Calibration and stability of the 64-channel dips

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Prepared by:	N. Ramanujam
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Name	SARAO Johannesburg Office (Rosebank, Gauteng)	SARAO, Cape Town Office (Observatory, Cape Town)	SARAO HartRAO (Hartebeesthoek, Gauteng)	SARAO, Karoo Astronomy Reserve (Carnarvon, Northen Cape)
Physical / Postal Address	1st Floor, 17 Baker Street Rosebank, Gauteng 2196, South Africa	2 Fir Street (North Entrance) Black River Park, Observatory Cape Town, 7925	PO Box 443 Krugersdorp 1740, South Africa	Posbus 69 Carnarvon 8925, South Africa
Tel.	+27 11 268 3400	+27 21 506 7300	+27 12 301 3100	+27 21 506 7300
Fax	+27 11 442 2454	+27 21 506 7375	+27 12 301 3300	+27 86 538 6836
Website	http://www.ska.ac.za	http:www.ska.ac.za	http:www.ska.ac.za	http:www.ska.ac.za

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CBF	Correlator and Beam Former
CB	Capture Block

1 Introduction

It has been known for a while now that data taken in both the 32K and 4K modes exhibit periodic dips every 64 channels. This is seen in the autocorrelations as well as in the visibility amplitudes. An example spectrum is shown in figure 1, using data which is a long track on J0408 in 32K mode in L band. The visibility amplitudes of the first 25 scans are median filtered and then averaged over time. The top panel shows this spectrum for XX polarisation and the bottom panel shows the same spectrum folded over every 256 channels. The periodic 64 channel dips are obvious. We see this issue in 32K and 4K data, in L band and UHF as well. These periodic dips are exactly 1 channel wide, and start at the first channel.

Amplitudes and folded versions, averaged over scans, median filtered for 1575475845

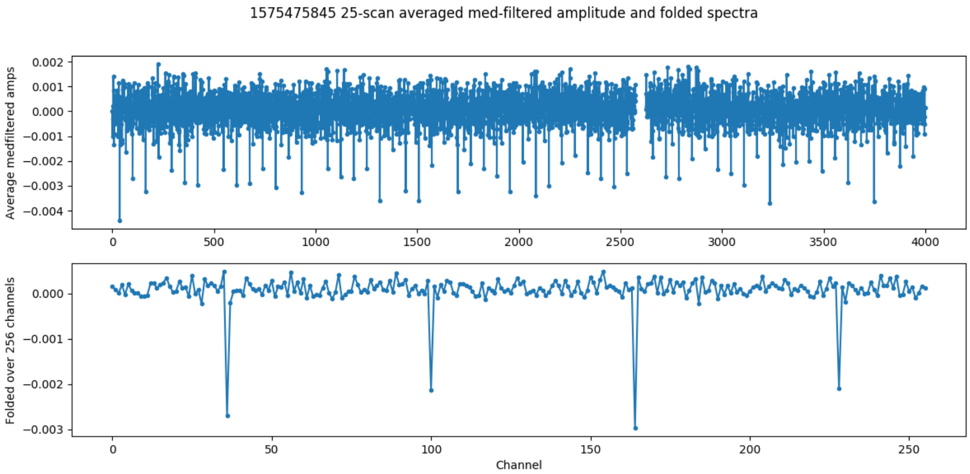

Figure 1: Example amplitude spectra and folded versions for 32K dataset

These dips are thought to be caused by the nature of the specific FFT algorithm used in the f-engine of the correlator and hence unavoidable. The CBF team has been optimising the *fftshift* parameter in order to reduce the strength of these dips, and this has been reasonably successful. Since it seems impossible to completely eliminate this problem, we investigate whether these dips are calibratable, and hence antenna decomposable.

2 Datasets used

We use long tracks on calibrators to investigate whether we can calibrate these periodic dips. Bright calibrators are chosen for a high signal to noise ratio on these dips, and long tracks are observed to study for what duration a given calibration is applicable. The analysis in this document is shown for 1586078244, but the results are similar for the other datasets as well.

