Backlash error in encoder assembly of the GMRT antennas

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Internal Technical Report

By

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Introduction

Any mechanical structure built following a design could suffer from imperfections. For GMRT, change in pointing offsets with change in azimuth and elevation for the antennas were noticed during its early operation. The approach to reduce it was first described by Kantharia (2008). Later, a pointing model was developed empirically by Roy & Kulkarni (2009), which is presently being used at GMRT.

However, the above cases only dealt with antenna based pointing errors, which increases as a function of angular displacement from the reference position. A mechanical system could also display direction dependent asymmetry in its motion. The simplest of which is backlash, and it typically arises due to loose couplings between different parts of a dynamical system. When the direction of motion in such a system is reversed, the driving system moves through a certain distance or angle without applying appreciable force or motion to the next part in the mechanical sequence.

Here we are discussing the backlash error in the encoder assembly and not the backlash error in the AZ EL gearboxes/drives. Gearbox/drive backlash error is avoided by using two motors and applying counter torques to the antenna axis.

We have noticed this issue mostly in the EL axis and rarely in the AZ axis. The possible reasons are as follows: (i) EL encoder assembly has the four mechanical joints with two couplings for connecting the encoder shaft to the antenna axis, while AZ axis has only two joints with single coupling (see Figs, 3 & 4). (ii) The limited movement of the EL axis. The EL axis only rotates between 17 deg to 90 deg, while the AZ axis rotates between +270 deg to -270 deg.

The motion of the antenna is not correctly transferred to the encoder due to possible looseness in the mechanical connection between the antenna and the encoder. The reason behind the looseness could be non-rigidity or twisting of the couplings due to the increased friction of the bearings of the encoder connection shaft.

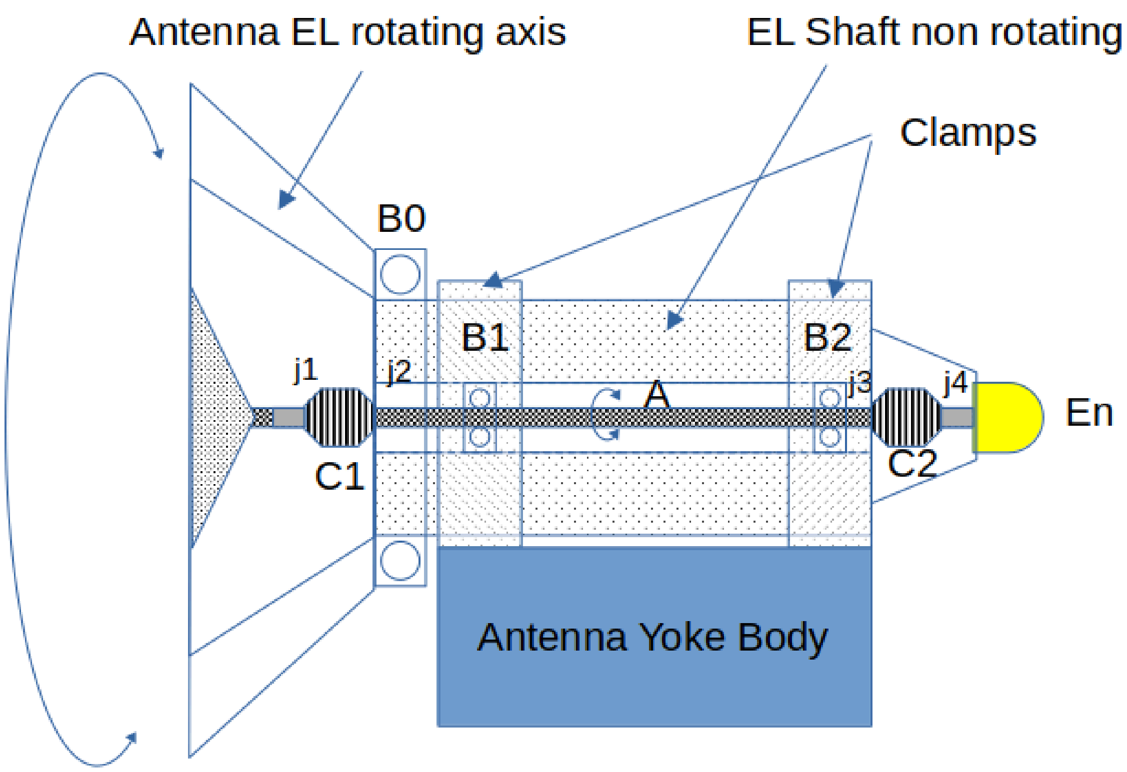
EL encoder assembly and its physical location at antenna

The following photographs show the EL encoder assembly and its location.

Fig 1. Red square box shows the EL axis encoder location

Fig 2. EL encoder assembly in the workshop

Schematic of EL encoder assembly.



A - Connecting shaft, EL axis to Encoder.

B0 - Elevation axis bearing.

B1,B2 - Small bearings to support shaft 'A'.

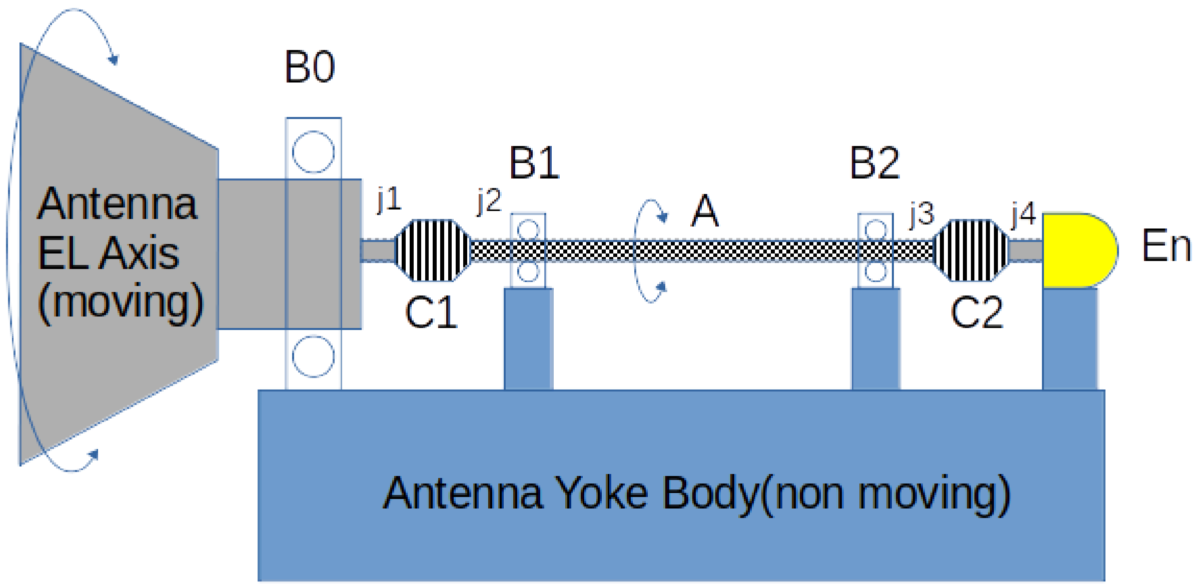
C1,C2 - Couplings.

j1,j2,j3,j4 - Joints.

En - Encoder

Fig 3. Schematic diagram of EL encoder assembly.

Elevation axis encoder assembly



A - Connecting shaft, EL axis to Encoder.

B0 - Elevation axis bearing.

B1,B2 - Small bearings to support shaft 'A'.

C1,C2 - Couplings.

j1,j2,j3,j4 - Joints.

En - Encoder

Fig 4. Simplified schematic diagram of the EL encoder assembly.

Error detection technique

In the ideal case, the encoder follows the antenna position in any direction of rotation. But when there is some issue with the encoder assembly, the encoder may not follow the antenna position correctly all the time and there will be a difference (offset) between actual antenna position and the encoder position (reading). This offset value keeps changing with time, position and in direction change. The maximum value of this difference is called a backlash error in the encoder assembly.

To measure the backlash error, the antenna has to point to some target position approaching from two different directions, up/down for the EL axis and left/right for the AZ axis. In the ideal case, antenna position and encoder reading after approaching from two different directions does match, and it does not match if there is a problem. So we need encoder reading and actual/physical antenna position for both directions. Encoder reading is available with the online Tango based Monitor & Control (TGC) system. Actual antenna position can be found (i) by detecting a known radio calibrator source in the sky for which the elevation and azimuth are easily available, or (ii) by Stow (parking) Position Sensor (STP) mounted on the antenna axis of each antenna.

Therefore, we use two methods to determine the backlash error in the antenna encoder assembly. As indicated above, the First one is the astronomical method and the second one, which is locally developed, is the STP indicator (flag) method. Astronomical method works for both axes, while the STP flag method works only for the EL axis (STP sensor is available only for EL axis). A schematic diagram to explain the 1st method is shown below (Fig. 5). More details of the two methods are given below.

