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HERA Memo 54
Bispectrum Phase around Fornax A Transit using IDR2.1 Data

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ABSTRACT

As part of our power spectral analysis of closure phase spectra for HERA, we present the measurements of the closure phase spectra from the IDR2.1 data. Our analysis focuses on the time range of ±30 min around the transit of Fornax A. We find:

- The closure phases within 20 min of transit of Fornax transit are well behaved, with the dominant point source leading to closure spectra with spectrally smooth fluctuations around $0^\circ \pm 20^\circ$.
- Significant systematic differences occur between triads, much larger than the noise.
- Significant differences between polarisations are seen on given triads.
- Time averaging of about 60sec is about the maximum for coherent averaging of closure spectra, before systematic changes dominate over noise.
- Two RFI-free frequency ranges are identified in the median filtered data: 110 MHz to 136 MHz, and 151 MHz to 173 MHz. These frequency ranges and times should be optimal for power spectral calculation.

1. DATA AND PROCESS

We analyzed data from the 18 days in the IDR2.1 database Dillon & Team (2018). We employ the raw visibility data, with no calibration. Some of this analysis parallels that of Carilli et al. (2018) but using the more recent IDR2.1 data.

Closure phase spectra were generated for all the days using the CASA closure software Carilli & Nikolic (2017). Data were selected at ±40 min of the transit time of Fornax A (RA = $03^h22^h42^s$, Dec = $-37^\circ12'30''$). We choose this time range for power spectral analysis for a number of reasons. First, since Fornax A is a strong radio source, unresolved on short baselines, it drives the closure phase values to $\sim 0^\circ$. Second, Fornax A transits at about the 10% point of the primary beam, so that, while still the dominant source in the field (apparent peak flux density ~ 70 Jy beam^{-1} at 150 MHz, vs. true flux density of Fornax A ~ 700 Jy), it does not overwhelm the system temperature. And third, the Fornax field is in the center of a Galactic cold patch at low frequencies.

The data from all the days were aligned in LST, and then LST binning was applied, taking the median value over the 18 days for each LST bin. Note that this not an exact binning, since the LST bin values shift by a few seconds from day to day. The records that most closely matched in LST (again, within a few seconds), were median filtered to obtain the final, LST-binned closure phase spectra with nominal 10.7 sec records.[1]

We employ five different triad types: equilateral triads of 14 m (EQ14) and 28 m (EQ28) baselines, and the shortest linear triads (two 14 m baselines and corresponding 28 m baseline), at three orientations: East-West, and $\pm 30°$ with respect to north.

The purpose of this memo is to summarize the behaviour of the closure phase spectra vs. time, polarisation, and triad type. Having this information immediately available is crucial when diagnosing the power spectra derived from the delay-spectrum analysis of closure phase spectra.

2. ANALYSIS AND RESULTS

An overview of the data is shown in Figure 1 as a waterfall plot of closure phase versus time for a single triad. It can be seen that the section of the data around transit (approximately 3 to 3.65 hours) and in channel number ranges 150 to 900 are smoothly varying, free of phase wraps and generally close to zero phase. Outside of this range wrapping of phase and sharper changes can be seen. In Figure 1 we also contrast the median-filtered versus original data. It can be seen that median filtering is effective at eliminating apparent intermittent RFI and other artefacts in the data.

In the median-filtered overview plot a vertical ribbed pattern can be noticed in large sections of the data. An enlarged plot accentuating the detail is shown in Figure 2. The ribbed pattern consists of regular repeated vertical fringe-like features superimposed on the smoothly varying background. The cycle period of the fringes is approximately 10 channels, and this corresponds to a ripple in thee individual closure phase spectra with a characteristic delay of approximately 1 microseconds. The ribbing pattern is mostly coherent over time with a slight but again noticeable drift in phase over time. We estimate ripples drift out of phase in about half an hour.

The working hypothesis is that the ripple is due to reflections in the cables which have a round-trip path travel of 300 m, i.e., 1 μsecond. We have not examined why the ripple shows through in the closure phase in spite of presumably being antenna-based.

Figure 3 shows the closure phase spectra for all Linear triads at PA = $-30°$, XX polarisation, for times ranging over ± 20 min of the transit of Fornax A. Time labeling is in record number, with Fornax A transit at record 208. The frames are spaced by 25 records, or 267.5 sec. The closure phase spectra converge toward zero closure phase as the Fornax A point source dominates the measurements. There remains broad structure in frequency at

[1] The sky calibrated IDR2 data have record lengths of 20 sec, but we used the raw data from the archive, which have 10.7 sec records.

the $\pm 20^\circ$ level, due other emission components in the beam, likely diffuse emission. The deviations between triads also tighten as Fornax transits, because the effect of non-redundancy between triads is reduced when a point source is dominant (see Carilli et al. 2018, for discussion). But even at the best of times, the spread in the closure spectra from triad to triad is much larger than the noise, and there are a few triads that stand out at some frequencies by $\sim 10^\circ$ to 20°.