Table 1: Data sets

Parameter	Dataset 1	Dataset 2	Dataset 3	Dataset 4	Dataset 5
CB ID	1589558455	1575475845	1586078244	1573662272	1574617721
Date	15 May 2020	4 Dec 2019	5 Apr 2020	13 Nov 2019	24 Nov 2019
Correlator	CMC 1	CMC 2	CMC 1	CMC 1	CMC 1
Setup	L band	L band, 8 sec	L band, 8 sec	L band, 8 sec	L band, 8 sec
Num of chans	32768	32768	4096	4096	4096
Target	J0408, J1939, 3C286	J0408	J0408	J0408	J0408
Duration	6 hrs	13 hrs	6 hrs	6 hrs	6 hrs

3 Nature of the periodicity

We can look at two aspects of these dips, viz. its strength and its exact periodicity. These dips are strong enough to be seen in individual scans for the autocorrelations. However, the visibility amplitudes need to averaged over a few scans in order to make the the dip in an individual channel be statistically significant. Since the targets are well approximated by a point source at the centre, at least in the L band and the higher side of the UHF band, we adopt the following procedure.

- RFI-free regions of the spectrum (1.31-1.51 GHz in L band and FILL in UHF) are used and only XX and YY pols are considered
- Each amplitude spectrum is averaged over a scan (typically 5-10 minutes duration), leading to npol X nbaseline X nscan spectra
- Each of these spectra are detrended by subtracting a median filtered version of length 101 for 32K data and 31 for 4K data
- For each of the two polarisations, these spectra are averaged over all scans and all baselines
- These are then folded over every 64 channels

Since each amplitude spectrum is subtracted using its median filter, the strength of the signal can be taken as the ratio of the dip amplitude to the mean visibility amplitude of the calibrator (averaged over the RFI-free band in question). For the datasets under consideration, the values obtained are between 0.005-0.01 %.

Though the periodicity of 64 channels is well known and is also visually obvious, we test whether (1) this is true and (2) any other periodicity is present. To do this, we take the scan-averaged baseline-averaged spectra for each polarisation in the RFI-free region. Fold periods from 3 up to half the spectrum length are considered, for all appropriate values of start channel. For each start-fold combination, the amplitudes every fold channels beginning from the start channel are taken and its absolute value is summed. The resultant matrix is shown in the left panel of figure 2. The highest value is always seen to be for a fold value of 64 and a start value corresponding to the first channel. All its appropriate harmonics and sub-harmonics are then deleted, resulting in the 'deconvolved' panel on the right. This latter figure is consistent with noise, indicating that no other periodicities are present.

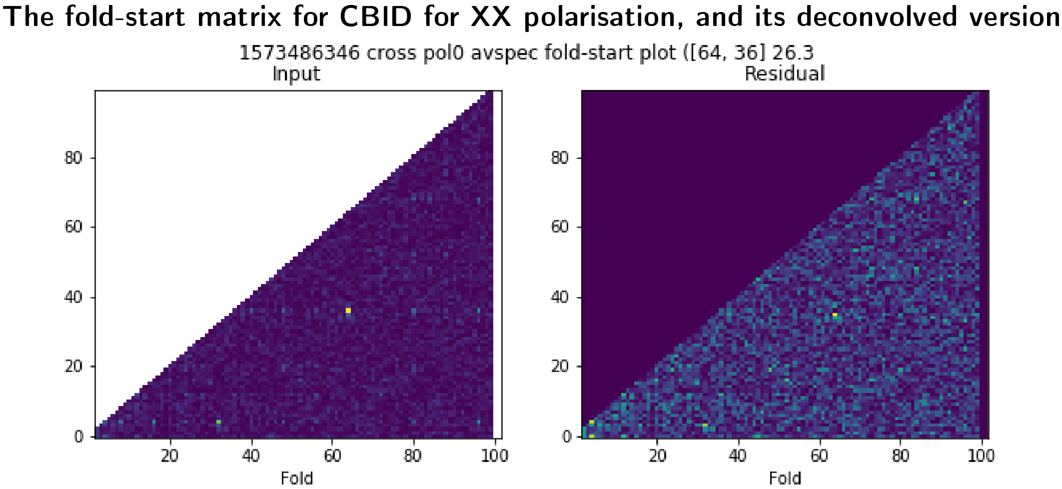

Figure 2: The fold-start matrix and its deconvolution

4 Analysis

The data are converted to a Measurement Set and further processing is done inside the CASA environment using its tasks and our own scripts. We ignore the autocorrelations, though they exhibit much stronger periodic dips than the visibilities, since we are focussing on the ability to calibrate these dips in this document.