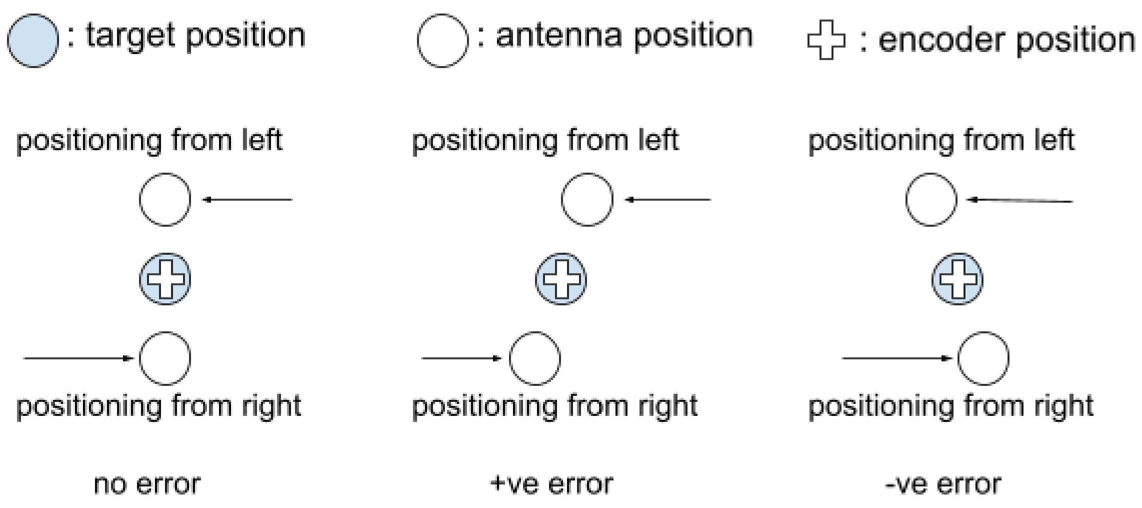


Fig 5. Backlash error schematic diagram

Astronomical (raster scan) method

In this method, we use the astronomical calibrator source to point/scan the antenna to a specific position, approaching or scanning from two different directions. To carry out the test, we use the L band setup due its smallest beamwidth (24'). We use the raster scan pointing offset finding procedure, in both directions (i.e. between left-to-right and right-to-left for the AZ axis or up-to-down and down-to-up for the EL axis). Finally, the difference between the two offsets is the backlash error.

Initially, we take the antenna away from the source and start scanning (moving) the antenna with the speed higher than the tracking speed and record the signals. When the correlation amplitude is plotted as a function of offset/time, we will get the Gaussian curve, which gives the offset value. This is done for both directions, if there is no problem then both direction curves should exactly overlap, otherwise there is backlash error. This scenario can be categorized into three different cases, as described below.

Case-1:
When there is looseness in the encoder assembly, and the antenna scans the target in any direction, then the antenna will catch the signal peak before the expected time/position. This has been illustrated in the Fig. no. 6 . The expected peak position (offset) is denoted by 'P'. While scanning from left to right and right to left, we will observe the signal peaks 'P1' and 'P2' earlier than the expected time. The difference value, E1 = P1-P2, is the backlash error and its value is always negative.

Case-2:
When there is a delayed tracking or delay in the signal path, and the antenna scans the target in any direction, then the antenna signal peak will be observed after the expected time/position. This has been illustrated in the Fig. no. 7 . The expected peak position (offset) is denoted by 'P'. While scanning from left to right and right to left, we will observe the signal peaks 'P1' and 'P2' later than the expected time. The difference value, E2 = P1-P2, is the backlash error and its value is always positive.

Case-3:
When there is a fixed time offset or fixed pointing offsets in the tracking system, and we are scanning the target in any direction, then 'P1' = 'P2' i.e. E3 = P1-P2 = 0. This has been illustrated in Fig. no 8. Hence, time offset or pointing offset in the tracking system does not produce any backlash error. But the time offset causes a sign change in the pointing offset after the source transit in the EL axis of the antenna.

Finally, the total backlash error, E = E1 + E2 + E3 = E1
Here we have assumed that E2 has zero value and E3 is ignored.

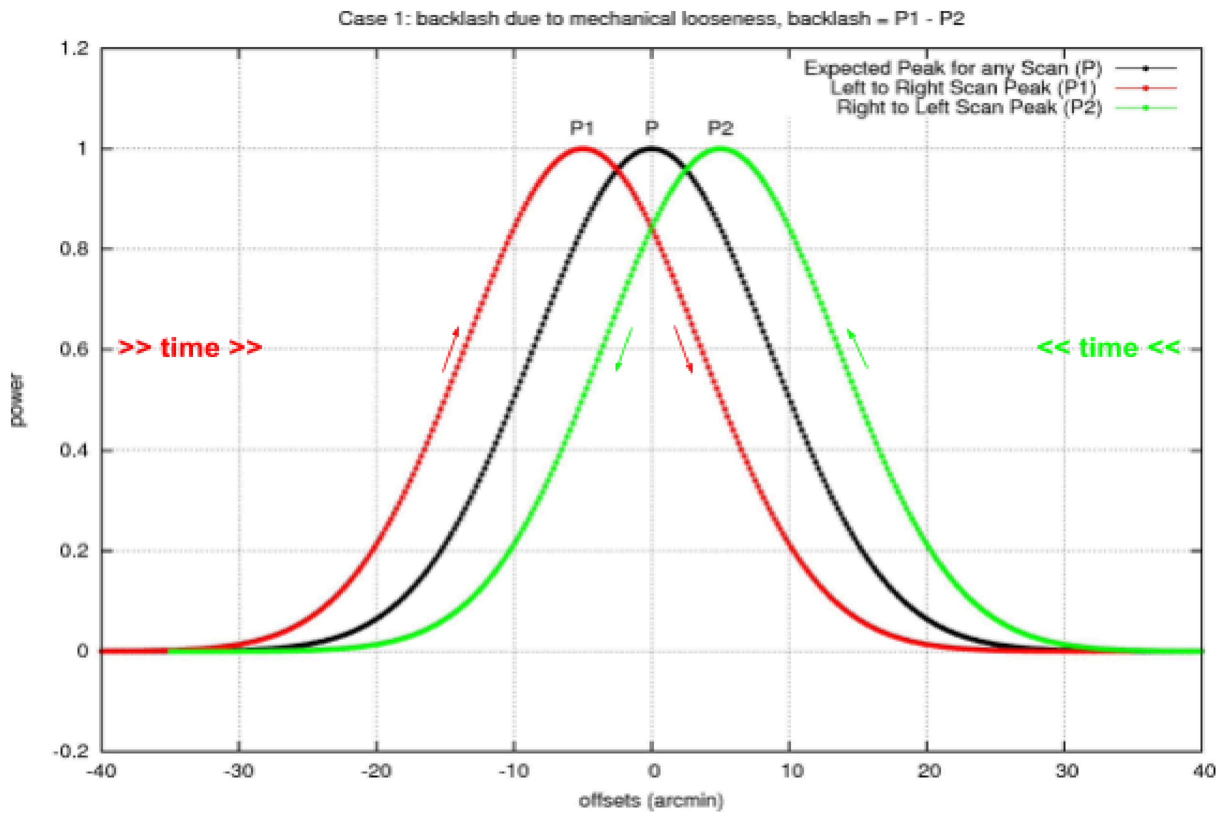


Fig 6. Case1 — Backlash due to mechanical looseness in encoder assembly

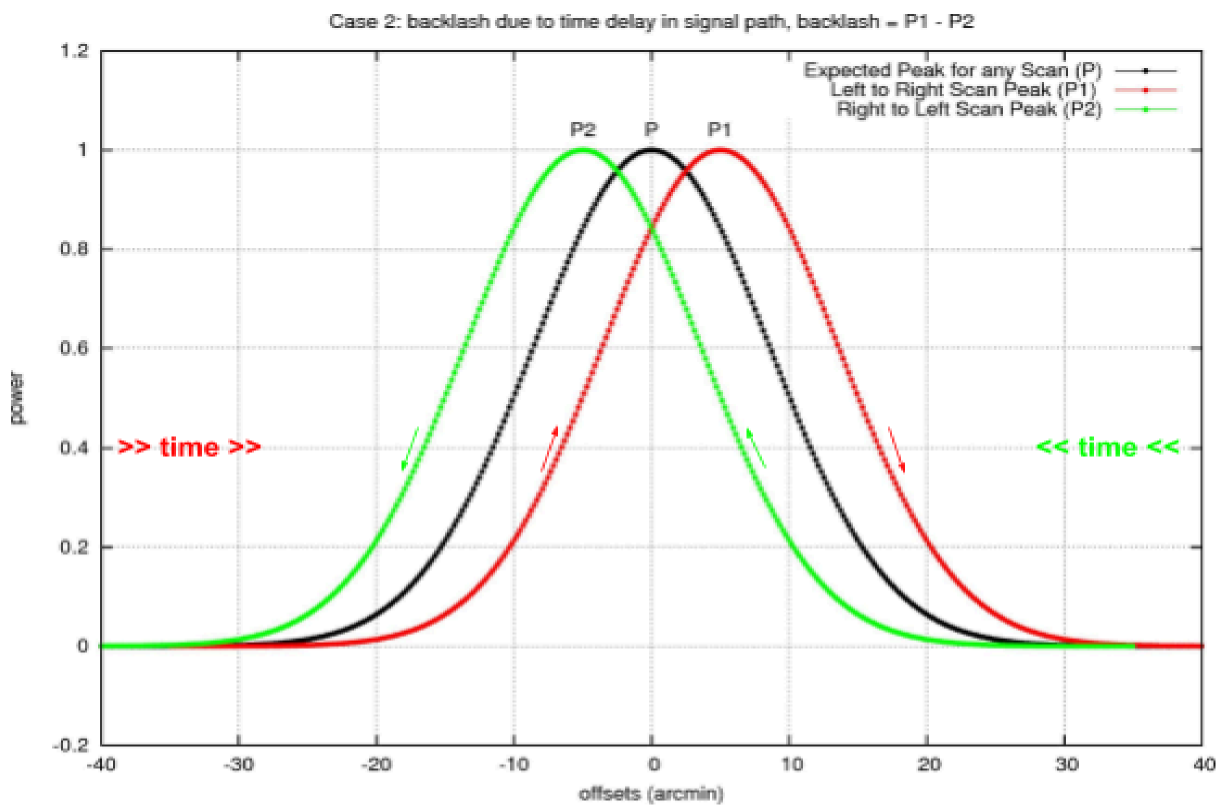


Fig 7: Case2 — Backlash due to delayed tracking or delayed signal in receiver chain

