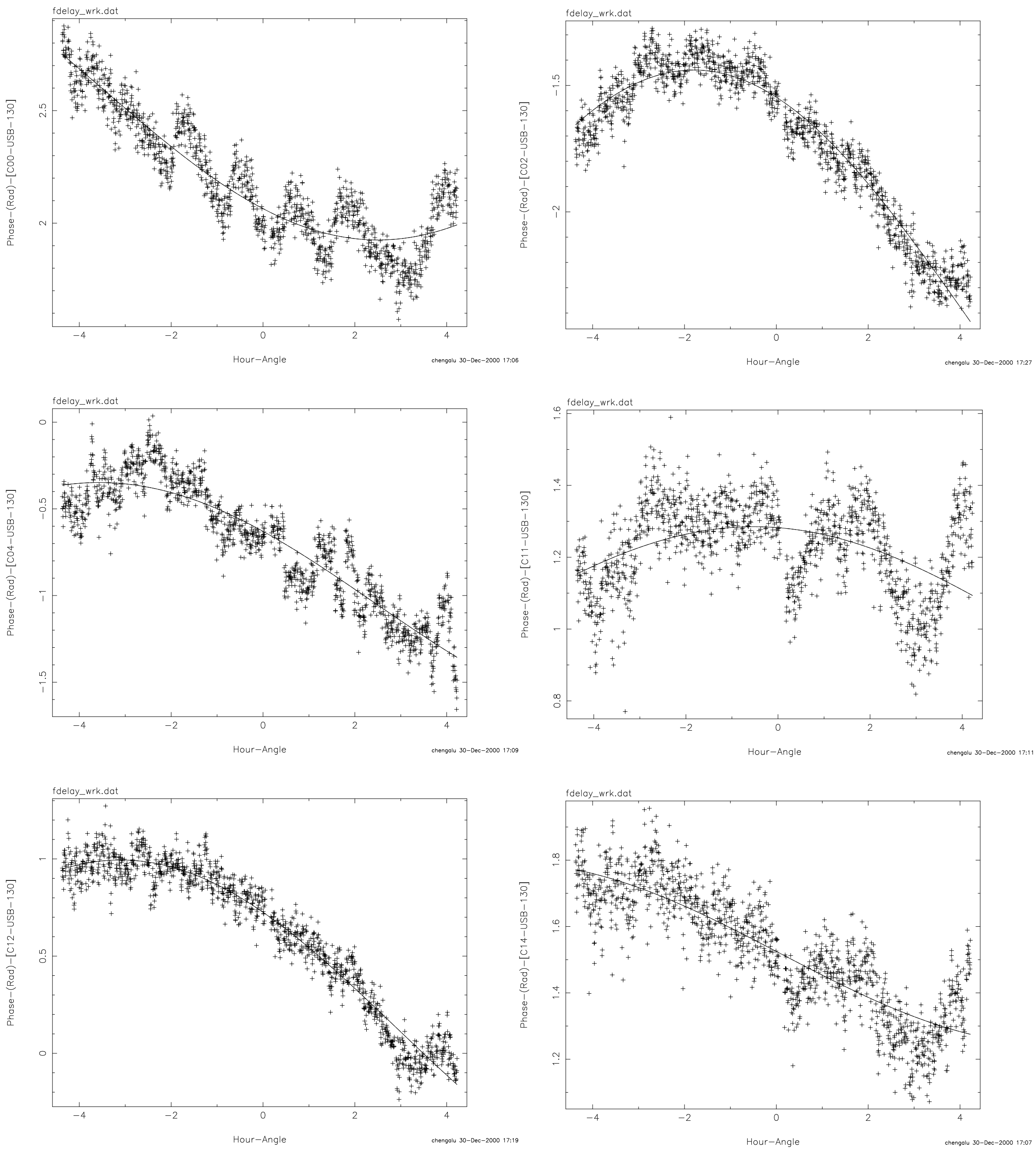

Figure 1: Antenna based phase as a function of hour angle (after correction for antenna position errors) for various central square antennas. The overlaid curves are fits for residual antenna position errors. The magnitude of the errors is $\leq 2-3$ cm. While this is a reasonably good fit to the data the derived position errors do not repeat for different sources.