- Data is split out for a RFI-free range starting from 1.31 GHz for L band (with 128 channels for 32K and 16 channels for 4K modes) and the WEIGHT_SPECTRUM column is deleted
- This data is then calibrated for every dump and inspected (and data is flagged as needed). The data is calibrated with this table and each scan data is split into a separate file
- Each scan is bandpass calibrated without normalising solutions
- For each scan, the relevant data is time averaged within the scan, and each spectrum is detrended using a polynomial filter of size 100. These are then averaged over all baselines to give one spectrum for each of the two polarisations
- This average spectrum is calculated for the split data (called raw), and after applying its own bandpass to itself (called self)
- The average spectrum is also calculated after applying the bandpasses of each of the other scans to every scan. We now have N+1 spectra for each of the N scans
- Each of these average spectra are then folded every 64 channels. Since we know where the 64-channel periodic dip will occur, we can calculate the SNR of these dips as well

5 Results

The bandpasses themselves show the presence of the 64-channel dips. Figure 3 shows the SNR of these dips in the 64-folded bandpass amplitudes after they have been detrended and averaged over all antennas for each scan.

As an example, figure 4 shows the averaged detrended amplitude spectra after folding over 64 channels for the dataset 1575475845. The top rows are for scan 1 and the bottom row is for scan 60. The left column

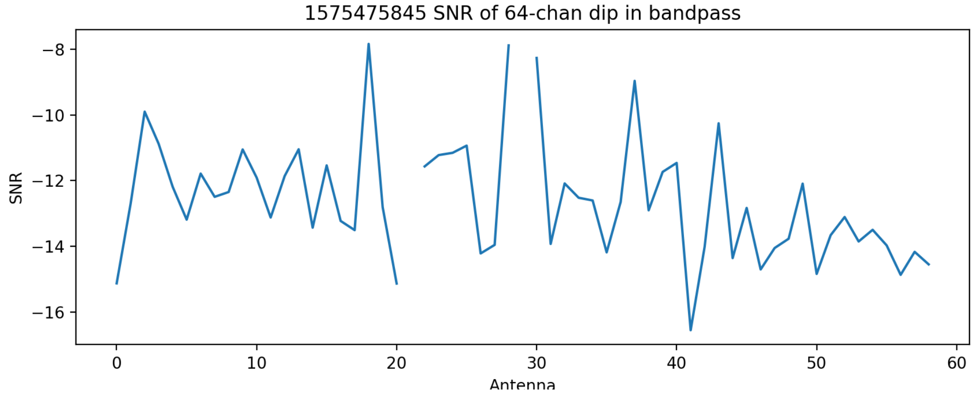

Figure 3: SNR of the 64-channel dips in the folded, antenna-averaged bandpass amplitudes

shows the spectra without any calibration, the middle column is after applying the bandpass calibration of the scan to itself, and the right column is after appling the calibrations of the two scans to each other. The expected position of the 64-channel dip is marked by a red dot. It is clear that applying any of the bandpasses removes the 64 channel periodicity.