We re-emphasize that these are raw data, i.e., no calibration applied. Interference is apparently less of a dominant issue in the closure phase measurements, and the median filtering is effective at further mitigating RFI. There are still some bad frequencies, such as Orbcom at 136 MHz, channel 511 in the center of the band (150 MHz), and at channel 176, or 174 MHz. There are two frequency ranges that are essentially RFI-free after median filtering: 110 MHz to 136 MHz, and 151 MHz to 173 MHz. These frequency ranges should be optimal for power spectral calculation.

The closure phase spectra show the least structure, and tightest correlation between triads, in the time range of record 125 to 275 (± 14 min around transit of Fornax A), although extending the analysis to 100 to 300 may be plausible.

Figures 4 and 5 show the closure phase spectra at record 175, five minutes before Fornax A transit, for all triad types, and both polarisations. There are significant differences between polarisations on a given triad type. This might be due to polarized sky emission, or differences in the XX and YY primary beams. There is no strong qualitative difference between EQ28 and EQ14, in terms of the magnitude of the structure with frequency. E28 YY appears to have the least structure of all the triad types and polarisation. The linear $+30^\circ$ XX triad shows the most structure with frequency of any triad type and polarisation. Note that smooth structure with frequency in the closure phase spectra, and even phase wraps, does not preclude power spectral analysis in search of the narrow-band HI 21cm signal (in particular, since the power spectral analysis is done on the complex quantities), as long as this structure is smoother in frequency than the HI signal (Thyagarajan et al. 2018).

Figure 6 shows closure phase spectra for ten random triads, for EQ28 YY data, averaged for 64 seconds. The spectra are similar, but show significant deviations between triads, significantly larger than the noise. The deviations are presumed to be due to non-redundancy. This suggests that any cross correlation of signal between different triads should be done with caution and after quantifying the impact of the non-redundancy.

The top panel of Figure 7 shows closure spectra for one linear EW polarisation XX triad starting at time record 175. In each case, a different averaging time was used, ranging from 2 records to 8 records. In each plot, 4 curves are shown, corresponding to four sequential records, after averaging. For instance, at 2 records, each curve is separated by 21 sec, and at 8 records, each curve is separated 86 sec. It is clear that the curves begin to diverge, meaning systematic offsets in the closure spectra larger than the scatter in some frequency ranges, at around 4 record averaging = 43 sec. This is also visible in the Allan variance plots shown in the lower panel of this figure. The Allen variance analysis bottoms-out at around 50 sec averaging time, indicating an appropriate timescale for coherent averaging of closure spectra.

In Figure 8 we compare an individual closure phase spectrum computed from the median of the first half of days versus second half of days. It can be seen there is a high degree of similarity between these spectra. This approach combines the effectiveness of median filtering to remove RFI and other bad measurements (as shown in Figure 1), with reproducibility of the observed signal over different days. The medians of the two halves of days appear to be a good strategy for cross-correlation.

3. SUMMARY

These plots of the closure phase spectra of different types and different times should be examined during the power spectral calculations, since any diagnosis of features in the power spectra must reflect something in the input data.

