Delay calibration of the phased array feed using observations of the South celestial pole

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Summary

The Boolardy Engineering Test Array (BETA) forms beams digitally by the weighted sum of up to 188 phased array feed (PAF) elements. Initially, we expected that the relative complex gains of the elements should only drift slowly with time, necessitating infrequent updates to the beam weights. During commissioning observations we noticed that beam sensitivity and quality would decay on time scales of days to weeks, with weights more likely to suffer catastrophic degradation after a major power cycle of the BETA equipment. This degradation has been traced to step changes in delay between individual elements. These are due to the random start-up phase of a clock divider in the digitisers. The current setup and calibration software associated with this hardware module does not adequately compensate for the fact that the digitisers can start in one of several clock states. This should be fixable in the long term.

Here we describe a method for measuring the inter-element delays by observing the South celestial pole, and show that the corrections made using the astronomical delay compensation machinery remove the inter-element delays.

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1 Introduction

The Boolardy Engineering Test Array (BETA) is a 6-antenna prototype of the Australian Square Kilometre Array Pathfinder (ASKAP) (Hotan et al., 2014). Each 12 m dish is equipped with a Phased Array Feed (PAF) comprising 188 elements arranged in a roughly circular pattern at the prime focus. Beamforming hardware at each antenna forms up 9 dual-polarisation beams by calculating the weighted sum of the elements. The weights are programmable and are determined offline from specially targeted observations of a reference source and a blank noise field, and uploaded to the beam former at the beginning of each observing run. The voltage stream from each beam is correlated with the same beam from all other antennas to form the interferometric visibilities.

In addition to forming beams, the beamformers can produce Array Covariance Matrices (ACMs), which are the complex cross correlation between all pairs of the 188 elements in a given antenna (E.g. Fig. 3.1). An ACM is formed for 64 1 MHz channels spread throughout the 300 MHz observing band (i.e. with a gap of 4–5 MHz between each ACM), and dumped on a programmable dump time, which is typically 1 second of integration downloaded every 2 seconds, where only every 4th sample is integrated in hardware. Longer integrations can be used if needed. Currently, the procedure for determining beam weights (maximum S/N) uses ACMs observed when pointing at a quiet part of the sky, as well as on a strong source (usually the Sun).

2 The problem: Integer sample delay jumps

The current observing model relies on the assumption that the gain and phase of each element across the entire PAF remains constant with time[1]. Put another way, the weights loaded into the beam formers assume that element gains and phases have not changed since the weights were determined.

In early investigations with BETA, it became clear that these assumptions were being violated. Two observations in particular lead to this conclusion. Firstly, the sensitivity of a formed beam appeared to dramatically reduce over a period of days (Fig. 2.1), when using a given set of weights, but could be restored by re-determining the weights. Secondly, interferometric investigations using single-port beams showed that the bandpass phase of a single port could change dramatically from one day to the next (Fig. 2.2). An analysis of these interferometric data showed that the delay jumps were always integer

[1] Bulk changes of gain and phase of the entire PAF are determined and compensated as part of the calibration and imaging steps based on the visibilities