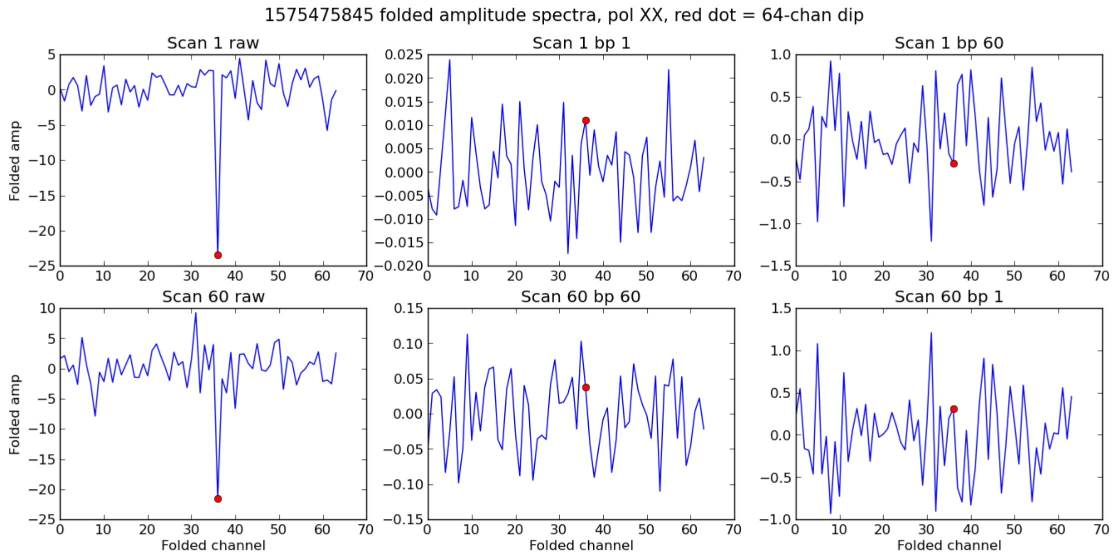

Figure 4: Averaged amplitude spectrum of scans with and without bandpass calibration

We next verify that the abscence of the 64-channel periodicity when a scan is calibrated with the bandpass from a different scan is indeed because of calibration rather than the bandpass phases at these channels randomising or diluting these dips. The bandpass phases for every 64th channel is considered in the RFI free region, and the difference between that channel and the average of the two neighbouring channels is calculated. This is done for the 64 possible starting channels, and then repeated for every antenna. We expect that the median and MAD for every antenna, is the same for fold channel 36 (where the dip will be present) as it is for other fold channels, which can seen to be true in figure 5. In other words, the bandpass phases at the channels where the 64-period dips occur are consistent with the phases in their neighbouring channels.

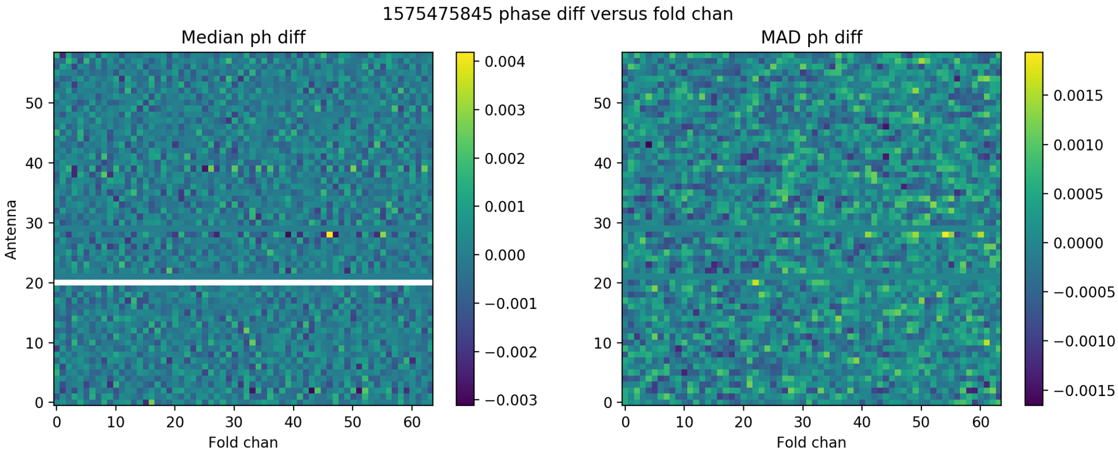

Figure 5: Median and MAD for each antenna and fold channel of bandpass phase differences

We now calculate the SNR in the folded baseline-averaged visibility amplitudes for each scan after applying different bandpasses to it. These are plotted in figure 6. The top panel shows the SNR of each scan and each colour indicates a different bandpass that is applied, as marked in the legend. The blue curve labelled raw corresponds to no bandpass calibration, and the 64-channel dips are indeed present at around 7-8σ. However, after bandpass calibration, it is seen that the signal at the dip channel is consistent with noise, both for self (using the bandpass of the scan itself) and after applying the bandpass of any other scan. The bottom panel shows the rms of the baseline-averaged visibility amplitude spectrum in each case, in log scale. As expected, the raw curve has the highest rms and the orange coloured spectrum corresponding to applying its own bandpass to each scan has the lowest rms. All other bandpass-scan combinations lie in between, with the curve marked self coinciding with the curves for each scan which has its own bandpass applied, as expected.

The entire is data is averaged and folded over 64 channels and the SNR of the dip is calculated after applying each of the bandpasses. There is no statistically significant dip present even after averaging the entire dataset, for any bandpass that is applied. To confirm that the absence of the 64-channel dip after applying any of the bandpass calibrations is due to the calibratability of the dips and not because the calibration randomises them, we repeat the exercise using the bandpass of scan 11. Each spectrum in this bandpass (for each antenna and polarisation), is shifted two channels to the right and then applied to all scans. The 64-folded spectra of the average detrended spectra of each of these scans are plotted in figure 7. All of these spectra show the original dip at folded channel 53 and a spike at channel 55, as expected.