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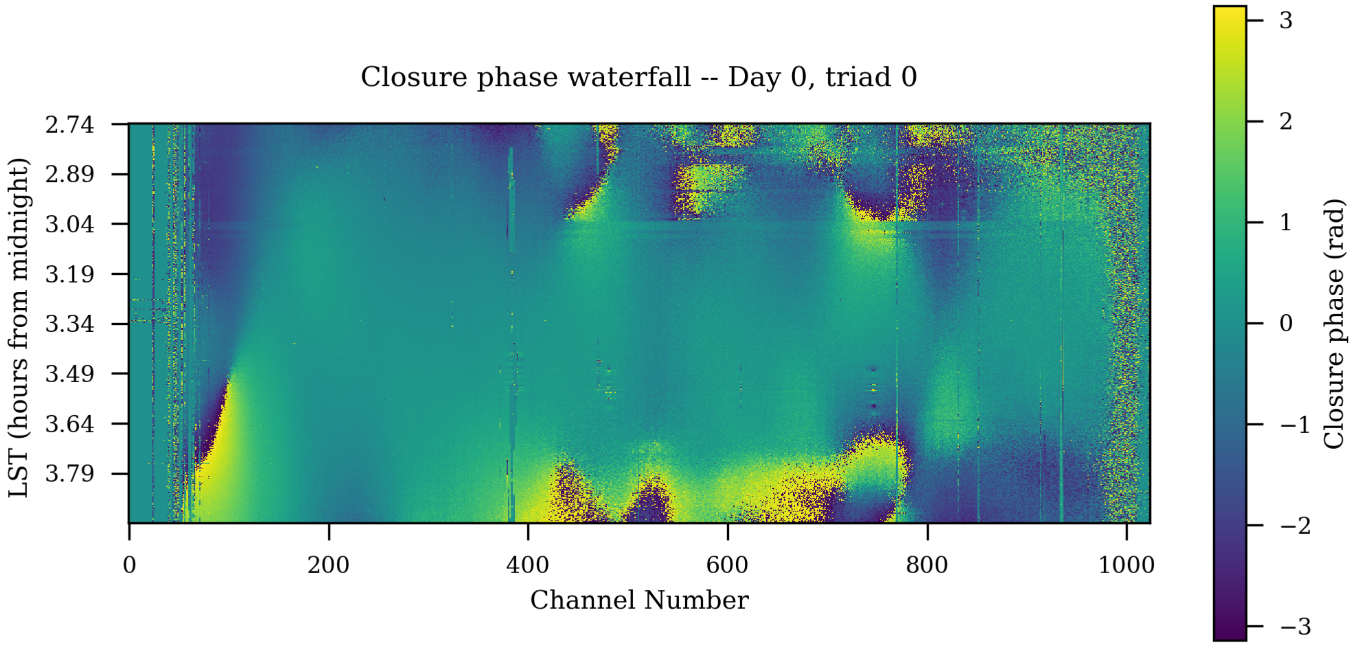
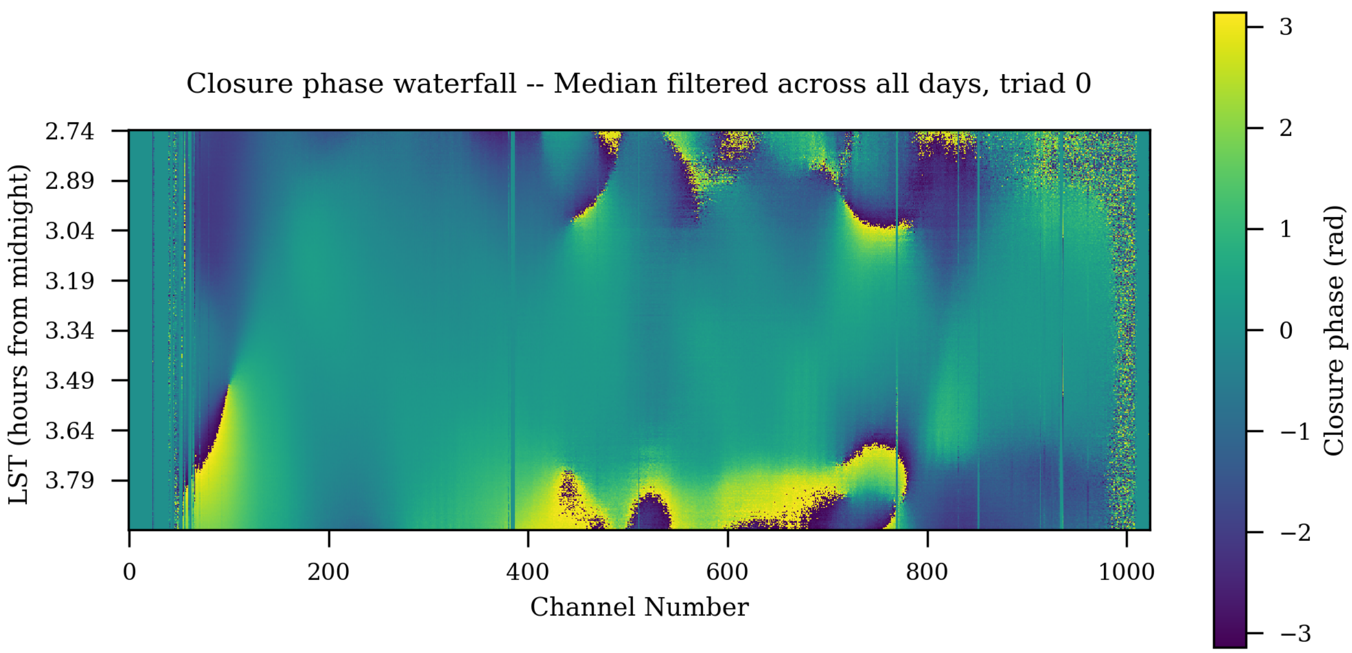


(a) First day



(b) Median filter across all days

Figure 1: Waterfall plot of closure phase as function of time (vertical axis) and frequency (horizontal axis) for the first triad. The two panels compare data from the first day versus the median filter across all of the days.