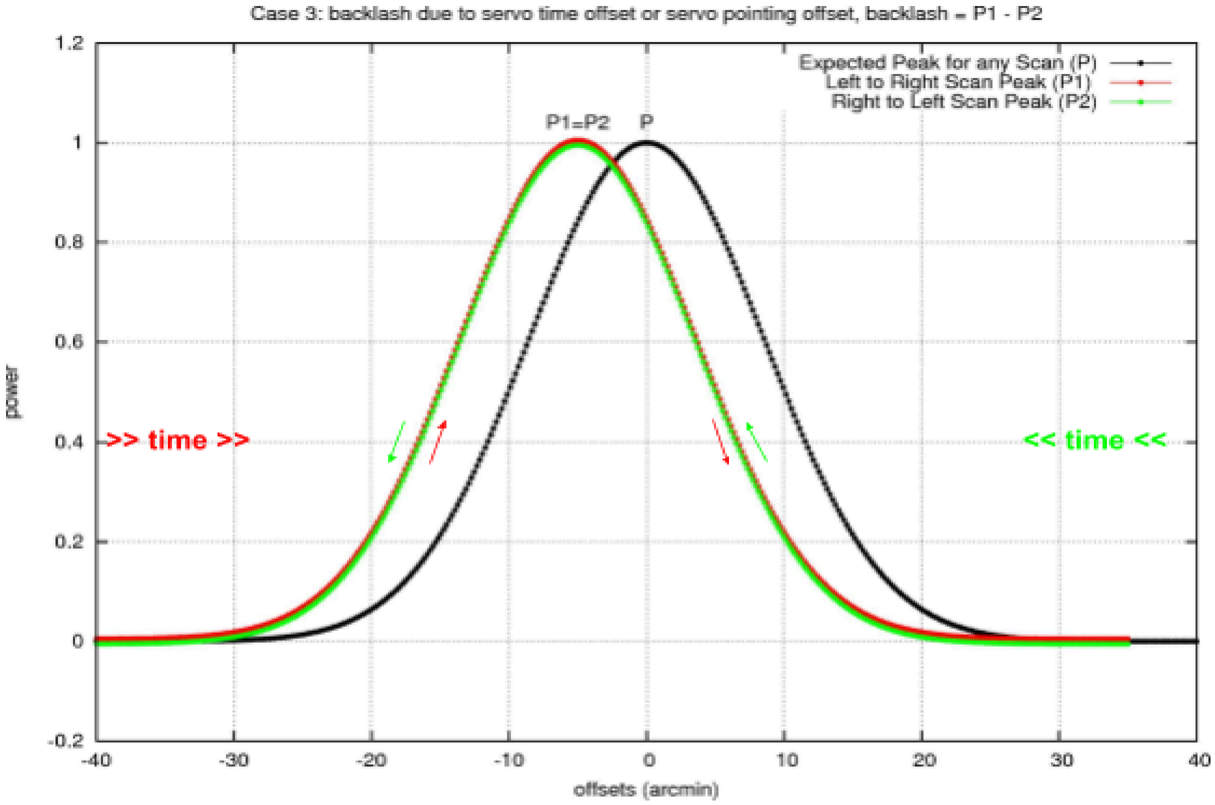


Fig: 8 Case3 — No backlash due to servo time offset or servo pointing offsets

STP flag method

In this method, we use a sensor to detect the antenna parking position near local zenith. This sensor is the indicator to get the exact physical position of the antenna for stowing purposes. It is available only in the EL axis, hence this method is useful in the EL axis only. This method is faster and no signal recording required, it also eliminates the backlash due to any time delay in tracking astronomical sources. The STP switch (sensor) is mounted on the antenna EL axis close to 90 deg elevation angle.

We track antennas in the EL axis from 89 deg to 91 deg and again back from 91 to 89 deg with some specific tracking speed. This has been done multiple times to get consistent readings. During this tracking, high speed (every 100ms) servo data is getting recorded for encoder position and STP flag. Finally, the STP flag is plotted as a function of the encoder position to get the backlash error.

This is illustrated in Fig. no 9, x-axis of the plot show the elevation angle and green coloured points are the STP flags. The arrows in the plots indicate the tracking direction, 89 to 91 is up direction and 91 to 89 is down direction. We are getting two different mean STP positions for two directions, which are shown in red color. The difference between these two red dots is the backlash error. For C11 antenna, the value is around -3.7 arc min. The Fig no 10 shows the backlash error of -0.3 arcmin in E06 antenna, which is not significant.