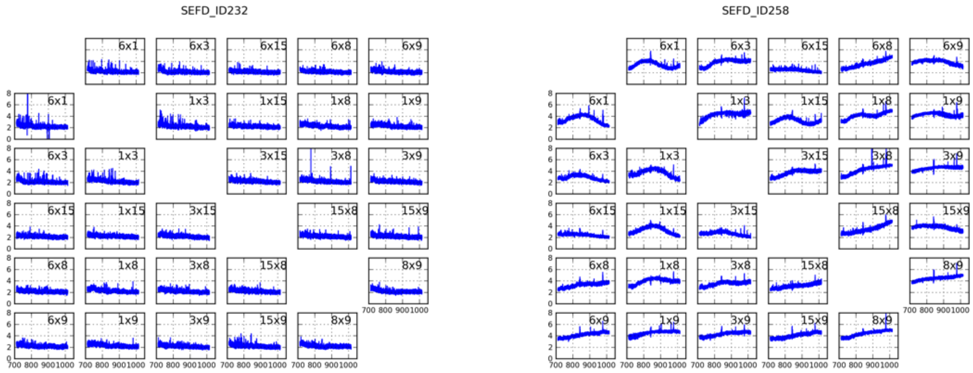


Figure 2.1: System equivalent flux density (kJy) of all 15 BETA baselines measured by observations of B1934-638 on 2014-07-16 (SBID 232, left) and 2014-07-28 (SBID 258, right). Both observations had identical max S/N beam weights files loaded. The top-right corner of each plot is the XX polarisation and the bottom left is the YY polarisation. Clear increases in SEFD (reduced sensitivity) can be seen on almost all antennas and polarisations. This is due to inter-element delay jumps invalidating the beam weights.

multiples of the 768 MHz sample clock.

The reason why delay jumps between ports should produce reduction in sensitivity is straightforward: Creating a well-formed beam requires that all elements on which power falls be added up in phase, essentially creating a beam by carefully choosing weights to constructively interfere. If the phase of an element should change, then it will cause *destructive* interference, and reduce the sensitivity of the beam.

Further investigations of the delay jumps showed that they occurred after a power-cycle of the digital receiver cards (the so-called DRX cards), but were neither caused by, or remedied by, a synchronous reset of the hardware.

3 The solution: ACMs of the South Celestial Pole

Given there is no available fix to correct the delay jumps at this time, that they occur quite regularly, and re-determining weights is a time-consuming exercise, it seems prudent to calibrate the delays using the astronomical delay tracking machinery. The natural tool for measuring the delays is to use the ACM, which is readily obtained and provides information on all ports simultaneously. The question arises, however, as to where one should point the antenna when the ACM is measured.

There are a number of options. Once could choose a strong source such as Virgo, or the Sun, but this requires that the source is up. Given that it is impossible to use a recently-