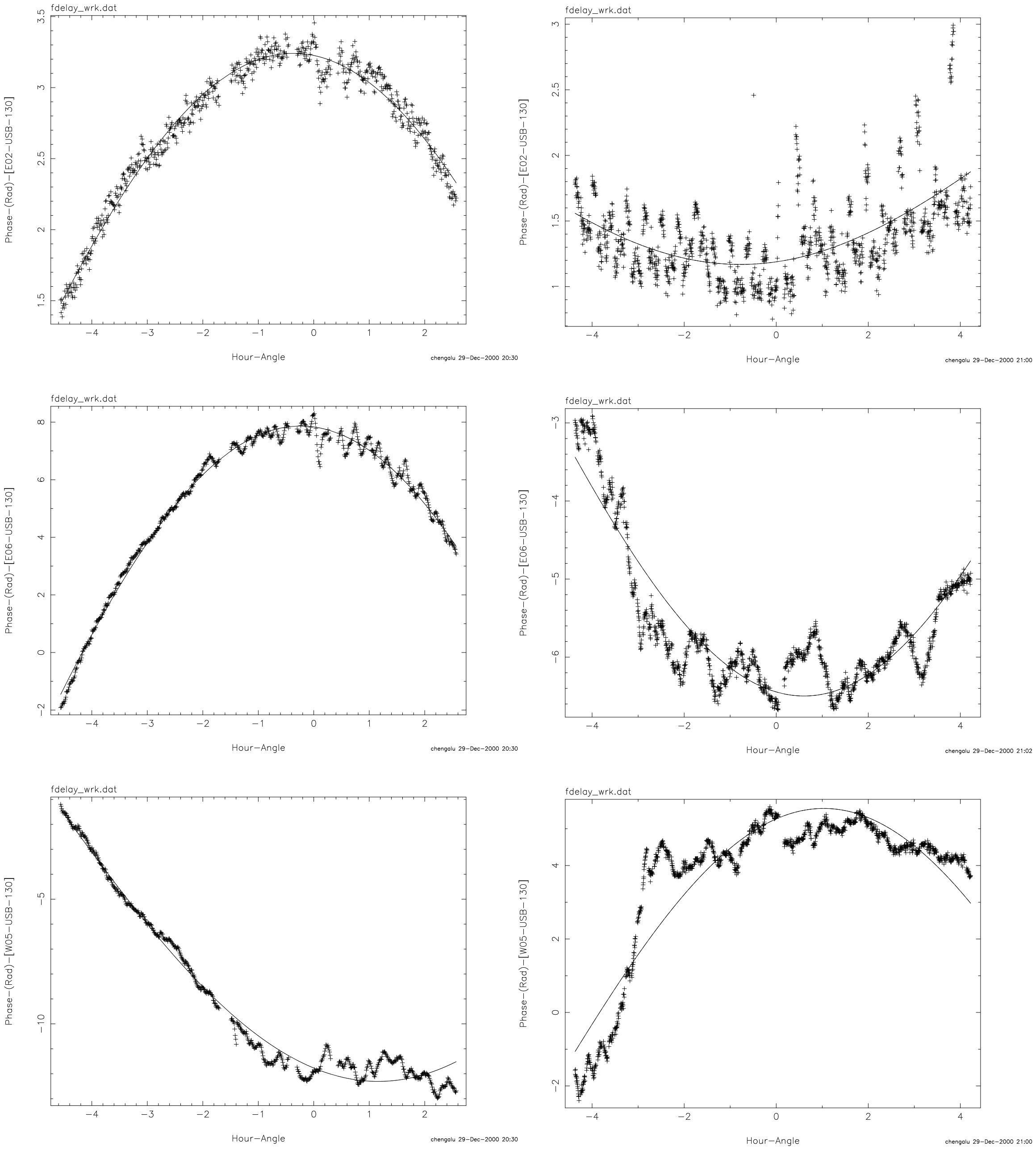

Figure 2: Antenna based phase as a function of hour angle for various arm antennas. The left hand panels are before correction for position errors while the right hand panels are after correction for antenna position errors. The overlaid curves are the fits from which the antenna position errors were determined. It can be seen that after one round of position correction the phase stability, while considerably improved, still shows non negligible variation. The magnitude of the residual errors for the extreme arm antennas is ~ 10 cm. However, the data is in general not well fit by a positional error model, and further the derived position errors do not repeat for different sources.