1586078244 snr of the 64-period dip for each scan after bandpass calibration and rms

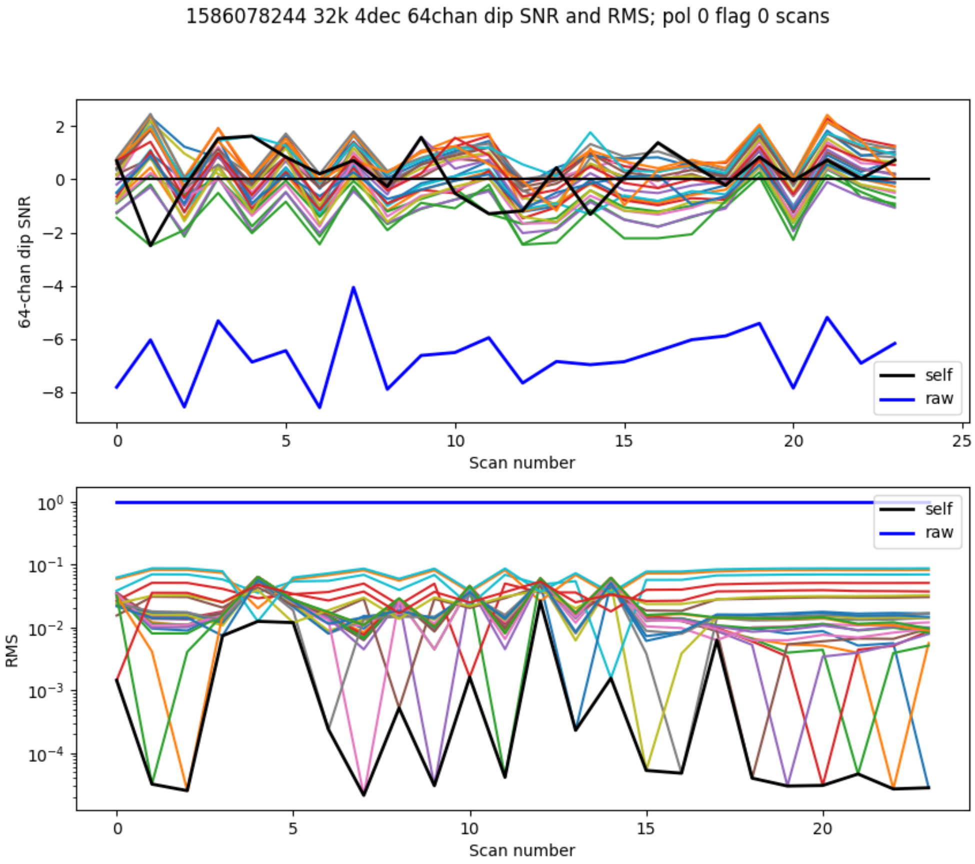

Figure 6: The SNR of the 64-chan dips in visibility amplitudes after applying various bandpasses

1586078244 folded av spectra for each scan using bandpass of scan 11 shifted by 2 chans