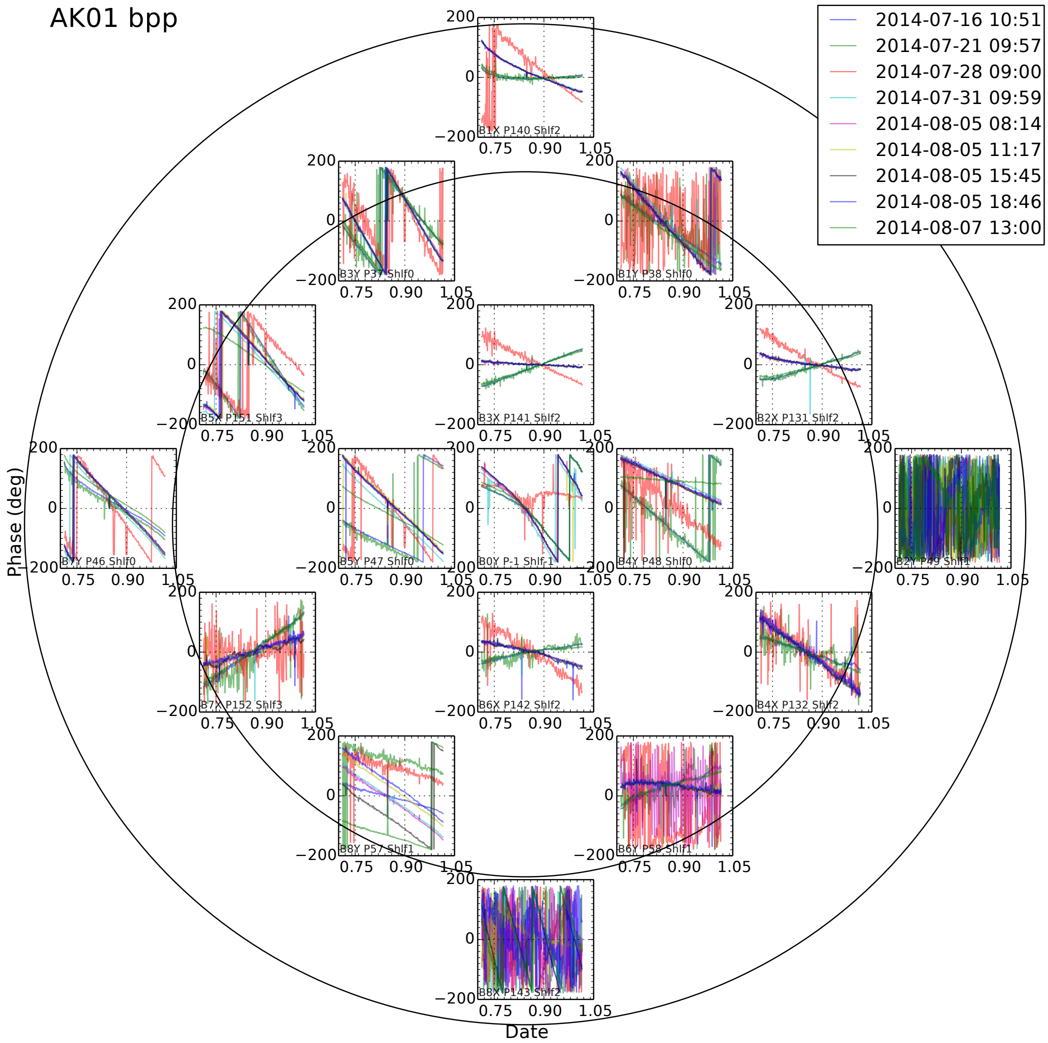


Figure 2.2: Bandpass phase of AK01 for an interferometric bandpass solution based on observations of B1934-638 on different days. Each square is the bandpass solution for a single PAF element with the position of the square indicating the location of the element on the PAF. The central square is the result for a maximum S/N formed beam on boresight. The slope of the single-element bandpass phase changes substantially on different days, indicating delay jumps. The x-axis is actually frequency (GHz). The circles indicate the position of the first null in the Airy pattern at the top and bottom of the 0.7-1 GHz observing band.

rebooted antenna without performing this step, it is something of a pain to have to wait for a strong source to be visible before performing the calibration. The Sun, especially, is a variable source, which means the variability can cause an additional complication when trying to normalise by a reference epoch (more on that later).

An alternative is to observe random 'blank' patch of sky. Such patches are readily available, but not all are equally blank. In the interest of controlling as many variables as possible, the South Celestial Pole (SCP) is a good choice. It is always up and relatively free of strong sources. We chose to observe the SCP with roll axis tracking turned off (i.e. $\mathrm{pa\_fixed} = 0$), as the majority of the ACM power is expected to be due to internal coupling, and spillover from the 290 K ground, rather than the roughly ~ 3 K sky.

A typical ACM of the SCP is shown in Fig. 3.1. The bright spots in the ACM are where there is large cross-correlation amplitude between elements. As there is no substantial contribution from the sky, the large cross-correlations are dominated by coupling between adjacent elements on the PAF. Ports that are separated by a large distance on the PAF have essentially no cross correlation amplitude.

We aim to use the ACM to measure the delay with respect to some reference. It is sufficient so simply choose a reference port on the PAF, which we define as the central ports, 47 and 141 (1-based) for the X and Y polarisations respectively. It is clear that we cannot simply fit the phase spectrum for each port with respect to the reference (essentially by picking out a line across the ACM), as many of the ports simply have insufficient correlation amplitude with the reference ports. They do, however, have sufficient correlation with their neighbouring ports. Therefore, we define a path for each port that traverses adjacent ports back to the reference port (Fig. 3.2).

Extracting the phase spectrum of each port, with its neighbouring port as defined by the path in Fig. 3.2 yields phase spectra with substantial structure (Fig. 3.3). This complicated phase structure can inhibit our ability to reliably fit for delays. We can therefore divide the complex spectrum by a reference epoch, to obtain (essentially) a bandpass calibrated phase spectrum (Fig. 6.1). We can now obtain the normalised phase spectrum of each pair of adjacent ports and fit for the delays (by fitting sinusoids to the real and imaginary part of the spectrum, after normalising to obtain unit amplitude). To measure the delay with respect to the reference port, we add up the delays along the path from each given port back to the reference port. We have found that it is necessary to round the measured delay at each step, to minimise the accumulation of small errors.