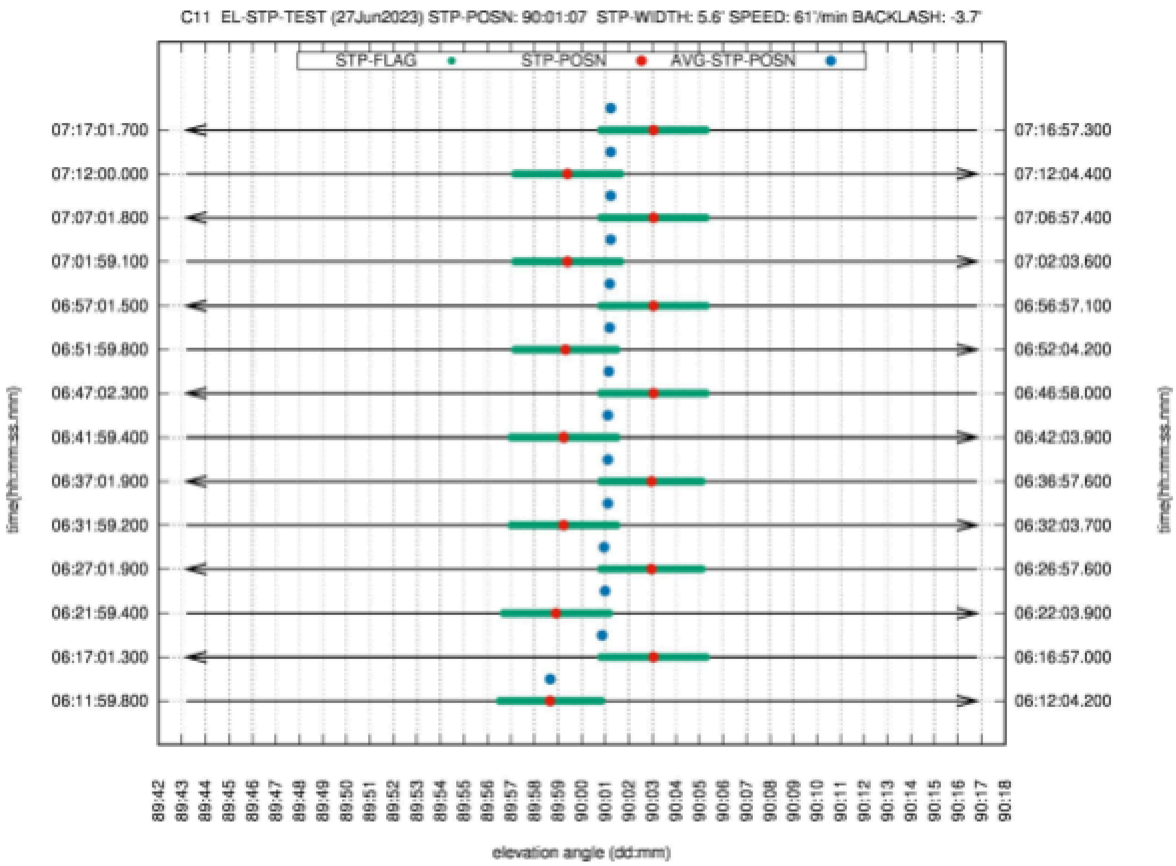


Fig. 9: Backlash error of -3.7 arc min in C11 antenna by STP method

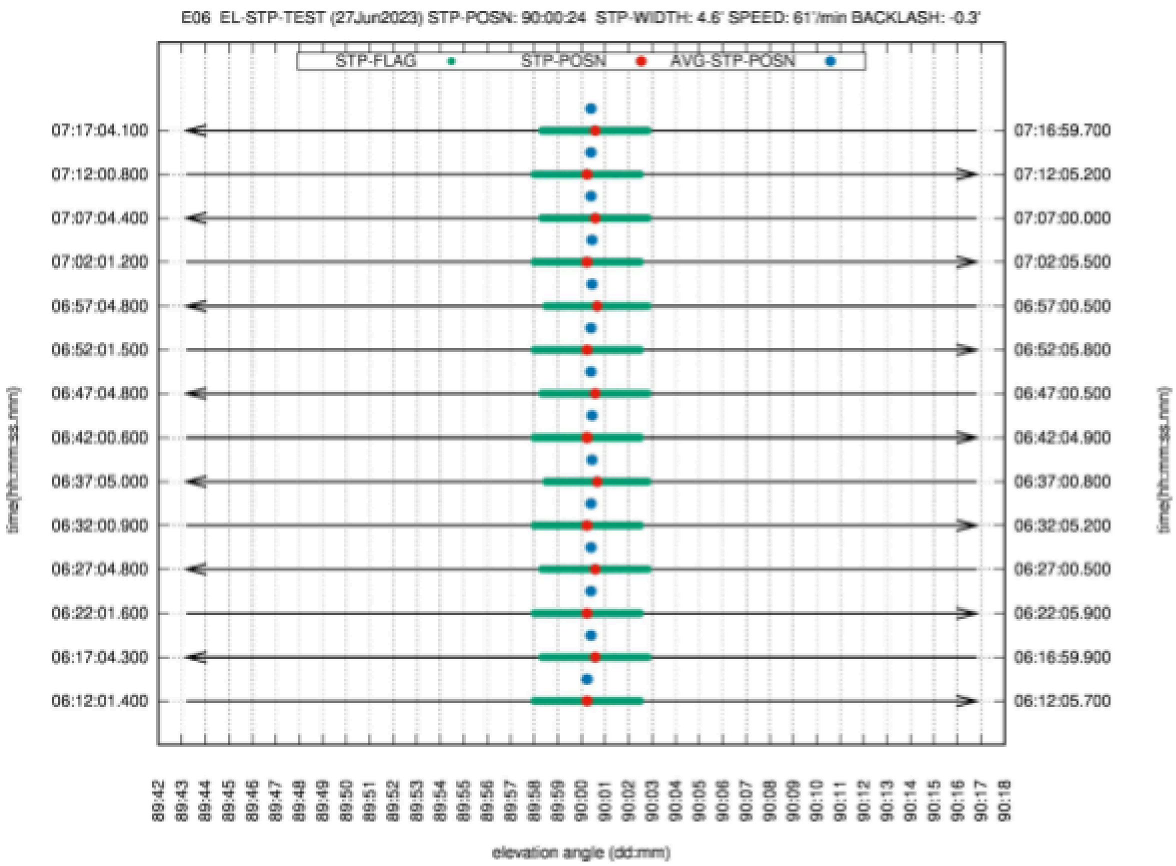


Fig 10: Backlash error of -0.3 arcmin in E06 antenna by STP method

Data analysis

Astronomical method:

We have developed the procedure and data analysis tool to get the backlash error values for all the antennas from astronomical methods. To conduct this test, Initially the command file is created, and then the observing plan is executed with the antennas. It takes 5 minutes to run a one direction scan for a single axis. To get one complete set of readings, it takes 5 X 2-directions X 2-axis, which takes around 20 minutes. Such multiple readings are taken to get more accurate results.

Antenna correlation amplitude is plotted as a function of offsets/time, and a Gaussian function is fitted on the data set to get the offset values. This is done for both directions, and finally, both the Gaussian plots are overlaid and the difference between the two peaks is the backlash error. Perl script and gnuplot are used for the gaussian fit and data plotting. Fig 11 & 12 show the plots. In all the plots involving data from the Astronomical method, the left column of the plot shows the results from one polarization (130MHz, typically called RR), and the right column shows the results from the other polarization (175 MHz, typically called LL).

STP flag method:
As mentioned earlier, we have developed the procedure and data analysis tool to get the backlash error values for all the antennas from STP flag methods. To conduct this test, Initially the command file is created then the plan is executed. It takes 5 minutes to run one direction tracking, to get one complete set of readings it takes 5 X 2-directions which takes around 10 minutes. Such multiple readings are taken to get more accurate results.

Antenna STP flags are plotted as a function of encoder position, from the plots and calculation we get the backlash error estimate for elevation axis. Perl script is used for data analysis and gnuplot is used for data plotting. Fig 9 & 10 show the plots.

Results

Astronomical (C14-EL—raster scan) method:
Fig. 13 and 14 show the results before and after correction of the problem. Antenna C14 showed an error of -6.6 arc min in EL axis (Fig. 13). The mechanical team has inspected this antenna. After fix, it shows an error of -2.1 arc-min (Fig. 14) and it is quite close to acceptable range.

Astronomical (W02-AZ—raster scan) method:
Fig. 15 and 16 show the results before and after correction of the problem. Antenna W02 showed an error of -3.3 arc min in AZ axis (Fig 15). The mechanical team has inspected this antenna. After fix, it shows the error of -0.5 arc-min (Fig. 16) and it is well within the acceptable range.

STP method (C14-EL):
Fig. 17 and 18 show the results before and after correction of the problem. Antenna C14 showed an error of -4.9 arc min in EL axis (Fig. 17). This has been fixed by the mechanical team. After fix, it shows the error of -2.2 arc-min (Fig. 18) and it is quite close to acceptable range.

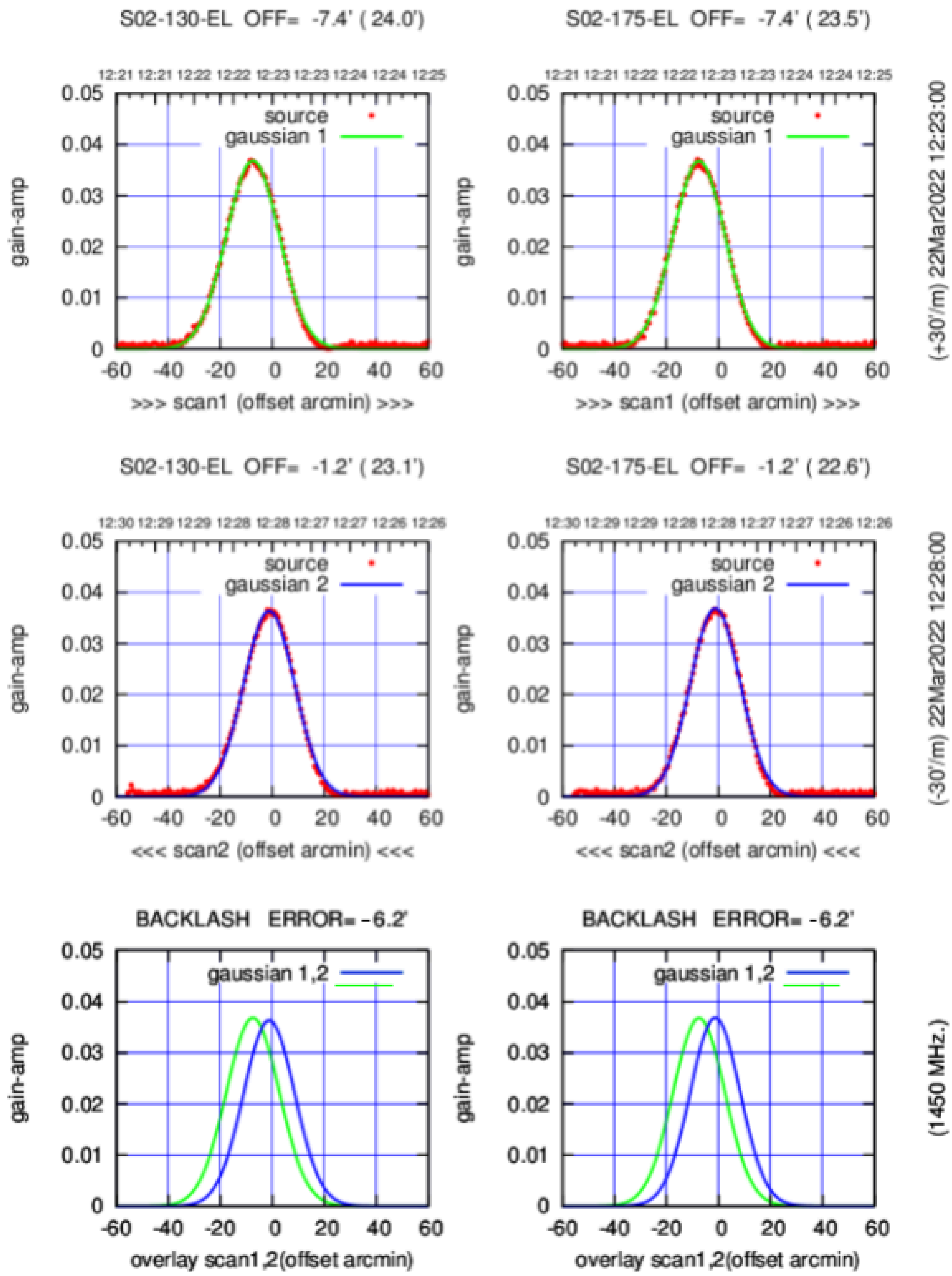


Fig 11. EL — backlash error of -6.2 arc min by astronomical method for S02 antenna