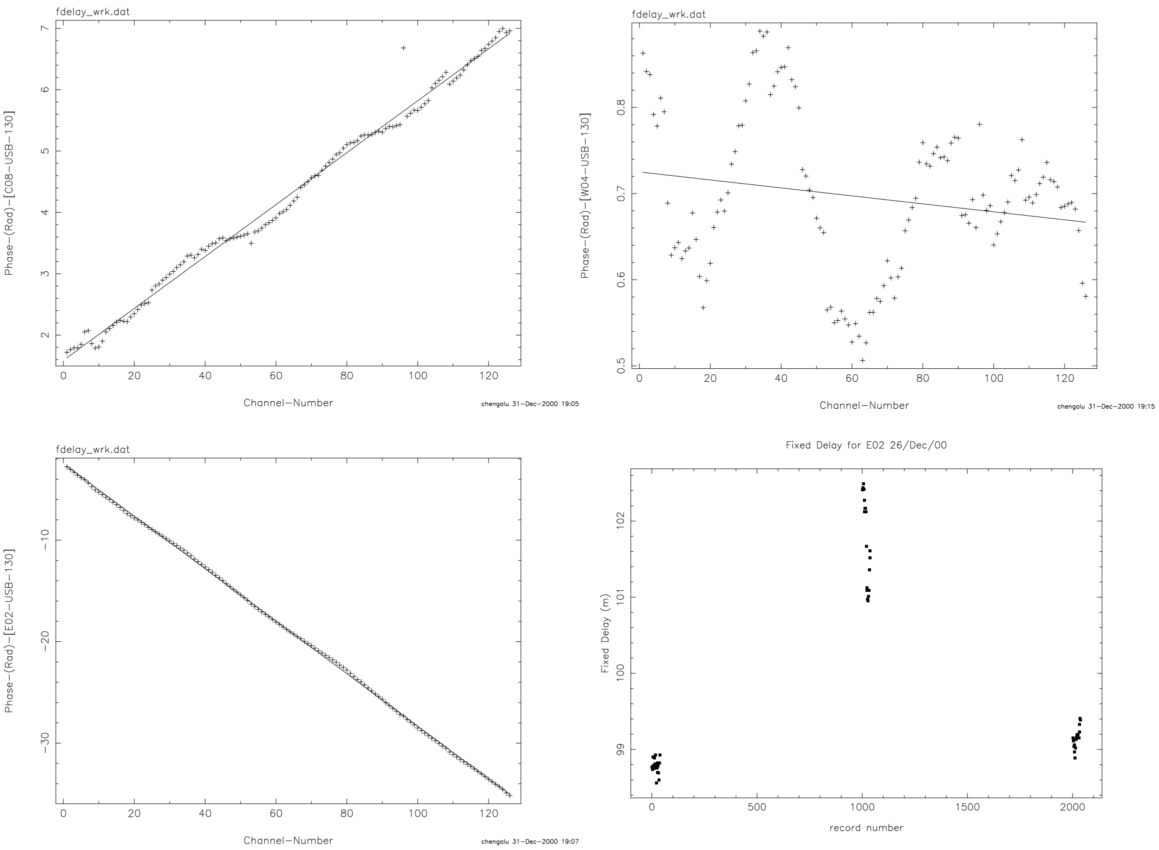

Figure 3: Variation of the antenna phase with channel number. The displayed fit is for an error in the fixed delay. For antenna C08 the error is $\sim$ 16 m, while for W04 there is no measurable error in the fixed delay. The antenna E02 has a very large fixed delay error $\sim$ 100 m which also appears to vary as a function of time. Measurements of the fixed delay for E02 for different scans separated by a few hours is shown in the lower right panel. The phase of the antenna E02 also appears to show sharp fluctuations (see Figure 2) which may be related to this change in fixed delay.

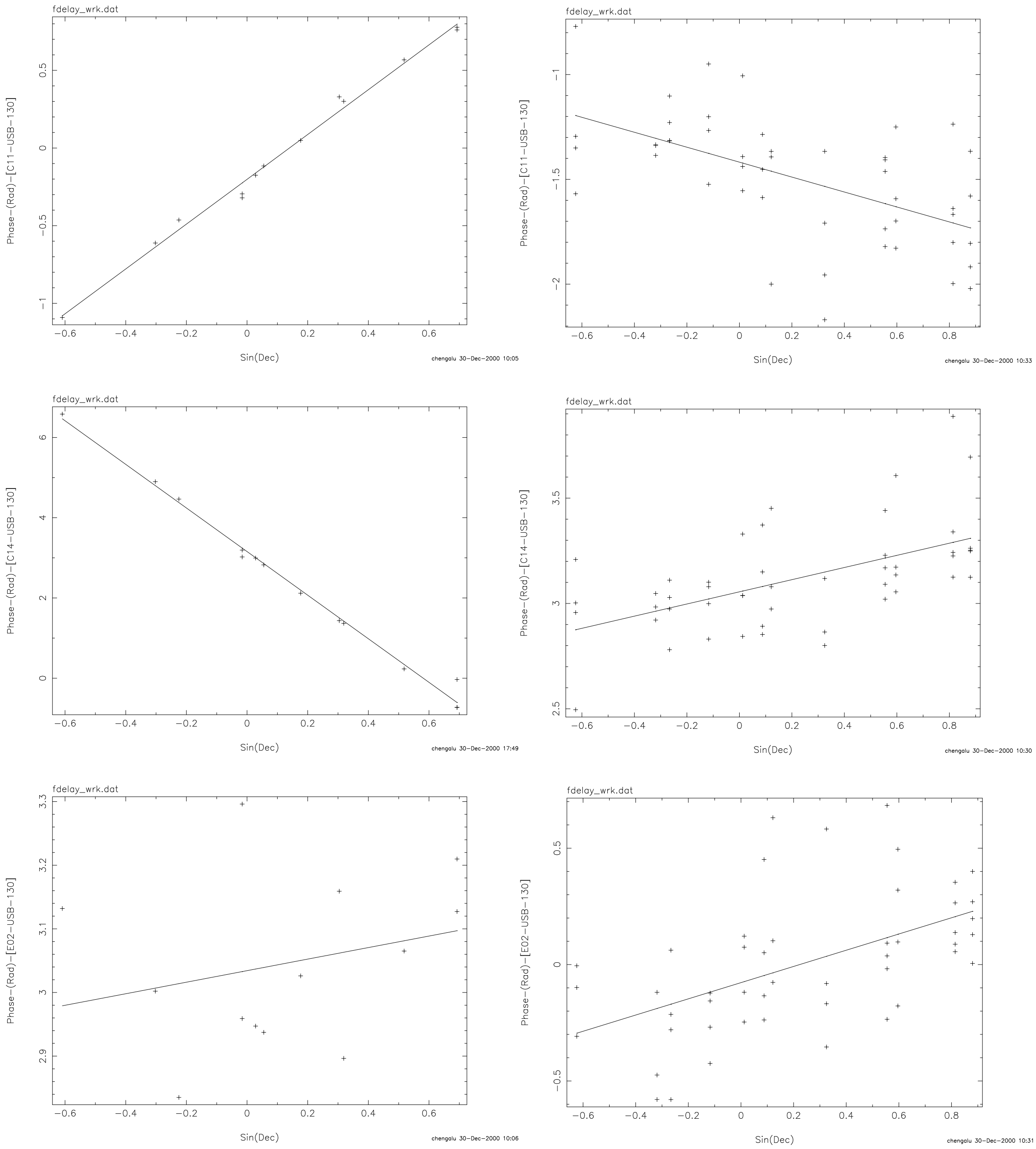

Figure 4: Antenna based phase as a function of declination for various antennas. The set of panels on the left are before correction of the Z antenna co-ordinate, while the right side panel are after correction. The residual errors as determined from the fits shown are $\leq$ 2cm. The Z co-ordinate of E02 was correct to begin with. The outer arm antennas do not show a systematic variation of phase with declination and hence no Z co-ordinate corrections could be derived for these antennas.