The procedure can be summarised as follows:

1. Point at the SCP without roll axis tracking (i.e. $\mathrm{pa\_fixed} = 0$)
2. Set delays to a reference point (2080 samples in our case).
3. Obtain a reference ACM.

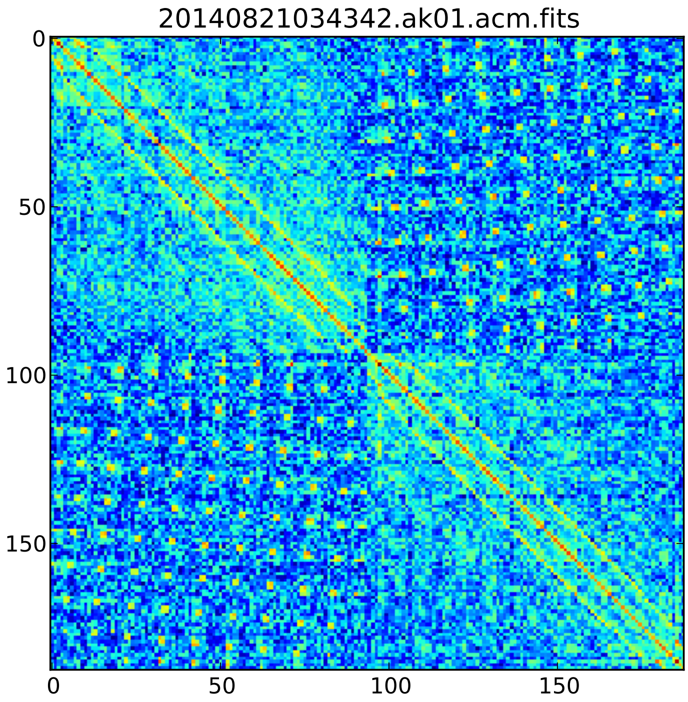


Figure 3.1: Amplitude (dB) of a typical ACM of 1 s duration, pointing at the SCP for a single 1 MHz channel near 850 MHz. The top-left and bottom-right quadrants show the co-polar XX and YY polarisations respectively, and the top-right and bottom left quadrants for the cross-polar XY and YX respectively. The three parallel diagonal lines in the co-polar quadrants are the autocorrelations and cross terms for which there is significant power (i.e. between adjacent co-polar elements).

4. Power-cycle an antenna.
5. Point at SCP without roll axis tracking (i.e. $\mathrm{pa\_fixed} = 0$).
6. Obtain ACM #1.
7. For each port from 1 to 188, find the adjacent port according to Fig. 3.2.
8. For each port, divide the ACM #1 spectrum by the reference spectrum for the same pair of ports.
9. Fit for the delay between adjacent ports by fitting sines and cosines to the normalised phase spectrum.
10. Add up delays between current port and reference port, by following the path shown in Fig. 3.2, rounding each delay to the nearest integer.
11. Apply delay to each port.
12. Obtain ACM #2.
13. Find delays between ACM #2 and reference.
14. Verify ACM #2 delays are zero.

As long as this procedure is executed after every power-cycle, all beam weights determined after the reference epoch will remain valid (at least as far as delay jumps are concerned).

4 Implementation

An OSL script osl_s_port_delays.py was written to automate the delay correction process. It must be run while the antennas are tracking the South celestial pole. The script records ACMs for 5 cycles, then calls a library routine that calculates the inter-port delays using the method described above. It then writes a calibration file into aktos01:/var/lib/askap/delays so that other scripts can access the measured values. Finally, the script loads the newly measured values and records another 5 cycles of ACM data to verify that the corrections, once applied in the DRx (see below), have had the desired effect.