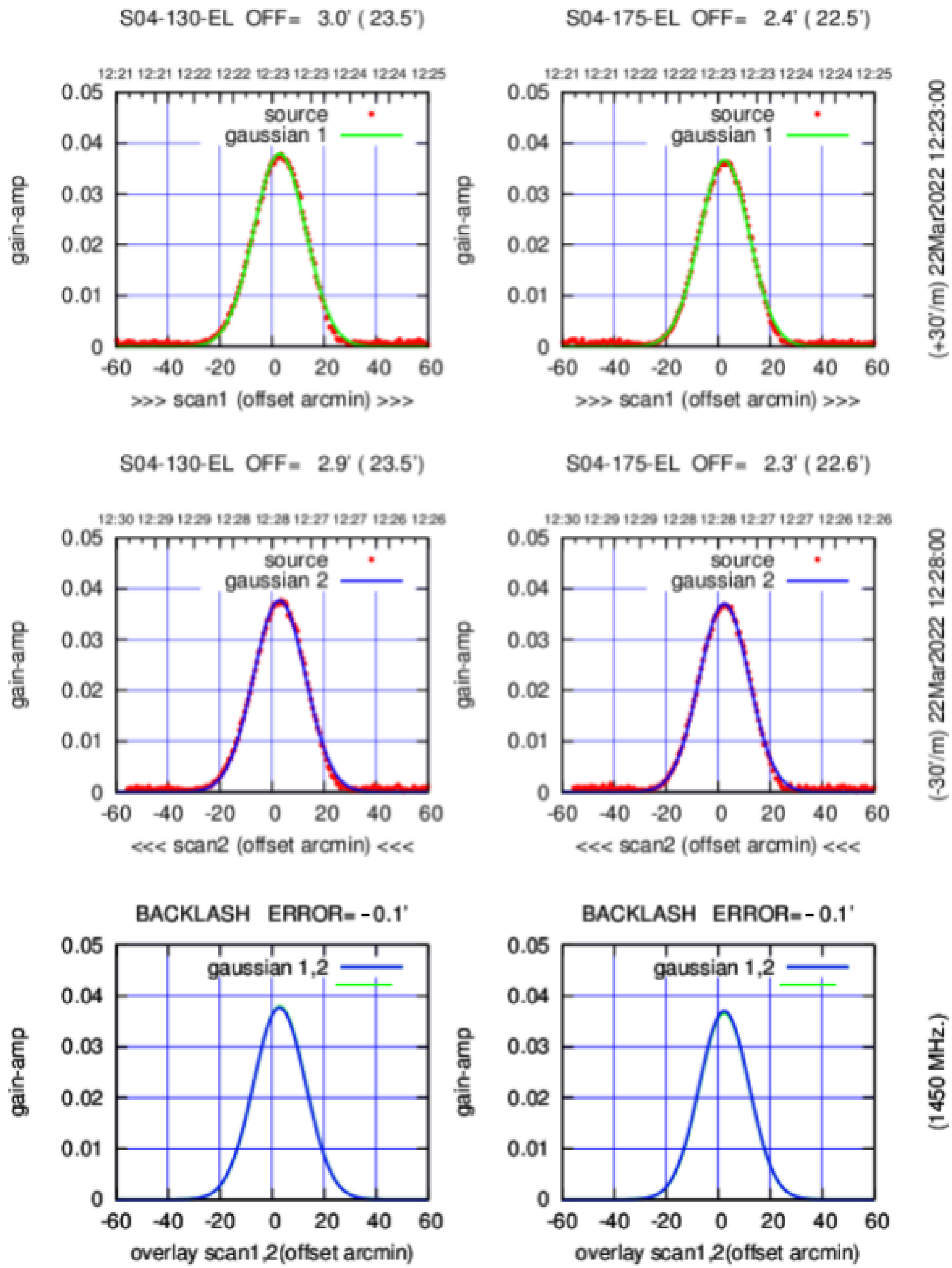


Fig 12. EL — backlash error of -0.1 arc-min by astronomical method for S04 antenna

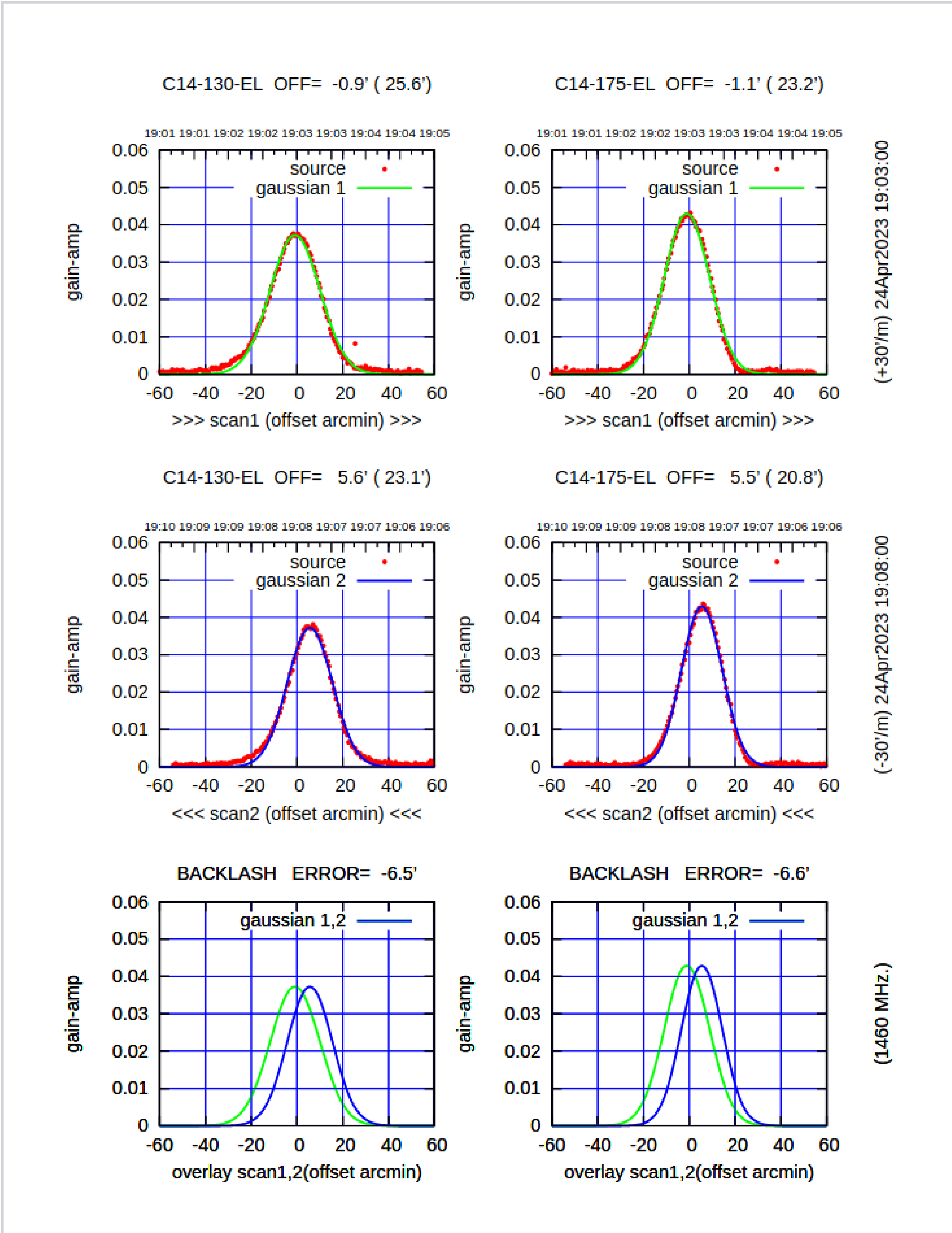


Fig 13. Before correction : EL — backlash error of -6.6 arc min by astronomical method for C14 antenna.

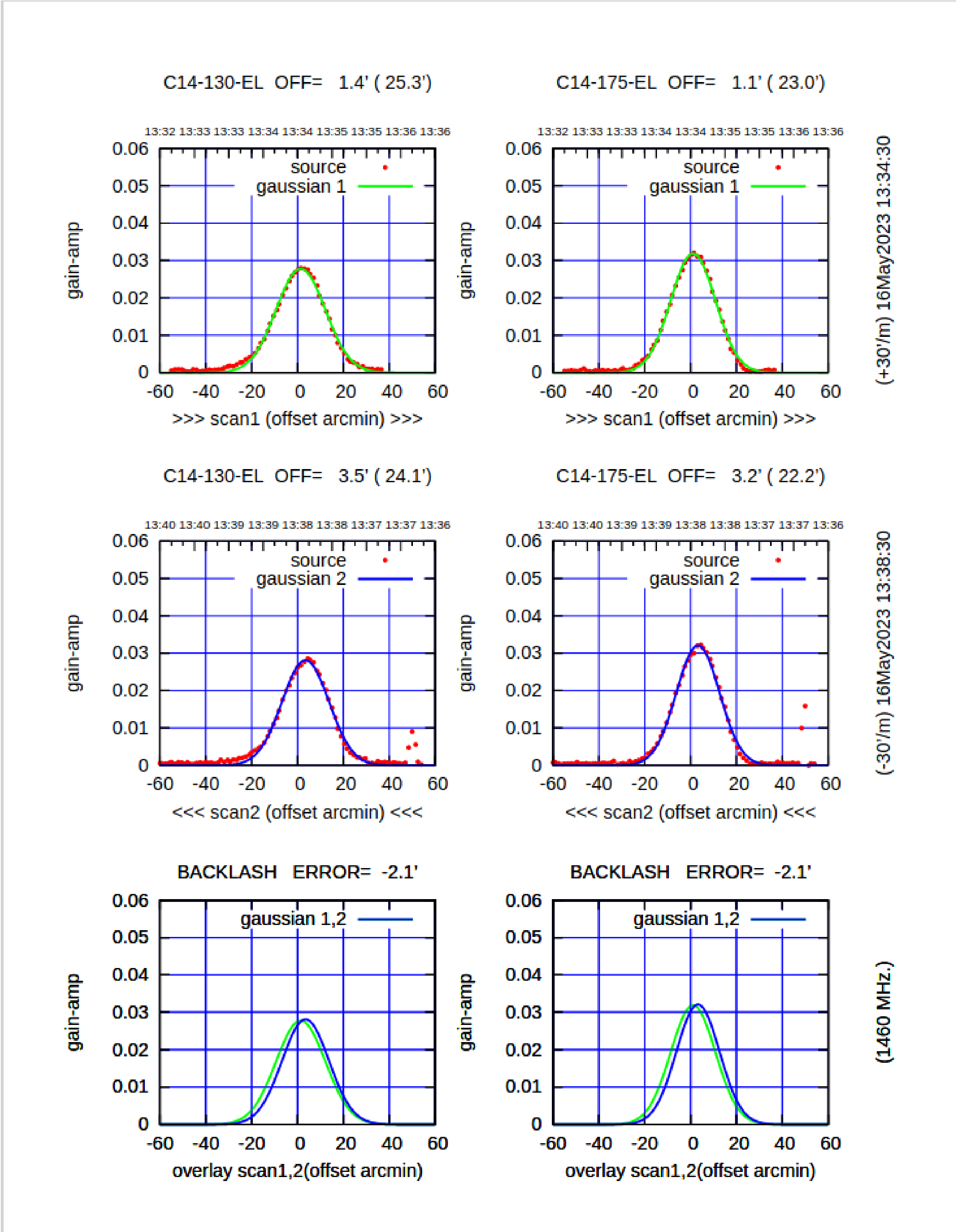


Fig 14. After correction : EL — backlash error of -2.1 arc min by astronomical method for C14 antenna.