AntId	Name	bx (m)	by (m)	bz (m)	delay0 (m)	delay1 (m)
ANT00	C00	6.95	687.88	-20.04	-497.89	-497.89
ANT01	C01	13.24	326.43	-40.35	179.15	179.15
ANT02	C02	0.00	0.00	0.00	588.10	588.10
ANT03	C03	-51.10	-372.72	133.59	480.47	480.47
ANT04	C04	-51.08	-565.94	123.43	80.98	80.98
ANT05	C05	79.09	67.82	-246.59	84.89	84.89
ANT06	C06	71.23	-31.44	-220.58	-177.43	-177.43
ANT07	C08	130.77	280.67	-400.33	-463.19	-463.19
ANT08	C09	48.56	41.92	-151.65	259.30	259.30
ANT09	C10	191.32	-164.88	-587.49	-442.73	-442.73
ANT10	C11	102.42	-603.28	-321.56	-284.13	-284.13
ANT11	C12	209.28	174.85	-635.54	-1044.71	-1044.71
ANT12	C13	368.58	-639.53	-1117.92	-1347.68	-1347.68
ANT13	C14	207.30	-473.71	-628.63	-423.23	-423.23
ANT14	E02	-348.04	2814.55	953.67	-3877.18	-3877.18
ANT15	E03	-707.58	4576.00	1932.46	-7742.26	-7742.26
ANT16	E04	-1037.11	7780.69	2903.29	-13748.08	-13748.08
ANT17	E05	-1177.37	10200.00	3343.20	-20440.99	-20440.99
ANT18	E06	-1571.32	12073.46	4543.13	-25151.18	-25151.18
ANT19	S01	942.99	633.92	-2805.93	-5486.16	-5486.16
ANT20	S02	1452.85	-367.30	-4279.16	-9232.06	-9232.06
ANT21	S03	2184.54	333.03	-6404.96	-13826.41	-13826.41
ANT22	S04	3072.86	947.68	-8979.50	-18670.27	-18670.27
ANT23	S06	4592.71	-369.04	-13382.48	-27847.16	-27847.16
ANT24	W01	-201.50	-1591.94	591.32	-1336.69	-1336.69
ANT25	W02	-482.67	-3099.41	1419.39	-4642.84	-4642.84
ANT26	W03	-992.01	-5199.90	2899.11	-9608.61	-9608.61
ANT27	W04	-1734.55	-7039.03	5067.53	-15280.83	-15280.83
ANT28	W05	-2706.09	-8103.13	7817.14	-21583.03	-21583.03
ANT29	W06	-3102.11	-11245.60	8916.26	-29257.26	-29257.26

Table 4: GMRT antenna co-ordinates (after astronomical calibration). See the text and Table 3 for more details. Note that the fixed delay has currently been set identically for both the 130 and the 175 IF channels since the current correlator's Delay/DPC unit sets the same delay for both channels. The second sideband correlator has the ability to set the fixed delay independently for the two IF channels channels, and when it is commissioned the fixed delays should be re-calibrated. Fixed delay calibration is a very rapid process, and should, in any case, be done periodically. `fdelay` has the ability to calibrate the two channels separately (see Appendix C for details.)

AntId	Name	bx (m)	by (m)	bz (m)
ANT00	C00	40.48	687.87	-8.43
ANT01	C01	41.47	326.43	-30.57
ANT02	C02	0.00	0.00	0.00
ANT03	C03	-41.88	-372.72	136.82
ANT04	C04	-42.21	-565.94	126.46
ANT05	C05	84.47	67.82	-244.74
ANT06	C06	80.11	-31.44	-217.50
ANT07	C08	139.65	280.67	-397.25
ANT08	C09	77.40	41.94	-141.69
ANT09	C10	200.22	-164.86	-584.43
ANT10	C11	135.99	-603.94	-309.88
ANT11	C12	214.67	174.85	-633.66
ANT12	C13	402.19	-639.50	-1106.31
ANT13	C14	229.27	-474.67	-621.28
ANT14	E02	-319.41	2814.54	963.63
ANT15	E03	-698.30	4575.99	1935.69
ANT16	E04	-1009.37	7780.52	2913.07
ANT17	E05	-1177.96	10199.78	3343.16
ANT18	E06	-1550.28	12073.19	4550.70
ANT19	S01	971.77	633.92	-2795.96
ANT20	S02	1462.21	-367.08	-4275.93
ANT21	S03	2212.71	333.12	-6395.07
ANT22	S04	3072.97	947.47	-8979.47
ANT23	S06	4614.59	-369.05	-13374.92
ANT24	W01	-167.79	-1591.91	602.93
ANT25	W02	-453.65	-3099.40	1429.36
ANT26	W03	-982.31	-5199.93	2902.34
ANT27	W04	-1705.86	-7039.01	5077.25
ANT28	W05	-2705.66	-8103.19	7817.06
ANT29	W06	-3079.50	-11245.58	8923.76

Table 5: GPS based co-ordinates of the GMRT antennas. These co-ordinates are derived from Appendix 4 of Kulkarni et al. (1997), i.e. the final ITRF based antenna co-ordinates. The co-ordinates tabulated here are however in the same system as that used for Table 4. See section 4 for details of how the ITRF co-ordinates were transformed to the system at use at the GMRT.