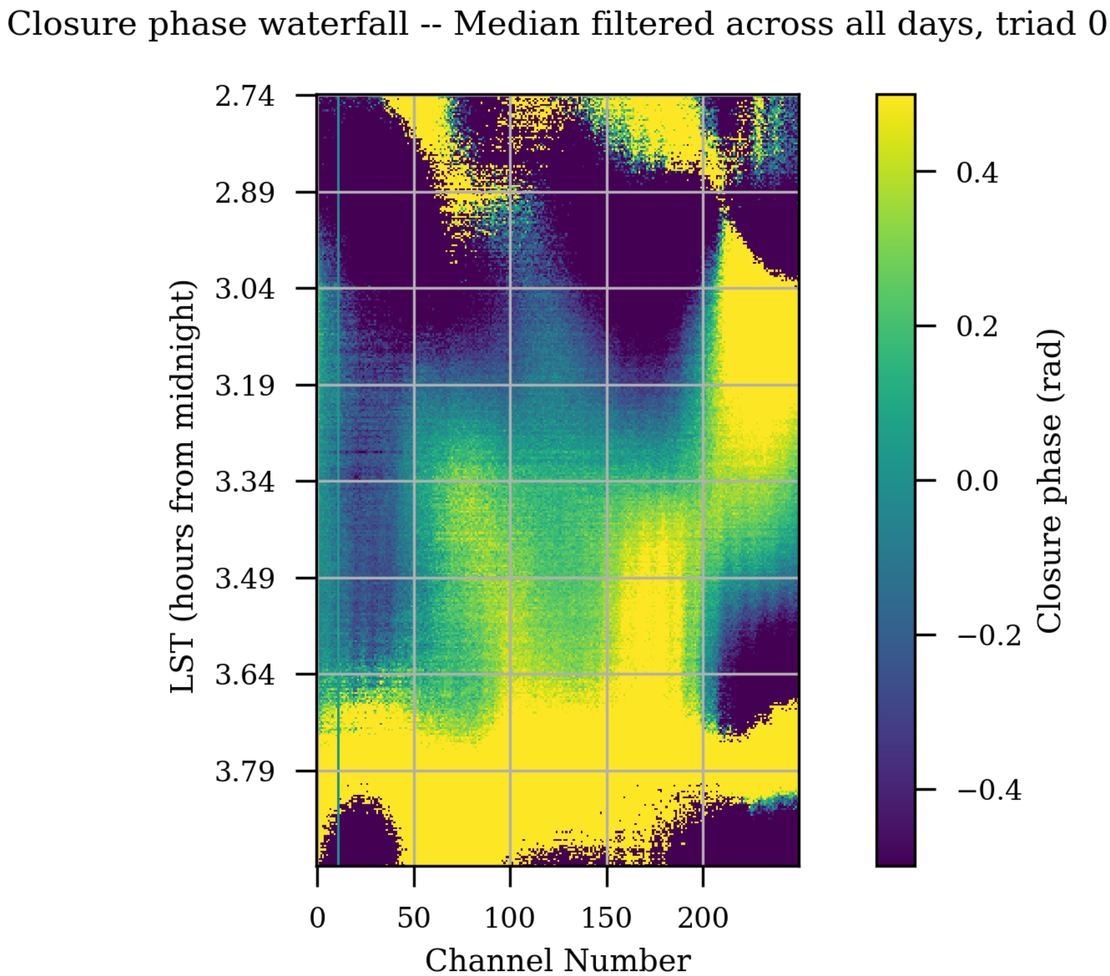


Figure 2: Waterfall plot of closure phase after median filtering for a subsection of data. Grid has been added to aid measuring the ribbed pattern and colour scale range adjusted to accentuate the detail.