5 Delay Correction

Once the measured inter-port delays are known, we need a way to compensate for them. For BETA, astronomical delay tracking is accomplished via a combination of a digital delay line (one per PAF port) in the DRx firmware and a fringe rotator (one per antenna) in the beamformer. The firmware would support per-beam fringe rotation with

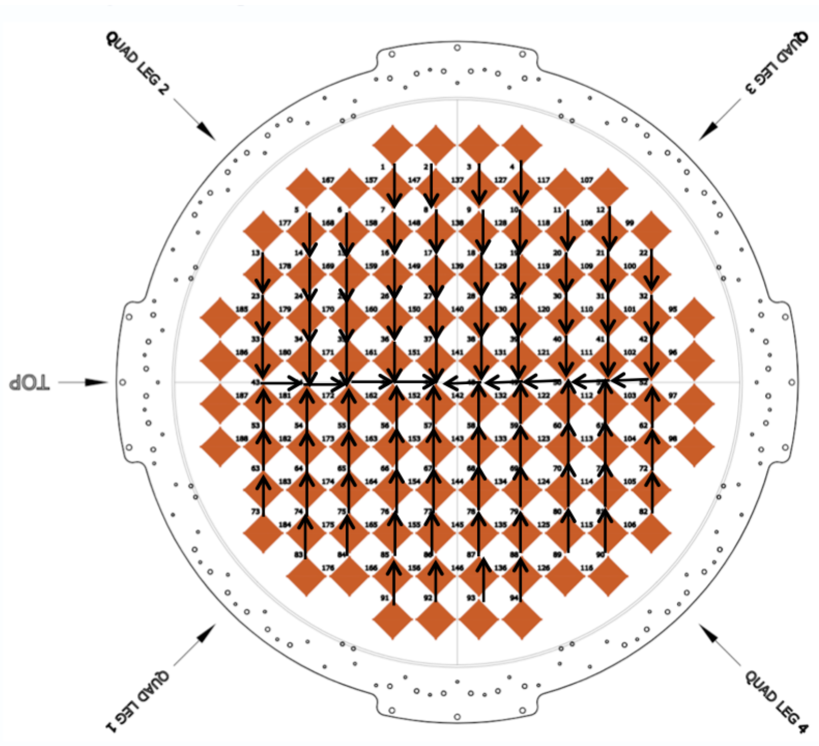


Figure 3.2: Routes taken to 'walk' from every X-polarisation port back to it's reference port (47 1-based). The route follows adjacent ports back to the centreline, and then along the centre-line to the reference port.

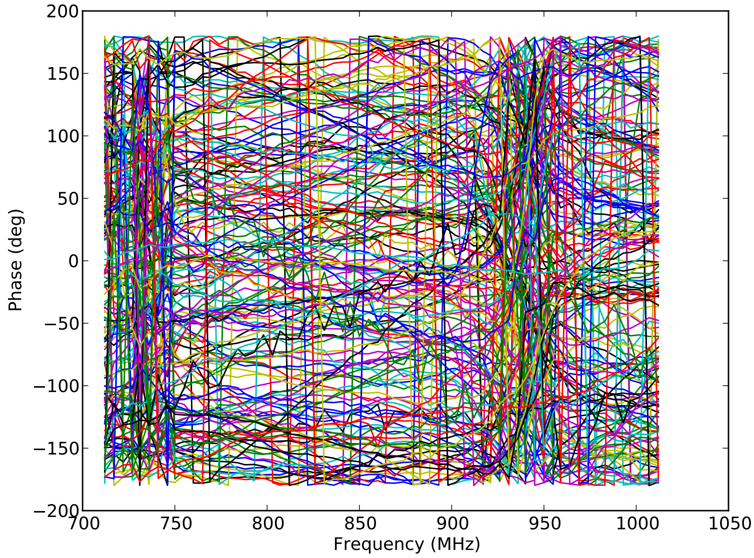


Figure 3.3: Phase spectrum of the ACM between each port, and its adjacent port for AK03 for the reference epoch. All ports show substantial phase structure, including a resonance around 950 MHz, many ports have intrinsic phase slopes.

some additional software development, but we need to adjust delays on each PAF port independently, so the only option is to use the DRx delay line.

