Memo: On using multiple phase calibration tones

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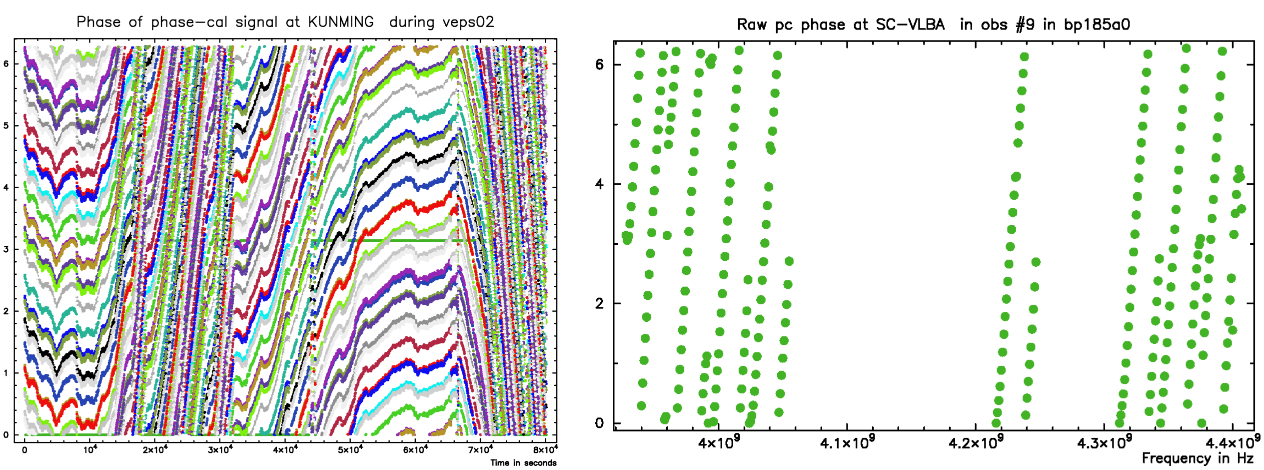
1 Introduction

The ability to extract all phase calibration (hereafter pc) tones was introduced in DiFX correlator in 2013. This feature did not became default since early versions of AIPS crashed in processing a dataset with more than two pc tones per intermediate frequency (hereafter, IF). The principal investigator should ask the correlator to modify the control file and to write all the pc tones into the output FITS-IDI file. Below is a summary of my experience in processing the data with all pc tones extracted.

2 Pcal data preprocessing

Raw phase calibration data with multiple tones extracted are not very informative (see Figure 1)[1]. The Pc phase for non-VLBA stations may varies at several cycles during an experiment. Delay in the cable contributes to a strong frequency dependence of pc phases. Therefore, the pc data are pre-processed.

Figure 1: Example of raw pc phases as a function of time. *Left:* pc phases versus time. Phases at different frequencies are shown with different colors. *Right:* pc phases versus frequency.



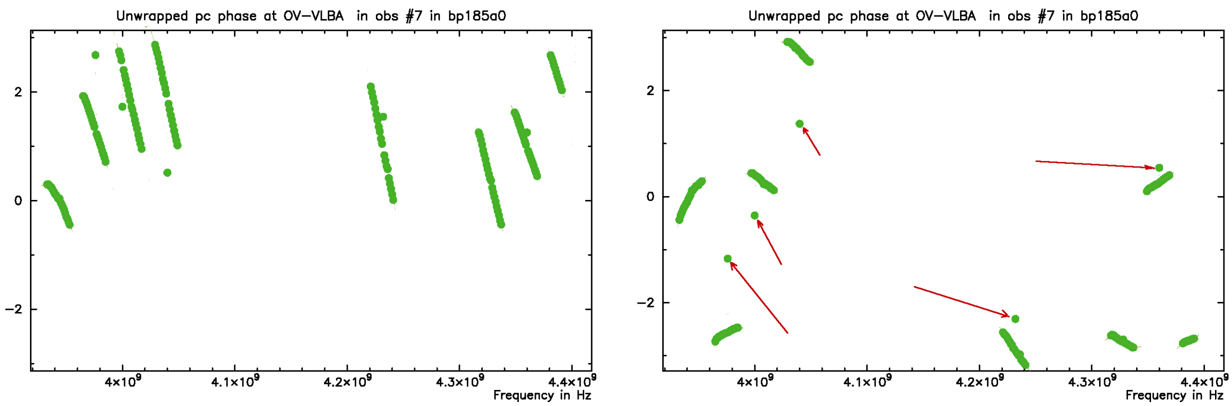
First, group delay in pc phase is evaluated and removed. This can be done in several ways. The first way is to evaluate the group delay over the entire band. Pc complex data with the amplitude set to 1 are put on a grid with a step of $\Delta f/M$, where $Deltaf$ is the pcal frequency step (usually 1 MHz) and M is the oversampling factor, usually 4. Other values at the grid nodes

[1] SI units are used throughout this memo. SI unit for angle is radian

where no pcal is available are set to zero. Then the grid array is Fourier transformed and the maximum is sought. The frequency that corresponds to the maximum of the Fourier transform of the grid array is the pc group delay.

Another approach is to evaluate the group delay over each IF separately and then average out the IF-dependent group delay over the band. Due to historic reasons I call this delay "single-band" delay. Which approach to use is a matter of taste. Plots of pcal phases after removal group delays and fixing phase ambiguities within each IF are shown in Figure 2.