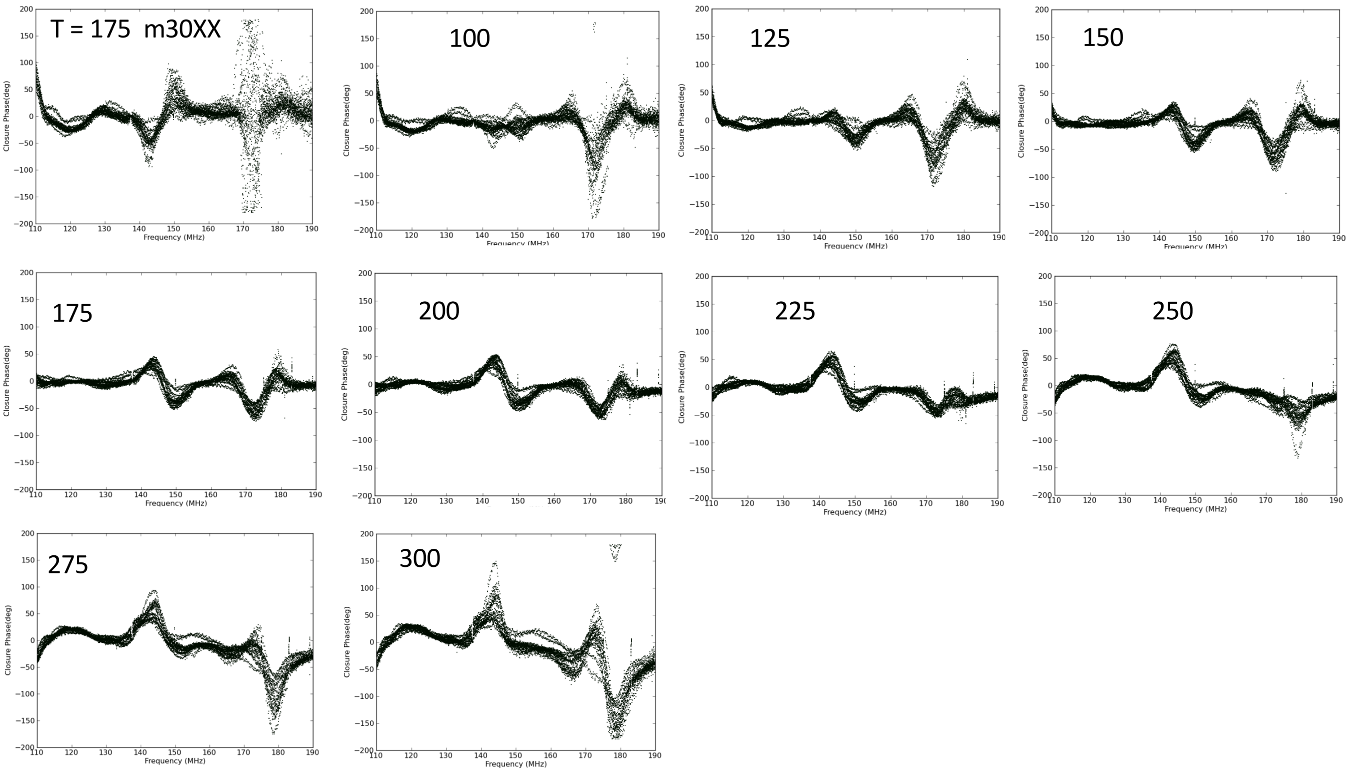


Figure 3: Close phase spectra after median binning in LST of 18 days from IDR2. The data are for all short linear triads with at PA = $-30°$. The time stamps in each frame are record numbers, with 10.7sec records. Record 208 is at Fornax transit (03hr 23m).