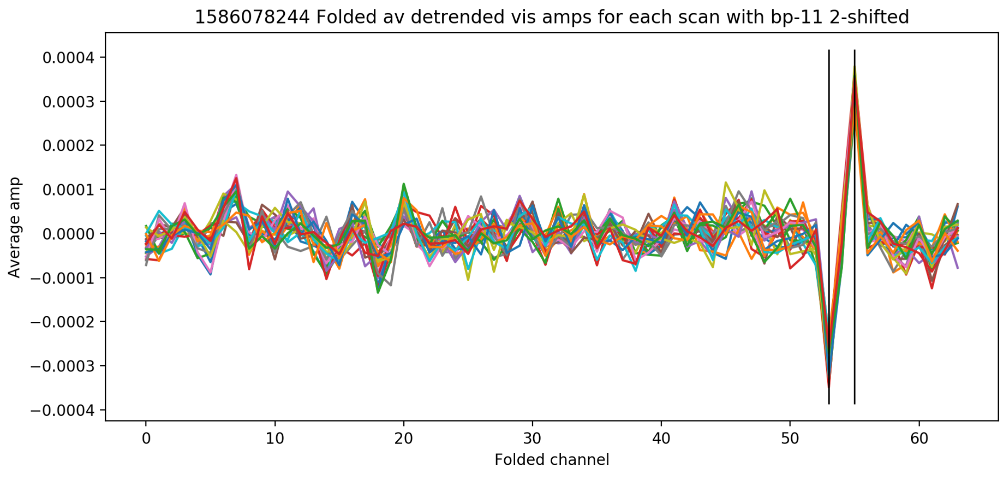

Figure 7: Folded average spectra of each scan using shifted bandpass

The observations 1589558455 contains scans on J0408, J1939 and 3C 286 and is hence a good dataset to test whether bandpasses on one source can be used to calibrate out the 64-channel dips in other sources. Figure 8 shows the SNR of the 64 channel dips in the top plot. This is for bandpasses of each scan applied to all other scans, which includes all three sources. The bottom plot shows the residual rms after applying the bandpasses. The blue, cyan and green dots are for bandpasses of sources applied to scans of the other two sources, and the orange, magenta and red dots are for bandpasses of sources applied to other scans of the source. The difference between these two sets is attributed to the effect of the field structure on the bandpasses. The significant result is that the 64-channel dips seem to be calibrated out when bandpasses of one source are applied to scans of another.

1589558455 snr of the dips for three different sources

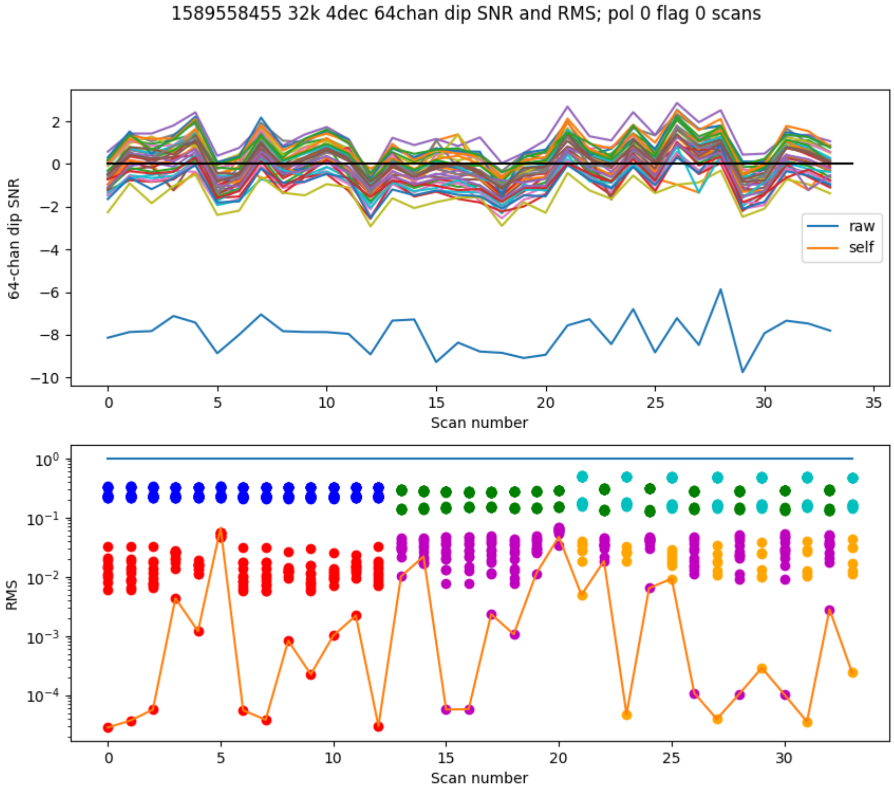

Figure 8: SNR of the dips for different sources

6 Conclusions

All 4K and 32K data show a periodic dip every 64 channels of roughly 0.005-0.01 % in the visibility amplitudes, and much stronger in the auto correlations. Though the strength of this dip has been reduced over successive correlator upgrades, it is expected to remain at this level since these dips are assumed to be an artefact of the fft algorithm used. Here, we show that these dips can be calibrated using bandpass calibrators quite effectively. In addition, bandpass solutions calculated at a given time are capable of calibrating out these dips many hours apart, even when the bandpasses and the data to be calibrated are of different sources.