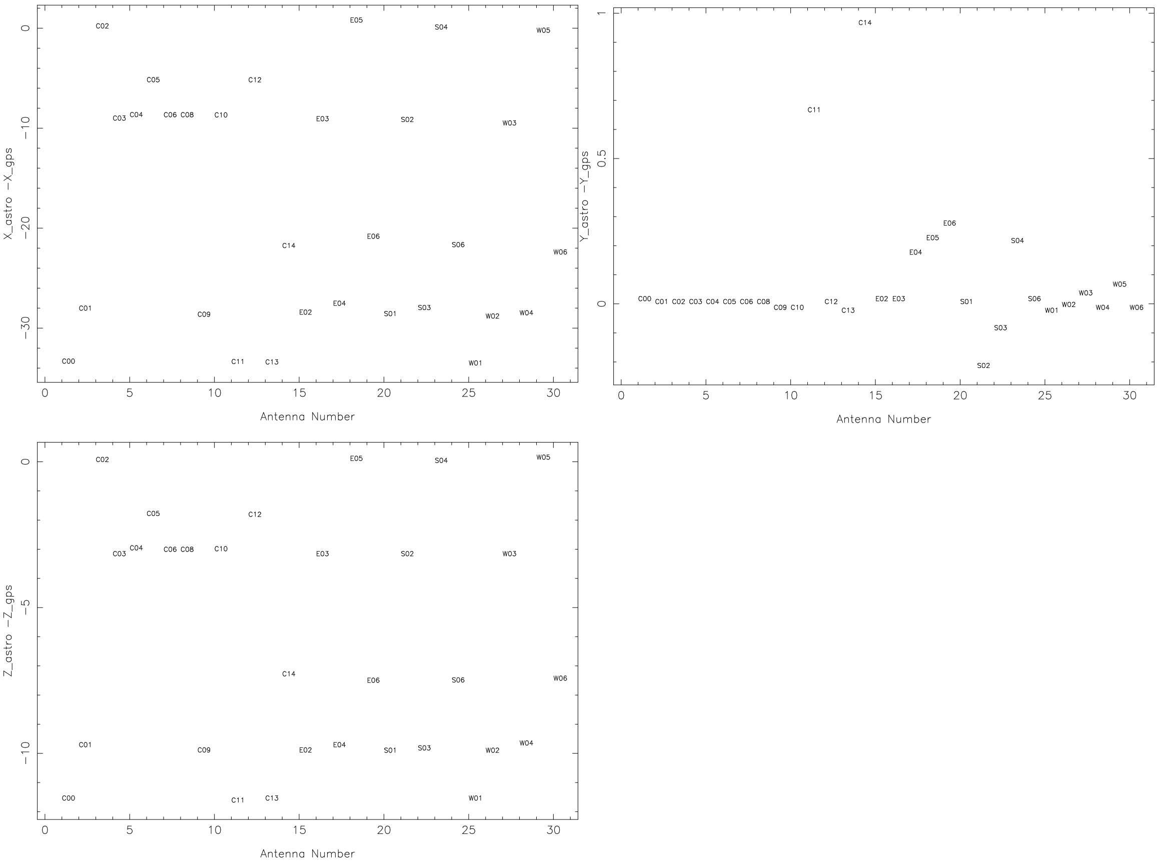

Figure 5: Differences between the astronomically determined and GPS based antenna co-ordinates. The Y co-ordinates are generally in good agreement. The X, Z co-ordinates however show differences of upto $\sim$ 30 m. As can be seen however, the errors are not randomly distributed. Instead there are several groups of antennas that have very similar errors. Antennas which are part of the same "occupation" (see Kulkarni 1997) have the same error. It appears likely that there was an error in converting these different sets of measurements into a common reference frame.

5 References

1. Bhatnagar S. 1999, "Computation of antenna dependent complex gains", NCRA, Technical Report, (R00172).

2. Bhatnagar S. & Rao A. P., 1996, "Baseline and Delay Calibration" NCRA, Technical Report.

3. Chengalur, J. N., 1998, "Delay tracking and Fringe Stopping for the GMRT Correlator", NCRA Technical Report (R00177)

4. Chengalur, J. N., 2000 "Subarray Operation at the GMRT", NCRA Technical Report (R00176)

5. Hoffman-Wellenhof B., Lichtenegger H. & Collins, J., 1992, "GPS Theory and practice" Fourth Revised Edition.

6. Kulkarni A. S. 1997, "Report on GPS measurements at GMRT", IIGM, Colaba, Mumbai.

7. Perley, R. A. & Taylor G. B., 1999, "The VLA Calibrator Manual".

8. Seidelmann, P. K., 1992, "Explanatory Supplement to the Astronomical Almanac"

9. Singh R. K., 1999, "The data acquisition system for the GMRT", Notes for the SERC School on Low Frequency Radio Astronomy, J. N. Chengalur, Y. Gupta, & K. S. Dwarakanath, eds.