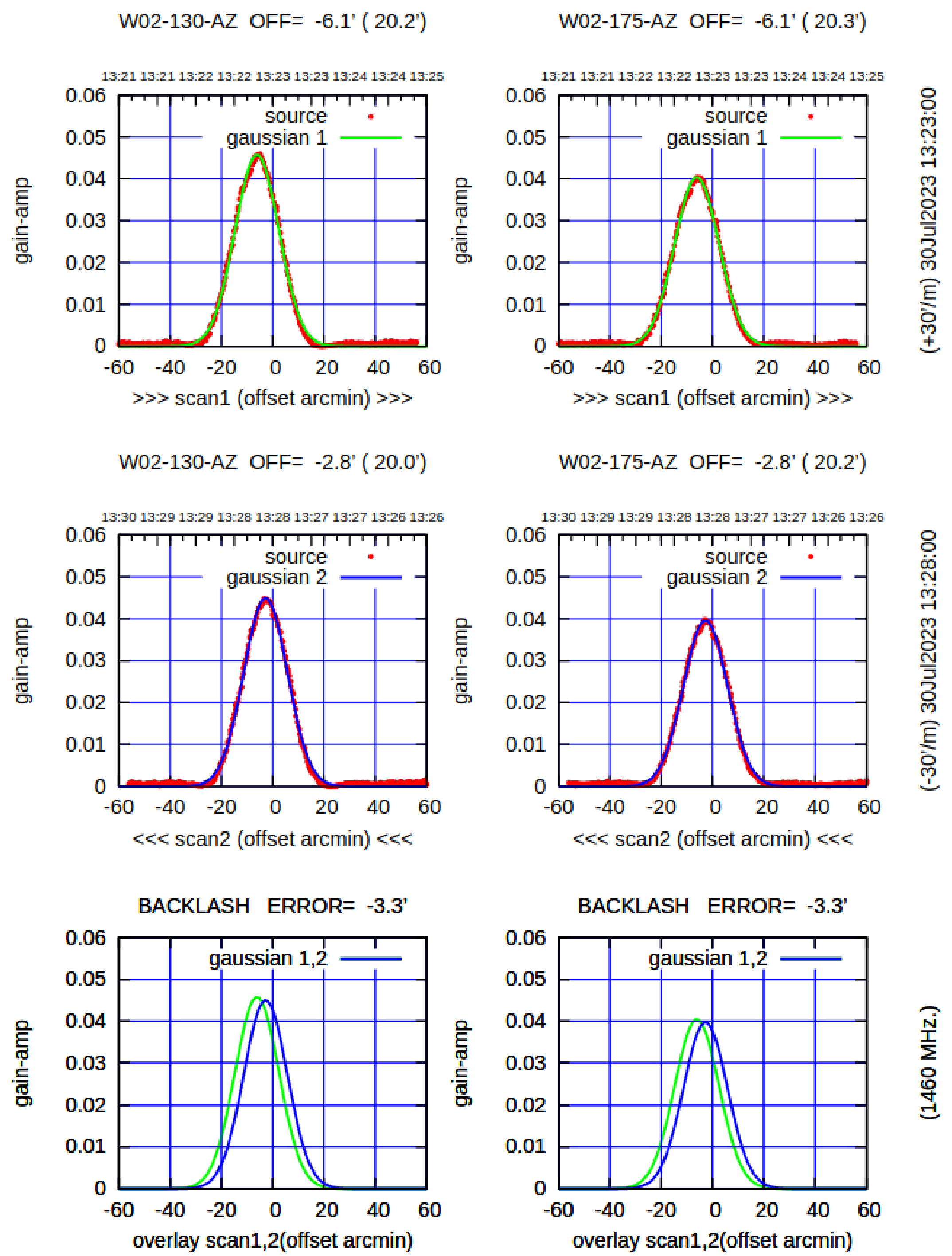


Fig 15. Before correction : AZ — backlash error of -3.3 arc min by astronomical method for W02 antenna.

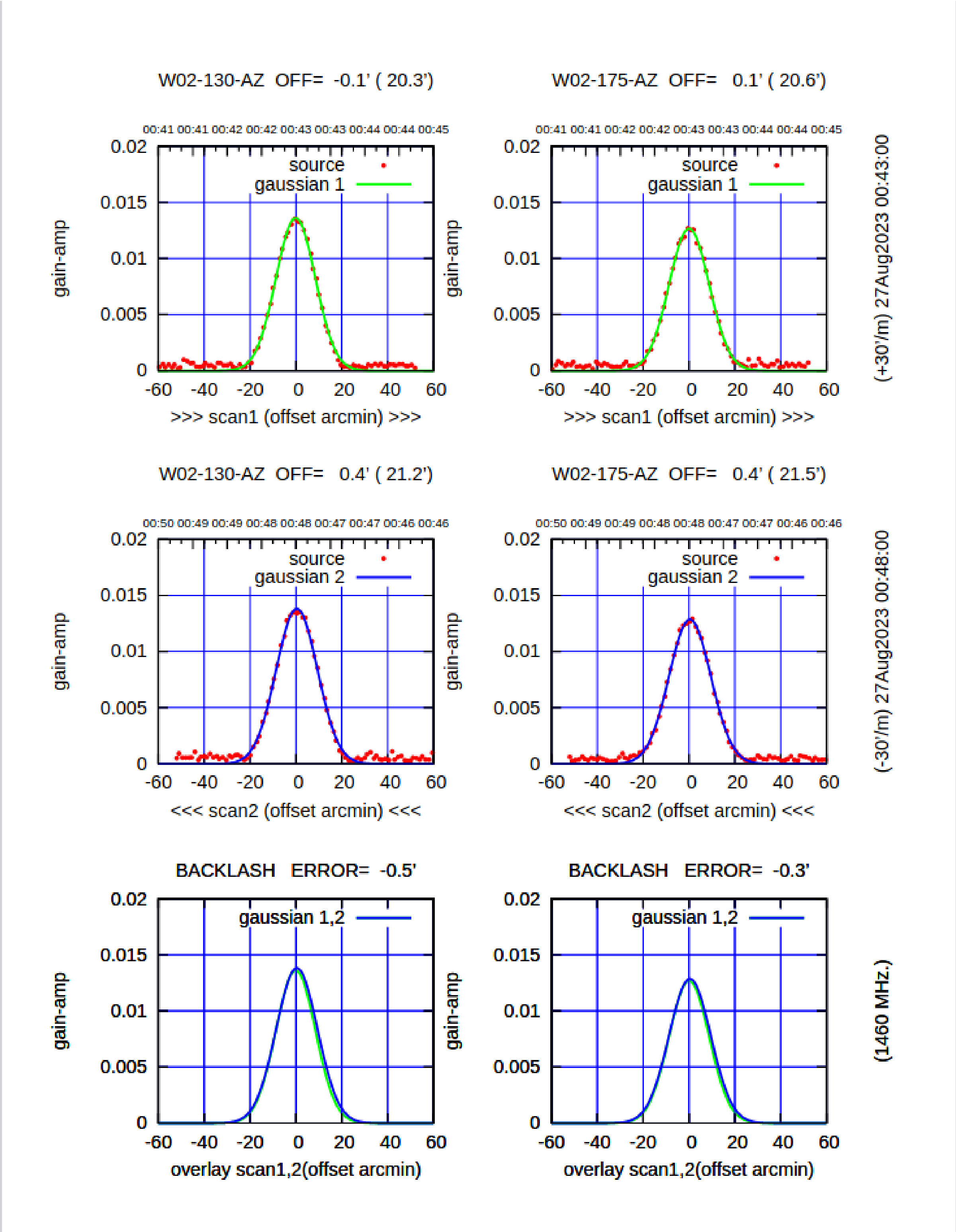


Fig 16. After correction : AZ—backlash error of -0.5 arc-min by astronomical method for W02 antenna.