The correlator ingest pipeline depends on a script called osl_s_ingest_rcvr.py, which listens over the network for commands which trigger the running of other OSL scripts to configure various aspects of the hardware. When the ingest pipeline calculates that the delay to a particular antenna has drifted past a certain threshold with respect to the geometric model, it issues a command to update the delay for that antenna, using osl_a_drx_fixdelay.py. This script in turn sends new values for the DRx delay lines to hardware via EPICS. Because the digital buffer can only store integer samples, the delay can only be adjusted in units of the sampling period (1.3 ns) using this method. The fringe rotator is responsible for fine delay compensation by applying a phase gradient across the frequency channels.

Since the observed inter-port delays come in units of integer samples, it made perfect sense to implement a correction at the level of the DRx delay line. This was done by making osl_a_drx_fixdelay.py read in a correction file that consists of a single-column list of integers representing the offset of each port with respect to the reference. When this script receives a command to change the overall delay for an antenna, it now reads the correction file and adds the offset to the bulk delay for each port before uploading the

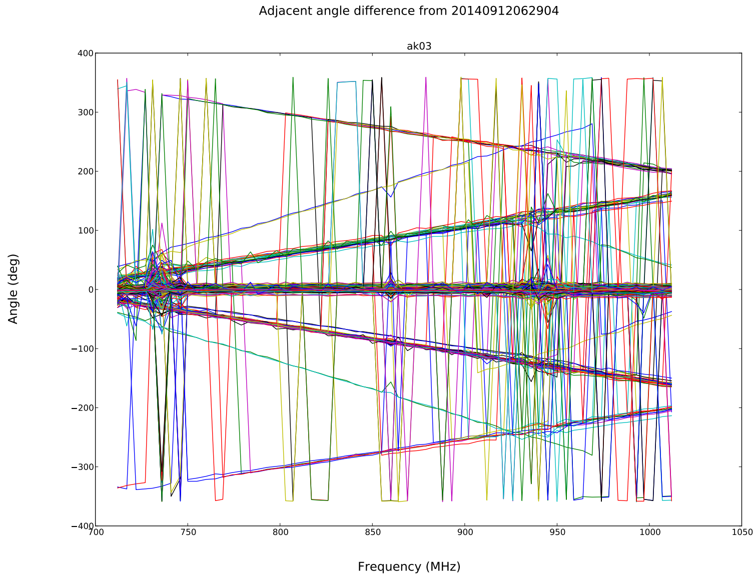


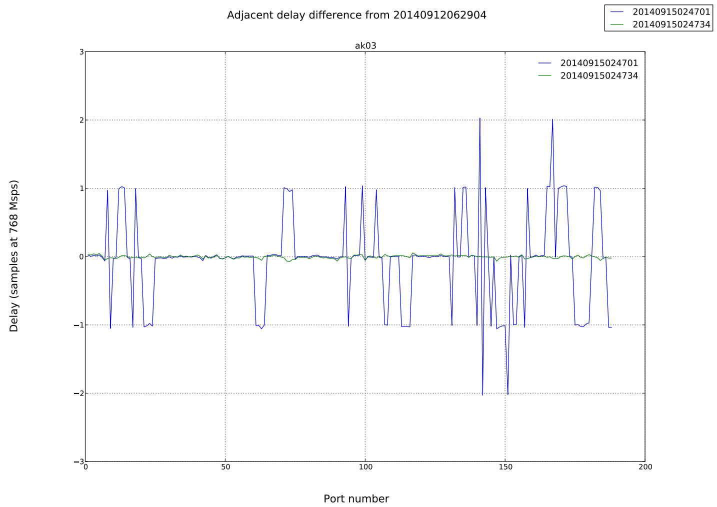
Figure 6.1: Phase spectrum of the ACM between each port, and its adjacent port for AK03 for an epoch, normalised by the reference epoch. Once the spectrum has been normalised, the phase structure disappears, and delay jumps are clearly visible.

new values to the firmware. Provided the correction file is kept up-to-date (this happens automatically when osl_s_port_delays.py is run) the port delays should always be the same as they were when the reference ACM was recorded.