10. Thompson, A. R., Moran, J. M. & Swenson, G. W., 1986, "Interferometry and Synthesis in Radio Astronomy", John Wiley.

A rantsol

Overview

The program rantsolcomputes the antenna based complex gains using the visibility database for an unresolved source. The visibility data however includes data from non-working/malfunctioning antennas and data effected by closure errors due to malfunctioning of the correlator. The antenna based complex gains are found using a global fit involving all the data, and presence of bad data can result into problems ranging from noisy solutions even for the good antennas to no convergence at all. This can happen even in the presence of a few antennas and/or presence of as small as 10-20% bad baselines. It is therefore important to remove bad data before attempting to solve for the antenna gains. This is done by doing two passes for every solution interval. Solutions from the first pass are examined and antennas with amplitude gain less than the user defined threshold are marked as bad for the second pass. Antennas which are found to be bad in this manner are assigned a complex gain of (1,0).

rantsolwrites the following in the output file: **(1)** antenna gains, **(2)** the residual gains (Amp,Phs), **(3)** the input gains (Amp,Phs), and **(4)** the model gains (Amp,Phs) as function of hour angle (HA).

Some of the details, relevant form the point of view baseline calibration, about the working of rantsoland the output it generates are described below. For a more details, use the on-line help via the `explain` command of the rantsoluser interface.

The output file is formatted as follows.

- A line beginning with "P:" contains some parameter from the LTA database (for e.g. RF frequency of observation, the channel width etc.).
- A line beginning with "#" has a list of antenna names for which the solution was attempted. The names are appended with the index (in square brackets ('[' and ']')) of the physical sampler numbers to which the named antenna is connected.
- A line beginning with "G:" has the following fields:

(1) Source name **(2)** Channel number **(3)** HA (Hr) **(4)** Dec (deg) **(5)** IST (hr)

This is followed by a list of amplitude and phase of the antenna gains for the various antennas listed in the line beginning with "#" (in the same order).

- A line beginning with "R:" has the baseline based "residuals" (defined as the ratio of the observed visibility and the modeled visibility). Such lines have the following fields:

  (1) Source Name **(2)** Sampler 1 **(3)** Sampler 2 **(4)** HA(Hr) **(5)** Dec (deg) **(6)** Residual Amp. **(7)** Residual Phase (deg) **(8)** Observed Amp. **(9)** Observed Phase (deg) **(10)** Modeled Amp. **(11)** Modeled Phase (deg) **(12)** U (Lambda) **(13)** V (Lambda)

  A mean residual amplitude of ~ 1.0 and mean residual phase of ~ 0 for a point source is an indicator of good solutions.

  It is recommended that the residual amplitude and phase must be examined to make sure that one is not using bad solutions. However if one is sure that the solutions will converge, the "R:" lines can be removed from the output by using "`| grep -v R: > FILENAME`" as the `rantsol`output file name (this will considerably reduce the size of the output file) (here `FILENAME` is the name of the file in which the output will be stored)

`in (default=stdin)`

The name of the input GMRT LTA format file.

`out (default=stdout)`

The name of the output file.

Use "`| grep -v R: > FILENAME`*" to strip the "R:" lines from the output recorded in the file name* `FILENAME`.

`obj (default ==> ALL)`

A regular expression to match the object name for which the solutions will be found.

`scans (default ==> ALL)`

List of scans of the selected object on which the solver is to be invoked.

The scans are the logical scan numbers of the selected sources. For e.g. if the source selected via keyword "obj" has physical scan numbers 2,5,7, the corresponding list of logical scan numbers would be 0,1,2.

Use `obj` *and* `scans` *keywords to extract solutions for calibrator scans from a LTA file with other non-calibrator scans.*

`mode (default = 2)`

The mode of operation.

Mode = 0 ==> solve only for phases

Mode = 1 ==> solve only for amplitudes

Mode = 2 ==> solve for Amp and Phs simultaneously

For the purpose of baseline calibration, always use the default `mode=2`*.*

r̂esid (default=10 (percent))

The maximum acceptable residual error as a percentage of the source flux. A residual error of more than this value implies a bad solution and the corresponding solutions are discarded.

While for most observations, the default value works, it may be increased to reject noisy solutions.

`refant (default = First antenna in use)`

The name of the antenna to be used for phase referencing. The name should be one of those listed in the antenna file.

If this name matches more than one antenna present in the database, the first match is accepted as the reference antenna.

It is important to use a "good" antenna as reference for which solutions are stable and which is available for the entire length of the observations.

`badbase (default=None)`

List of bad baselines which are to be flagged while solving for antenna gains. This could be given as just the antenna name, all baselines of which are to be flagged, baseline number or a fully qualified baseline names which alone is to be flagged (for more on antenna/baseline name construction, see the on-line help via the `explain baselines:xtract` command in the user interface of `rantsol`).

Antennas which are fully flagged due the selection of bad baselines, will be omitted in the output.