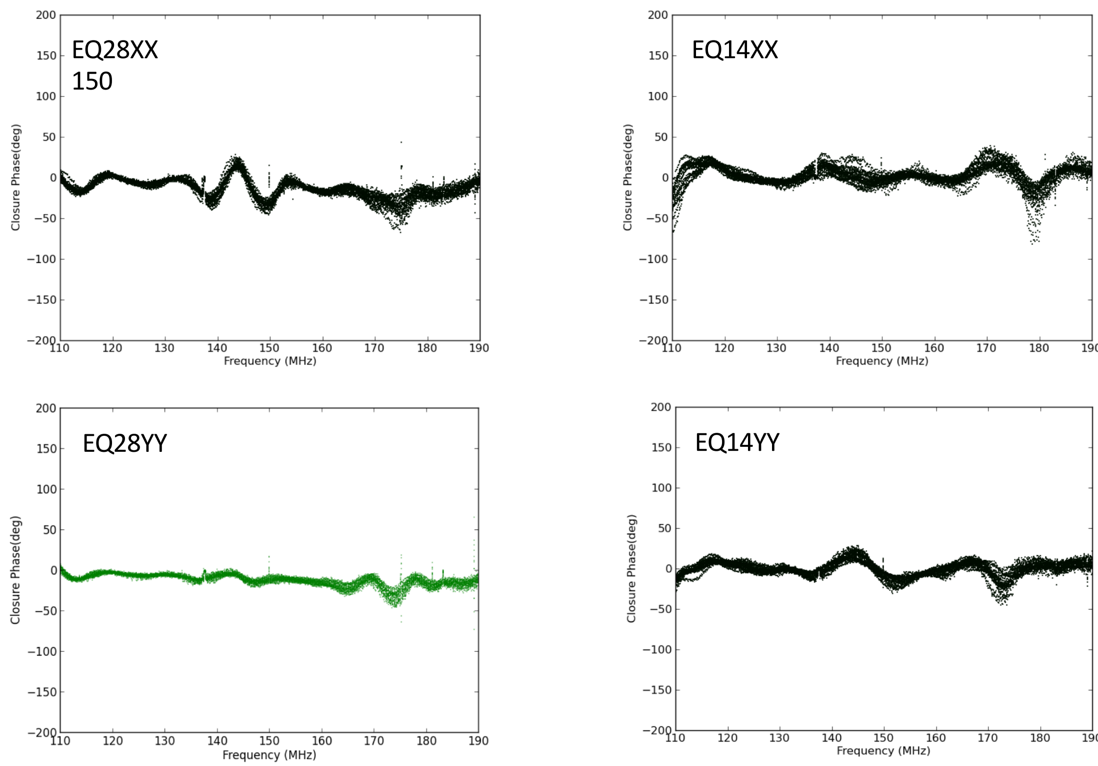


Figure 4: Closure phase spectra at record 150 (8min before Fornax transit), for EQ14 and EQ28 triads. Both polarisations are shown.

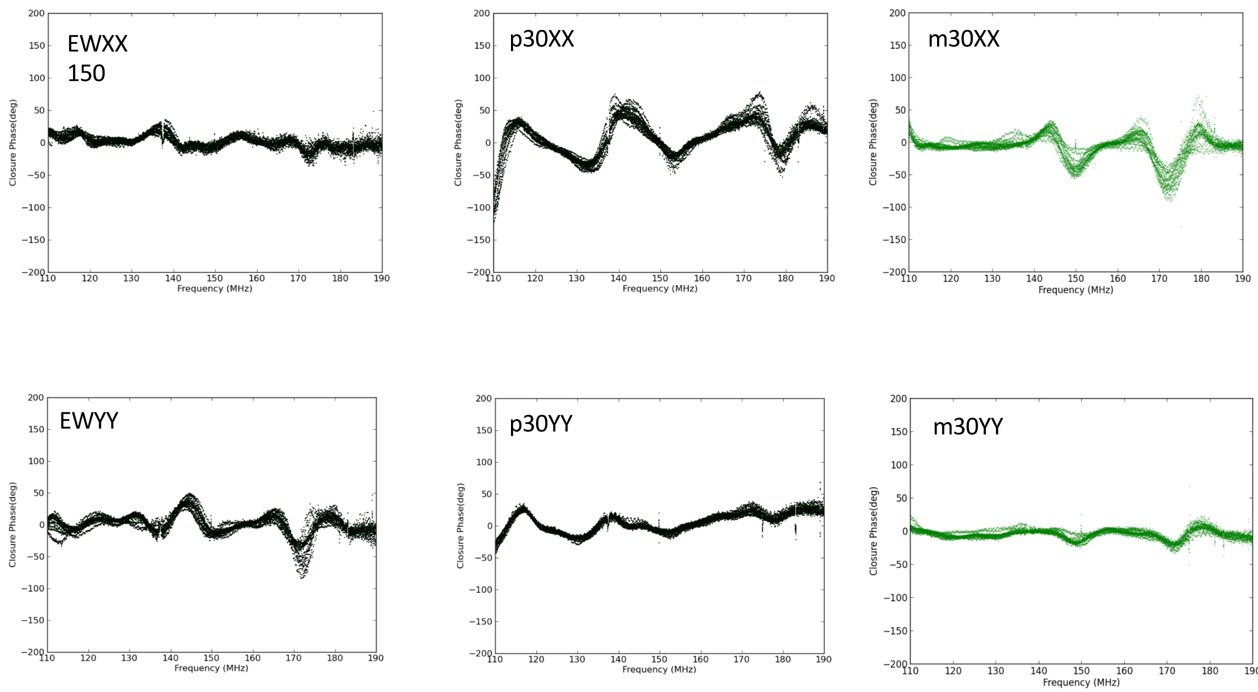


Figure 5: Closure phase spectra at record 150 (8min before Fornax transit), for short linear triads. Both polarisations are shown.