6 Results: A test on AK03

We tested this procedure on antenna AK03. A reference ACM was obtained for all antennas (ACM ID 2014091202904), which is saved in /work/askap/reference_acm/ on aktos01. The DRXs were power-cycled on AK03, and the calibration routine was executed, with ACM #1 having ID 20140915024701 and ACM #2 having ID 20150915024734. The calibration procedure took less that one minute.

The normalised phase spectra for each port are shown in Fig. 6.1. They shows clear ramps and almost no residual phase structure. This proves that the power-cycle can cause delay jumps, and that the phase normalisation (i.e. bandpass calibration) is working as expected. The delays between adjacent elements, and the delays with respect to the reference ports, before and after correction, are shown in Fig. 6.2). These plots clearly show that the delay jumps are integer samples of 768 MHz, that they are caused by the power cycle, and are correctly calibrated by the procedure described above.



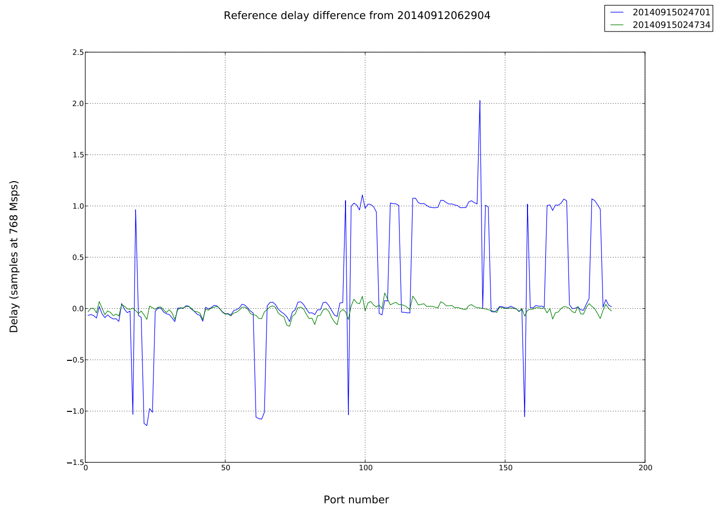


Figure 6.2: Demonstration of delay compensation with SCP observations for AK03. The AK03 DRX hardware was deliberately power cycled between the observations of the reference ACM and the first of the two plotted ACMs. The top panel shows the fitted delay between adjacent ports. The bottom panel shows the delay with respect to the reference port.. The blue line (20140915024701) shows the delays before correction, and the green line (20140915024734) shows the delays after the corrections were applied. The integer-sample delays have been successfully removed.

7 Discussion

Calibrating the inter-element delays would have been easier if we'd had a vertex radiator. This would illuminate the whole PAF, then we would only need to extract the line from the ACM corresponding to the copy of the noise radiator signal and fit for the delays across all ports (no need to walk through the ports in phase). Our procedure also suffers from a problem where, if a port fails (i.e. fails to produce enough power for the cross correlation to be evident between the failed port, and adjacent ports), then all ports downstream of that port could produce erroneous delay measurements.

In the long term, this procedure should not be required as it should be possible to implement a digitiser calibration routine that ensures correct compensation for the startup phase of the clock divider in the device. However, it will still be useful to have this method as an independent diagnostic.

8 Conclusions

We have shown that delay jumps between PAF elements occur after antenna DRX power cycles and found a way of calibrating them out using an observation of the South Celestial Pole. The procedure has been written as a standard telescope script and can be executed in about 1 minute.

References

Hotan, A. W., et al. (2014). PASA, 31 e041.

9 Acknowledgements

The idea of observing the SCP as an always-up, fairly constant piece of sky was that of Aaron Chippendale. Thanks to John Tuthill for ongoing analysis and debugging of the digitiser firmware and calibration methods.

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