It has been noticed for a very few cases, presence of a single bad antenna renders the automatic bad antennas and baseline determination algorithm ineffective. This results into non-convergence, even when most of the data is actually good. Flagging just that one antenna by hand (leaving out of possibly many more bad antennas to be handled by `rantsol`*!) produces good solutions. The reasons for this condition to happen are not fully understood yet. While this condition has happened only a few time so far, use this keyword to find and flag the offending antenna in case this condition is encountered.*

`integ (default = 0)`

The number of seconds for which integration should be done before solving for the gains.

Currently if the data is input via a pipe, any value other than the default will result into run-time error.

Integration will always stop at the scan boundaries. The program will stop processing after the total number of records used for gain solutions is greater than or equal to the number of records requested via the `timerange` keyword.

Use higher integration time for weaker source to improve the signal-to-noise ratio. However the integration time must be much smaller than the time scale over which the antenna phase varies by, say, a radian.

`poln (default = -1 ==> 130 MHz channel)`

The polarization to be used. The only other value it can take is 1 ==> 175 MHz. channel.

`rantsol`*works on one polarization at a time. Use this keyword to select the polarization channel to be used. Make sure that this is consistent with the polarization state of the reference antenna.*

`chan (default = 100)`

The channel number to be used. This keyword optionally takes 3 values: start_channel, stop_channel, step. If only one value is given, the task will work on the given channel. If two values are given, the task will work from start_channel to stop_channel in steps of 1. If the third value is given, it will be treated as the step.

Use this keyword to compute the antennas gains across the observing band, which is used for delay calibration.

`avgmode (default = vector)`

Mode of averaging the visibilities before solving for antenna based gains. Default averaging is vector averaging. If the value of this keyword is set to “scalar”, scalar averaging will be done. Any other value will revert to vector averaging. Note that with scalar averaging, it only makes sense to set `mode=1`.

For the purpose of baseline and delay calibration, always use vector averaging, if required.

`threshold (default = 5E-3)        [dbg class keyword]`

Antenna based amplitude threshold below which the antenna is marked as bad. This keyword is of the "dbg" class and hence to set it's value (to something other than default), one has to run the application as "`rantsol help=dbg`".

The default value is picked up from the `$GDEFAULTS/rantsol.def` file.

`skip (default = 1m)        [dbg class keyword]`

The length of time (in seconds if supplied without units) for which initial data in each scan is skipped (actually eaten, to be precise).

This is "dbg" class keyword and its default value is picked up from `$GDEFAULTS/rantsol.def`.

B antpos

Overview

An error in the antenna co-ordinates will give rise to a residual phase after compensating for the nominal geometric phase. It can be easily shown that errors in the (X,Y) co-ordinates give rise to a sinosoidal variation of phase with hour angle for observations of a point source. For an antenna with no (X,Y) position errors the phase will vary linearly with sin(dec) for observations of point sources with different declinations.

antpos uses these facts to compute corrections to the (X,Y,Z) positions of the GMRT antennas. For fits as a function of hour angle antpos fits a sinosiodal function (plus constant to account for instruemntal phase and a possible error in the Z co-ordinate) to the antenna based phase. This antenna based phase can be obtained by using rantsol to decompose the visibilities obtained using a long observation of a calibrator source (i.e. a sufficiently bright point source placed at the phase center) into antenna based amplitudes and phases. It is important to have good hour angle coverage because otherwise it is difficult to distinguish between terms that vary as cos(hour angle) and terms that vary as sin (hour angle).

The correction to the Z co-ordinate can be computed only after the (X,Y) co-ordinates have been corrected. Typically the telescope is made to cycle through a set of sources which cover a large range of declinations. The visibilities should then be decomposed using rantsol. antpos will then read the rantsol output file, compute the correction to the Z co-ordinate, and then update the antsys.hdr file appropriately. See the bzfit option for more details.

The output from (r)antsol is an ASCII file, this file is directly read by antpos. At the GMRT the co-ordinates (and other relevant antenna parameters) are stored in a file called antsys.hdr. antpos reads this file (or a copy of the master file) and generates a new file in this exact same format, except that the (bx, by, bz) co-ordinates of the relevant antennas are updated. If the user is satisfied with these new co-ordinates s/he can request the maintainer of the master antsys.hdr file replace the master file with this new file.

For both (X,Y) fits as well as Z fits the computed baseline errors are also written to the file antpos.log. Experiments with simulated data suggest that after a few hours observation, the (X,Y) positions of the antennas can be determined to within about 1cm accuracy provided the rms in the phase is of the order of 10 degrees. In practise this accuracy is never achieved with real data because of systematic non geometric contributions to the antenna phase.

Inputs

`linefit (default no)` If set to 1, antpos will fit a straight line instead of a sinosoid to the phase as a function of hour angle. This is useful esentially when checking for errors in time keeping or errors in the assumed source position.

`bzfit (default no)` Fit for the Z co-ordinate instead of the (X,Y) co-ordinates. antpos assumes that the gainfile contains data for several sources (at least 5) with different declinations and fits a straight line (as a function of sin(dec) to the phase. Only the median phase for all the records in each scan on each source is used in the fitting. One can drop scans using the srcdrop option.

`gainfile (no default)` The name of the antsol output file.

`hdrfile (no default)` The name of the "antsys.hdr" file.

`chansep (default rantsol file value)` The channel separation in kHz. By default the value in the rantsol output file will be used.