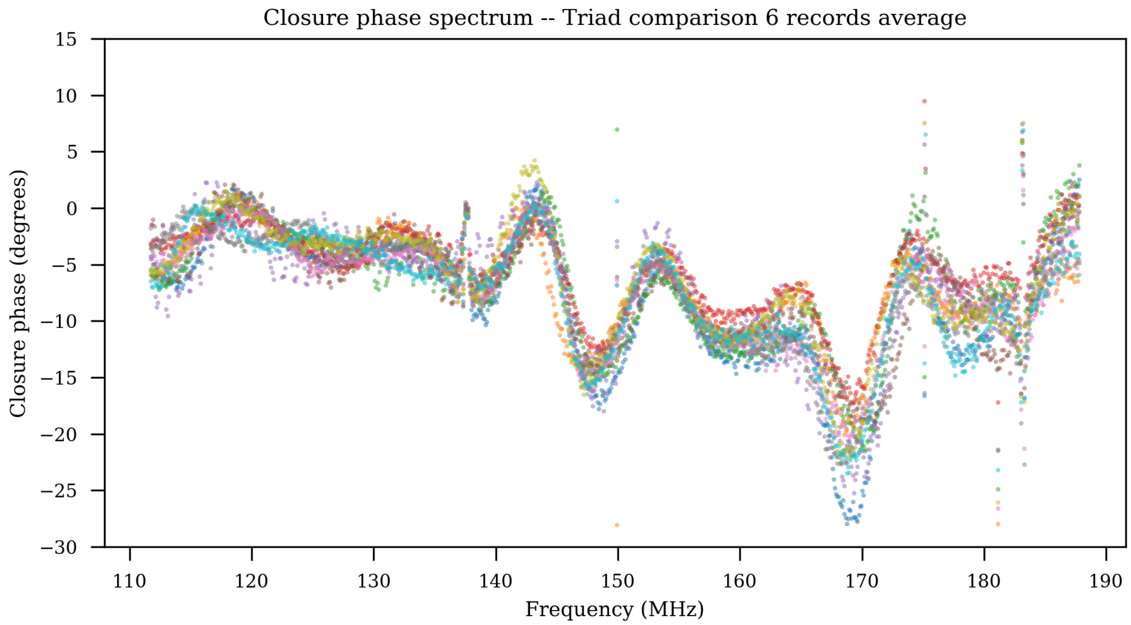
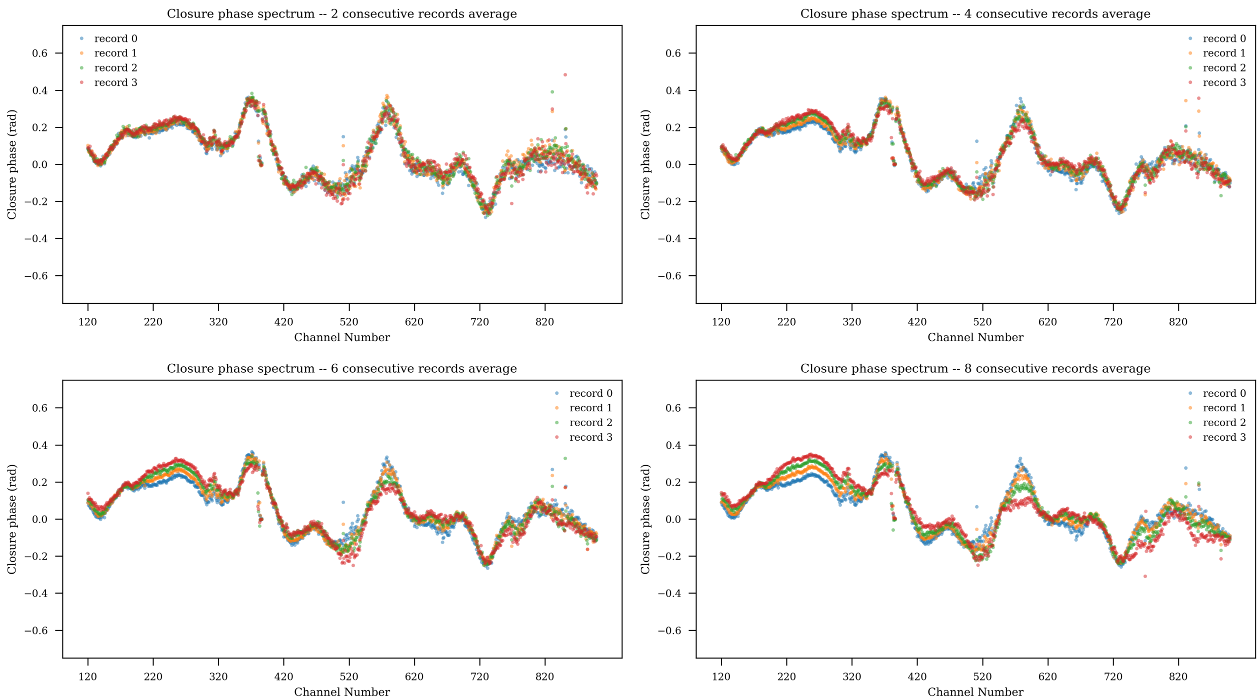
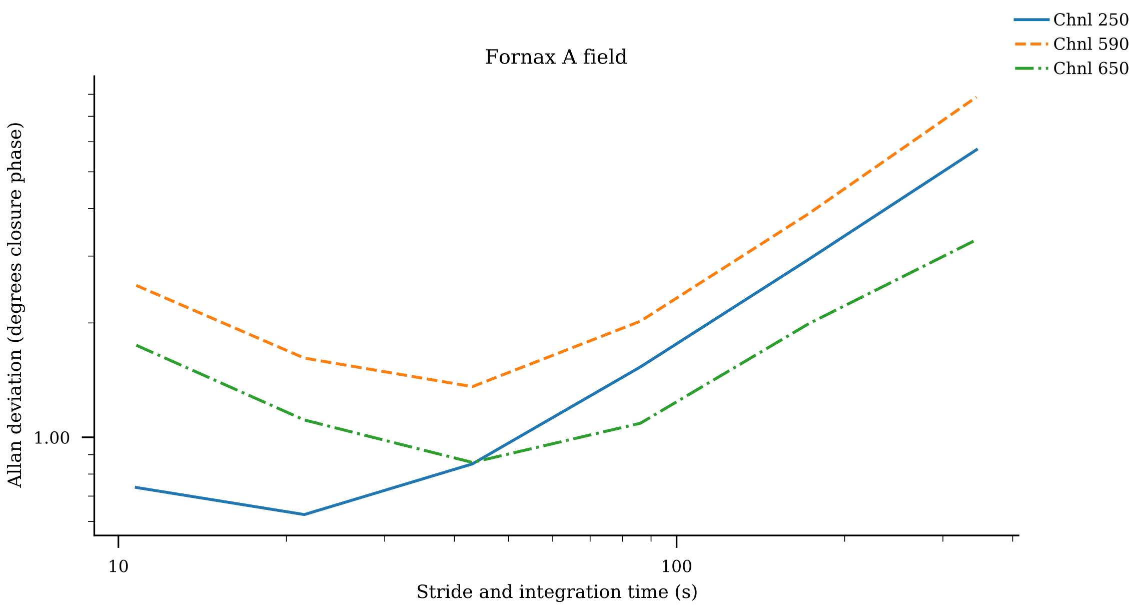