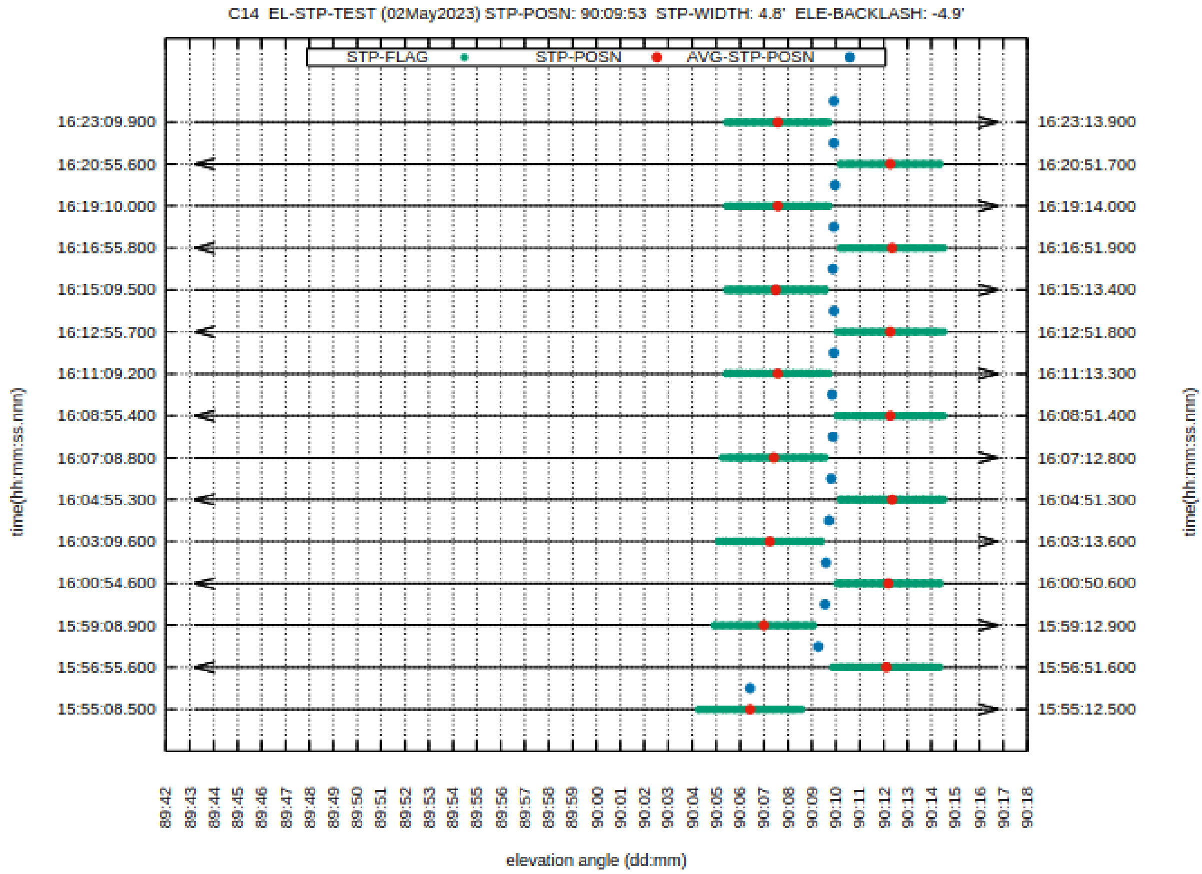


Fig 17. Before correction : EL — backlash error of -4.9 arc min by STP method for C14 antenna.

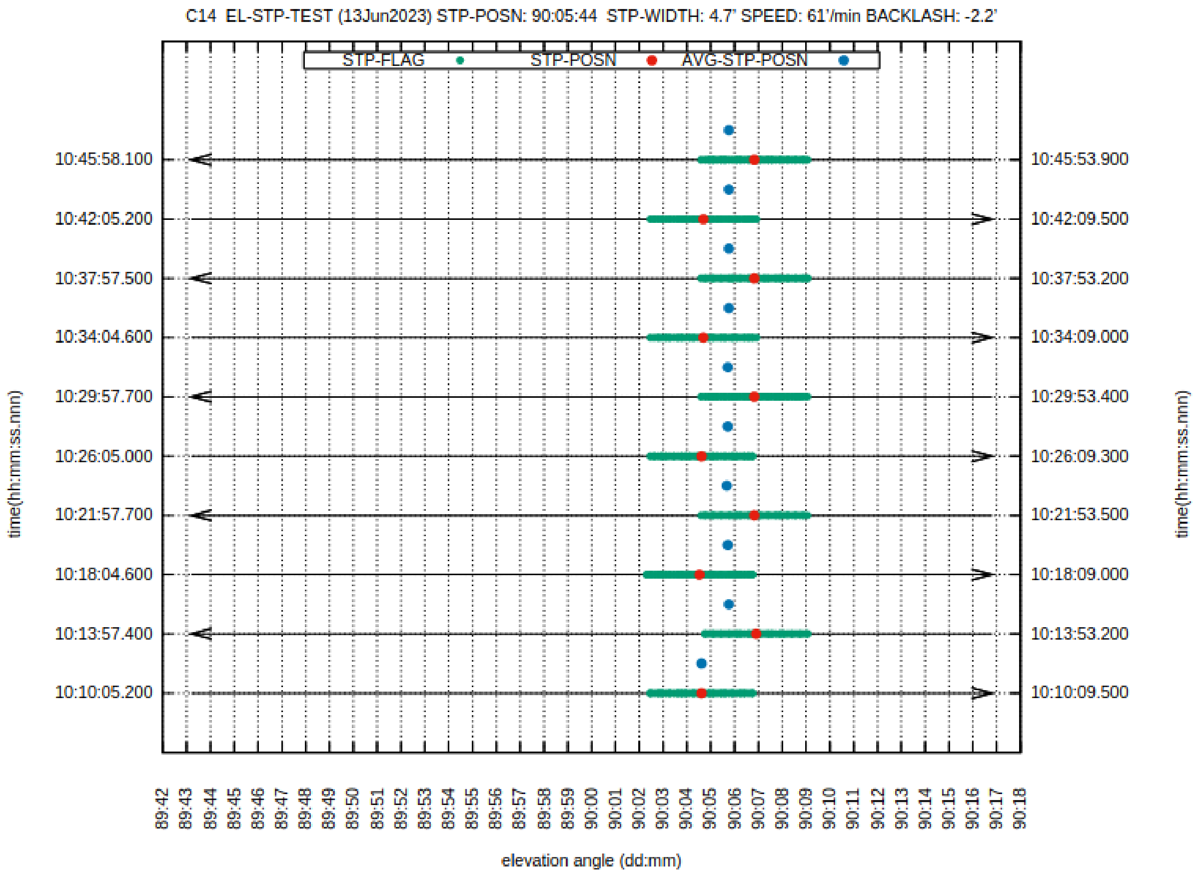


Fig 18. After correction : EL — backlash error of -2.2 arc min by STP method for C14 antenna.

Comparison of astronomical method with STP for elevation backlash

We compared the results from the two methods for all the working antennas when tests were conducted using both the methods on the same day. These tests were done on 16 & 30 Nov, 14 & 28 Dec 2023; 25 Jan, 08 & 22 Feb, 07 Mar and 06 Jun 2024 respectively (total 9 days of observations). Fig. 19 shows the mean offsets and their standard-deviations from the astronomical methods over 9 days.

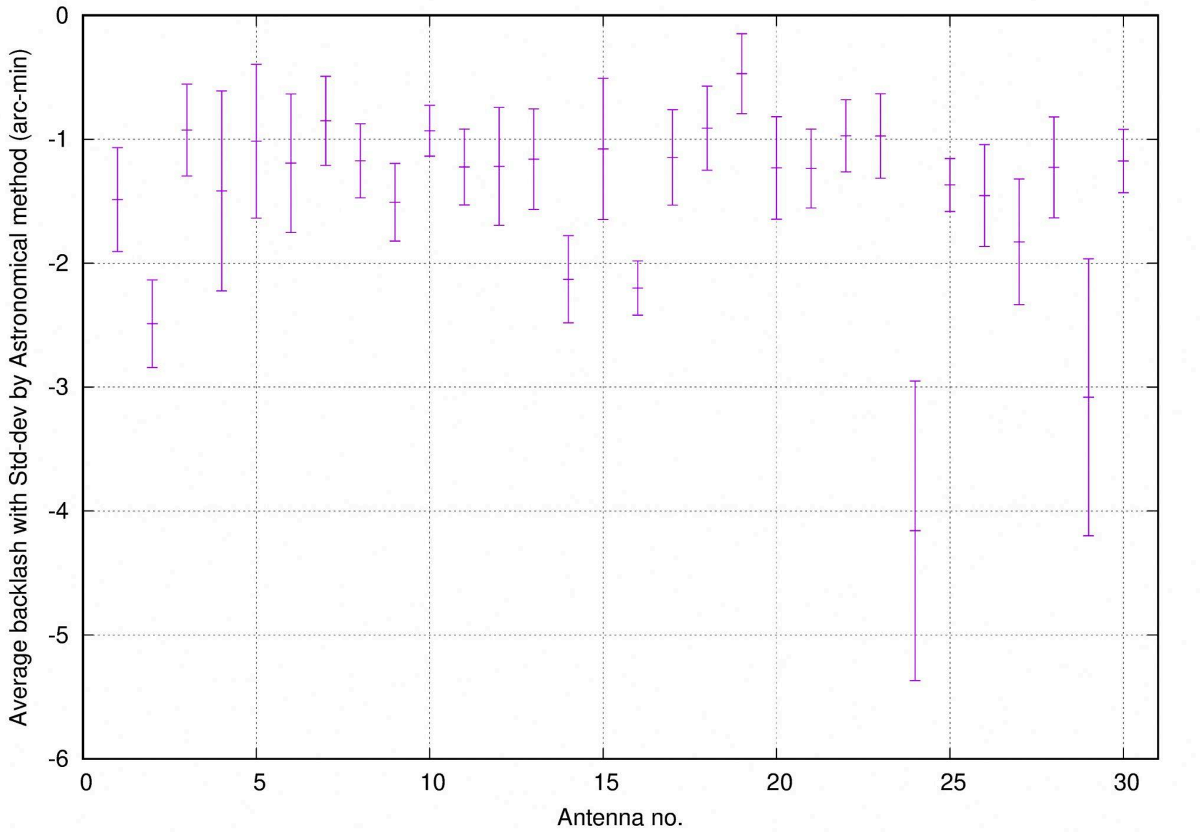


Fig. 19: Average backlash (in arc-minute) as measured from 9 different days of observations using the Astronomical method. To indicate typical day-to-day variation, standard deviations from 9 different days have been computed for the 30 antennas, which are shown as error-bars.