`lo1 (default rantsol file value)` The frequency of the first LO in MHz. This is used to determine the sign of the position correction. By default the value in the rantsol output file is used. This switch is provided just in case you want to override that for reasons of your own.

`rf (default rantsol file value)` The rf frequency in MHz. By default the value in the rantsol output file will be used.

`dec (default rantsol file value)` The declination of the calibration source. By default the value in the rantsol output file is used. This switch is provided just in case you want to override that for reasons of your own. This is used only in the case of fitting for the (X,Y) co-ordinate errors.

ants (default all) A comma separated list of antennas for which to compute the co-ordinate error. Since rantsol works for only one polarization at a time this is could be a simple name (eg C00, or S06) and not a "fully qualified" name like C00-USB-130. It is not an error to give a fully qualified name. The program will silently ignore antennas which are specified here but which are not present in the antsol output file.

srcdrop (default none) scans to ignore when fitting for the Z co-ordinate error. Scans can also be dropped interactively.

harange The hour angle range to be used for fitting. The format is ha1,ha2,...haN. Only the data streches between [ha1,ha2] [ha3,ha4]...are used for fitting. This defaults to all available data. Hour angle ranges can also be specified interactively.

timerange (default first record) The time range to read in from the rantsol file. By default all availabe records are read. The format is Rec1,RecN. Where Rec1 and RecN are the first and last records to read.

chanrange (default all) The channel ranges to read from the rantsol file. The data for these channels are averaged before the fit is made. The format is Chan1,ChaN, where Chan1 and ChanN are the first and last channels to use. The visibility is (complex) averaged for all the channels in the range specified. NOTE: In case there are missing channels in this range, the computed wavelength (and hence the co-ordinate correction) could be slightly in error.

unwrap (default yes) Should the program attempt to detect 2PI wraps in the phase and unwrap before attempting the fit? The default is yes.

pre_unwrap (default yes) Should the program attempt to detect 2PI wraps before selecting the HaRange to fit for? If set to yes, the unwrapping is done on the original data. If set to no, the unwrapping is done using only the data within the specified hour angle ranges.

interactive (default yes) Should the fits be done interactively? It is strongly recommended that you inspect the quality of the fits before accepting them. Interactive fitting also allows fine tuning of the fitting parameters etc.

C fdelay

Overview

An error in the fixed delay for a given antenna will give rise to a phase gradient (across channels) in the bandpass of that antenna for observations of a point source. fdelay uses this fact to compute the fixed delay error by fitting a straight line to the phase of the bandpass. The bandpass phase itself can be obtained by using rantsol to decompose the visibilities obtained while observing a calibrator source (i.e. a sufficiently bright point source placed at the phase center) into antenna based amplitudes and phases. The output from rantsol is an ascii file which is read directly by fdelay. At the GMRT the fixed delays (and other relevant antenna parameters) are stored in a file called antsys.hdr. fdelay reads this file (or a copy of the master file) and generates a new file in this exact same format, except that the fixed delays of the relevant antennas are updated. If the user is satisfied with these new fixed delays s/he can request the maintainer of the master antsys.hdr file replace the master file with this new file. The fixed delay errors computed by fdelay are logged in the file fdelay.log in the current working directory. Experience with simulated data suggests that a phase rms of 10 degrees translates to an RMS of about 1 to 2 meters in the fixed delays corrections.

Inputs

`ants (default all)` A comma separated list of antennas for which to compute the fixed delay error. Since rantsol works for only one polarization at a time this is could be a simple name (eg C00, or S06) and not a "fully qualified" name like C00-USB-130. It is not an error to give a fully qualified name. The program will silently ignore antennas which are specified here but which are not present in the rantsol output file.

`gainfile (no default)` The name of the rantsol output file.

`hdrfile (no default)` The name of the "antsys.hdr" file.

`chansep (default rantsol file value)` The channel separation in kHz. By default the value in the rantsol output file will be used. This will be correct if some contiguous range of channels was observed. However if only every alternate channel, or something even more exotic was observed, you will have to give the channel separation by hand.

`lo1 (default rantsol file value)` The frequency of the first LO in MHz. This is used to determine whether a positive phase gradient corresponds to a positive or a negative fixed delay correction. By default the value in the rantsol output file is used. This switch is provided just in case you want to override that for reasons of your own.

`timerange (default first record)` The time range to use while fitting the phase gradient. By default only the first record is used. The format is Rec1,RecN. Where Rec1 and RecN are the first and last records to use. The complex visibility data for all chosen timestamps is averaged before the fitting is done.

`channel (default all)` The channel range to use for fitting. This a comma separated list of channel ranges, i.e. should be c1,c2,c3,c4...c2N. This specifies N ranges of channels to be used in the fit. For example channel=10,20,40,80 will cause only channels from 10 to 20 (inclusive) and channels 40 to 80 to be used for the fit. Of course, only the subset of channels for which data is actually present in the rantsol file will be used.

`ignorepol (default yes)` Should the fixed delay error be applied to both polarizations? The default is yes.

`unwrap (default yes)` Should the program attempt to detect 2PI wraps in the phase and unwrap before attempting the linear fit? The default is yes.

`interactive (default yes)` Should the fits to the phase gradient be displayed? It is strongly recommended that you inspect the quality of the fits before accepting them.