Figure 6: Comparison of closure phase spectra for ten random triads of type EQ28 YY, averaged over 64 seconds starting at record 200.



(a) Time averaging was employed, with the number of records averaged listed in the panels. Each frame has four spectra, corresponding to the sequential spectra after averaging in each case, such that by 8 record averaging, the red and blue curves (start and end), are separated by about 4 min.



(b) Allan variance as function of integration time for thee different channels.

Figure 7: Analysis of time variation in closure phase spectra for a single linear EW triad around record 175. Data were median-filtered across days to reduce noise and RFI and other artefacts.

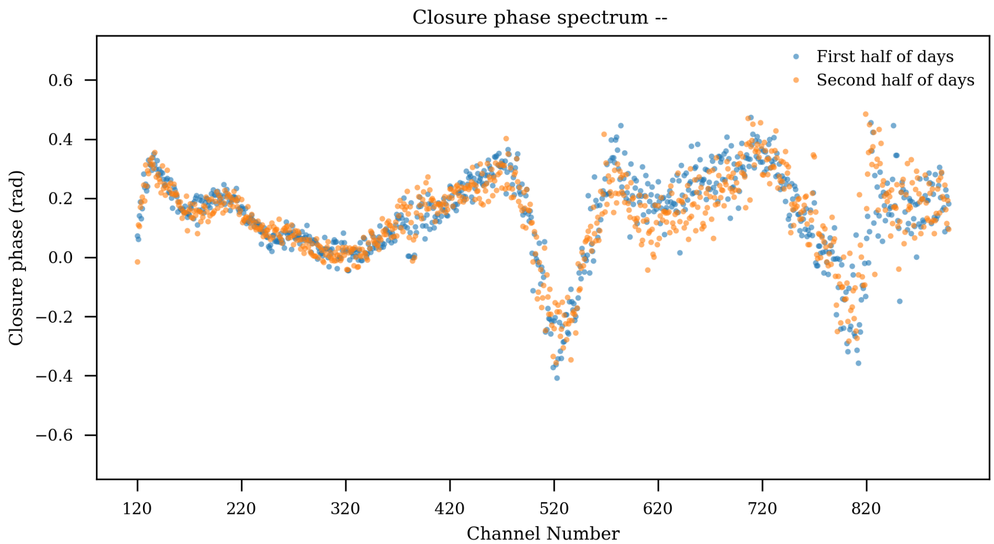


Figure 8: Median closure phase spectrum in a single LST time slot at Fornax A transit. The median has been computed over the first and second half of days in the dataset. The spectrum is for EQ14 triad number 0 polarisation XX.