As can be seen from the plots, the typical backlash is non-zero, and the average is -1.4’. The typical variation of backlash errors are ~0.4’. Considering offset from the mean over 1’ (2.5 Sigma) to be significant, we notice two antennas, S06 (24) and W05 (29). These antennas, therefore, show large backlash errors. Fig. 20 shows the difference between Astronomical and STP methods. We notice that S06 and W05 also show a significant difference of backlash as determined from the 2 methods. They also show larger standard-deviation of differences between the 2 methods.

However, leaving the above 2 antennas, the difference between the 2 methods are not significant for the rest of the 28 antennas.

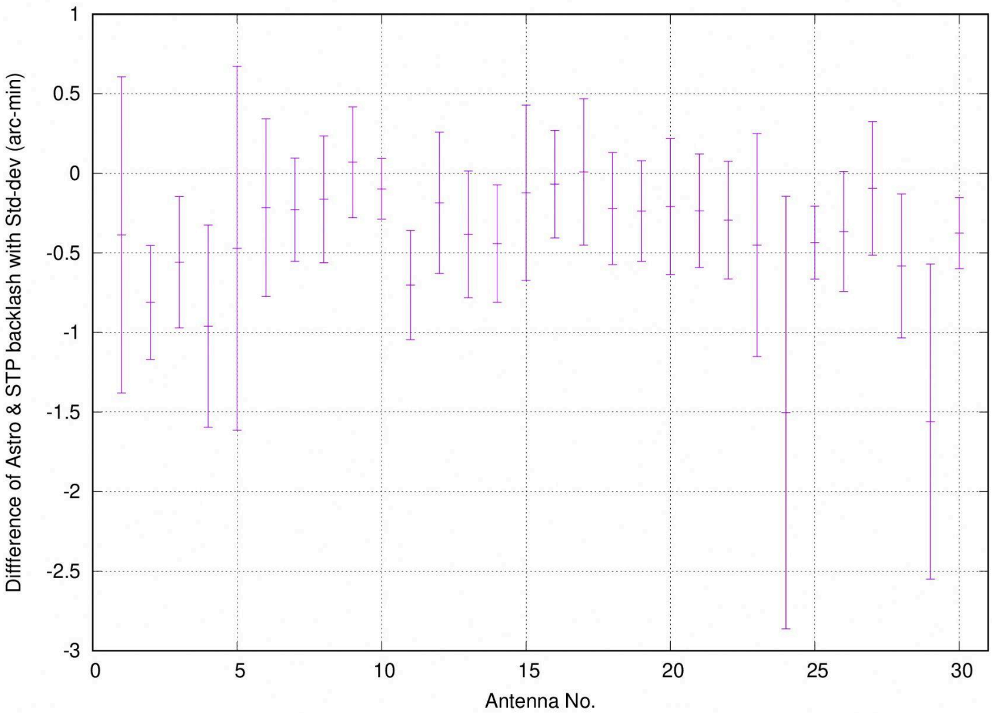


Fig: 20: Average difference of backlash (in arc-minute) between Astronomical and STP method as measured from 9 different days of observations. To indicate typical day-to-day variation, standard deviations from 9 different days of observations have been obtained for the antennas, which are shown as error-bars.

Discussions

From the tests carried out, S06 and W05 are the antennas which have significantly large backlash errors in elevation, and these need to be checked by the mechanical team. Backlash error could depend on elevation angle, and if so, that would explain the larger differences seen between the results from Astronomical (done over a range of elevations angles) and STP method (done close to an elevation of 90 deg). This would also explain the non-zero mean difference seen for most of the antennas (mean difference is about -0.4 arc-min averaged over 30 antennas). Backlash errors from the Astronomical and STP method have the same sign ('+' or '-') for all the antennas, and the differences for 28 out of 30 antennas are comparable to inherent measurement error. Therefore, STP method could be relied on in measuring backlash errors in elevation.

Backlash error significantly beyond the typical pointing errors (~1 arc-min) in the antenna axis shall cause pointing error depending on the direction of antenna movement. These would degrade pointing accuracy during astronomical observations. As the antenna primary beam can be modelled by a Gaussian, the fractional change of source flux densities due to pointing errors is minimum along the axis of the antennas, and increase with angular distance from the axis. Therefore, sources near the edge of the primary beam are most affected. Moreover, the pointing errors/backlash are not constant over time, but could change as a function of elevation angle of the pointing direction. Imaging of astronomical sources is done by Fourier-transforming the calibrated visibilities obtained from pairs of antennas. In Fourier-transform, flux densities of sources are considered constant during observation. Variable flux densities of sources due to pointing/backlash errors then causes artifacts in imaging, and thereby reduces dynamic range of interferometric images (Roy 2013).

Therefore, it is important to keep track of these errors on a regular basis due to wear and tear of the mechanical system. The astronomical method works for both elevation and azimuth axes. However, doing the experiment also requires a significant amount of observing time, and it is possible to be impacted by tracking related timing errors while measuring the backlash error (E=E1+E2) as discussed earlier.

The STP method works only for the EL axis, but it is not affected by timing errors. It is also less time-consuming and should provide more accurate backlash value.

We suggest conducting a backlash measurement in elevation axis every two weeks by STP method and once every month by astronomical method in both axes to keep track of the mechanical health of the antennas.

The backlash problem is mostly seen in the EL axis only, due to the limited (17 deg to 90 deg) movement of the EL axis. Hence, we recommend conducting the "stress test" for the antennas every fortnight during backlash measurement. In the "stress test", the antenna has to be rotated through larger limits, beyond the tracking limits. For the EL axis, one can rotate the antenna from 17 deg to 104 deg. This will help to reduce the friction between the EL encoder assembly bearings.

SOP for conducting backlash test

STP method (EL axis):
This test has to be conducted every two weeks or so and the time required for this test is around 30–60 minutes. Here we need only a servo system and no correlator or receiver setup required. The steps to conduct this are given below.

1. Generate the command file by using command file generator script. (/data1/gtac/cmd/stp_posn/gen_stp_cmd.pl)
2. Move the antenna to EL 89 deg and apply the brakes to AZ axis only.
3. Start the command file. Here we do not have to record any servo data, servo data is already getting recorded on the TGC server machine.
4. Stop the command file after the desired time (minimum 30 min are required)
5. Now use a data analysis script on the tgc3 machine to get the results. Edit the script and enter the start and end timings of the test and execute the script. (/home/tgcuser/bin/get_stp_pos.pl)
   It will produce the PDF file for plots and summary for results.
6. If you find any antenna having error more than the acceptable range, then raise the call sheet.
7. It takes around 3 days for the mechanical team to fix this issue, hence redo this test after the mechanical fix for confirmation.

Astronomical method (EL and AZ axis):
This test has to be conducted every month or so and the time required for this test is around 60–90 minutes. Here we need a servo system, correlator (GWB) and receiver setup. The steps to conduct this are given below.

1. Generate the command file by using command file generator script. (/data1/gtac/cmd/bin/raster_cross_b5_pnt.pl)
2. Do Band-5 setup and track the calibrator source (3C) and check fringes.
3. Start the command file, lta data is getting recorded through the command file. Separate lta recording is not required.
4. Stop the command file after the desired time (minimum 60 min are required)
5. Now run the data analysis script on gwbh6 machine it will use “extract” program to get the cross data from the lta file, fit the Gaussian and get the offsets values and generate the text and PDF file for all antennas. For multiple readings, use another script to plot the offset as a function of time to get the more accurate error values.

6. By looking at the graphs and values, raise the call sheets for the problematic antennas.
7. It takes around 3 days for the mechanical team to fix this issue, hence redo this test after the mechanical fix for confirmation.

Additional results

These are test reports obtained from a large no. of tests conducted over the last one year, and could be checked through the links provided below.

STP flag method backlash test results
STP flag method backlash trends

Astronomical method backlash test results
Astronomical method backlash trends

References

Kantharia, N. G., 2008, in NCRA Technical report "Towards a pointing model for GMRT antennas - Part I"; original submission 2005.

Kantharia, N.G, Kulkarni, V. K., Nityananda, R., 2009, in NCRA Technical report "Towards a pointing model for GMRT antennas - Part II".

Roy Subhashis & Kulkarni Vasant, 2009, in NCRA Technical report "Towards a pointing model for GMRT antennas—Part III— model parameters and implementations".

Roy Subhashis, 2021, in NCRA Technical report "Pointing model evolution for GMRT antennas over the last decade".

Roy Subhashis, 2013, in NCRA Technical report "Antenna pointing error and its effect on dynamic range in radio interferometric imaging: results from simulation".

Lal Dharam Vir, Ishwara-Chandra C.H. & Rao A. P., 2005, in NCRA Technical report "The GMRT antenna pointing—II. Understanding the elevation offsets as a function of the hour angle of the source".