Figure 2: Example of pc phases after the contribution of group delay (*Left*) or single-band delay (*Right*) is subtracted from pc phases. The phases that are affected by internal RFI are shown in red arrows.



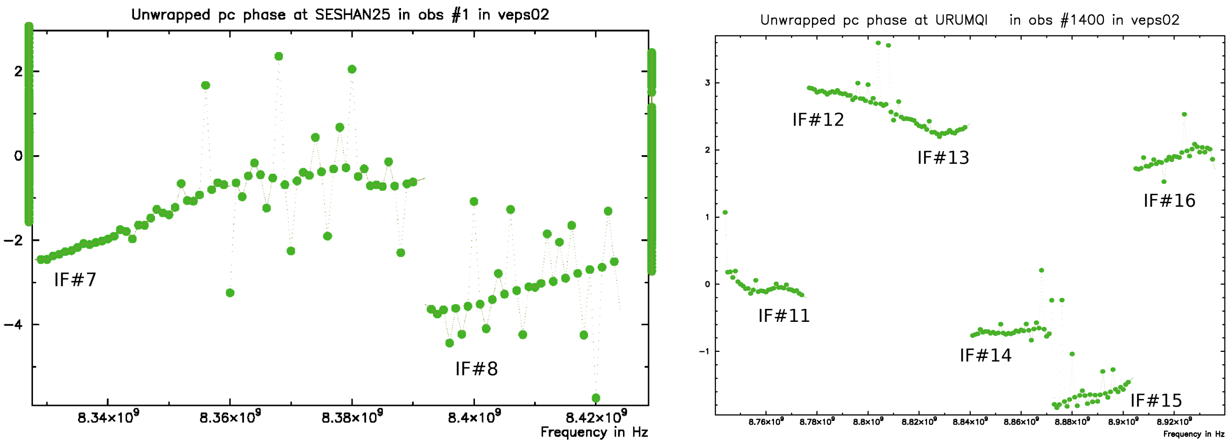
Examining these plots, we see outliers shown in Figure 2. These outliers are due to internal radio interference (RFI) also known as spurious signals. Comparing with cross-correlated phases of a signal from extragalactic sources, we can easily verify that these spikes are present in pc phases only, not in cross-correlated phases.

In a case of VLBA to identify frequencies with spurious pc phases and flag them out is rather simple. However, some non-VLBA stations may be plagued by internal to that extent that it is not easy to separate grain from chaff. See Figure 3. For these two stations shown in the Figure, only 2–4 IFs are peppered with RFI, other IFs are mostly clean. It is a challenge to design an automatic procedure that would correctly identify affected frequencies for this case.

An obvious workaround of the RFI problem is to identify and mask out suspected pc tones in a similar way how the autocorrelation and cross-correlation bandpasses are edited. Analysis of pc amplitudes may help it. Plots o pc amplitude versus frequency has a tooth-like shape. This dependence is close to the shape of a human tooth for good-behaved stations and to a shape of a shark tooth for bad-behaved stations. As Figure 4 shows, the spikes in pc phase due to internal RFI are often matched to spikes in pc amplitudes.

The spectral resolution of the correlator output is usually better than 1 MHz. Therefore, pc phases should be extrapolated over the frequency within an IF. Of course, the outliers caused by internal RFI should be eliminated before that. At the moment, I resort to a simple linear interpolation and linear extrapolation. Figure 5 shows an example of the pc phases cleaned for RFI, linearly interpolated between pc tones, and linearly extrapolated at the edges of the IFs.

Figure 3: Example of strong RFI spread over 32 MHz wide IFs.



3 The use of pcal with all tones

After determining which pc tones have to be masked out, and computing parameters of the pc model, the pc is ready for use. At the moment, I do not have a utility that would make this work automatically. Figure 6 shows an example of using pc with all tones extracted, 31 tone per IF. The fringe phases became significantly flatter when the pc model is applied, but the scatter is still visible. Better result can be obtained if complex bandpass is computed using cross-correlated visibilities of scans with high SNR (> 200). Figures 7 and 8 show examples from two another experiments. The visibilities at the edge of the IF are not correctly calibrated. This is a general feature of the pc system.

This feature can be explained if to assume there is contamination of the signal in a given IF with the signal from adjacent IFs. These signals that come from the receiver are not coherent and their mixture does not affect phases of cross-correlated signal, altthoug it reduses the fringe amplitude and raises the noise level. But the pc signal from leaked from adjacent IFs corrupts phases and amplitudes of pc signal. The leakage is the strongest at the edges of IFs. Another manifestation of the leakage is the drop of visibilities amplitudes below the square root of the product of autocorrelations.

4 Discussion

It is obvious that visibility phases should be calibrated during data analysis. There are two approaches for doing that. The first approach is to compute the complex bandpass using a number of strong sources with high SNR. SNR > 200 is desirable. Historically, this approach is called “manual phase calibration”, although nowadays, the bandpass is computed completely automatically. Provided the complex bandpass is stable with time, this is sufficient. I saw cases when the complex bandpass jumped. Usually, this is related to some abrupt changes in hardware, such as power reset. I do not remember cases where I observe a gradual change in bandpass. If this happens, the change was not strong enough to be easily detected.

The pc system was supposed to track the bandpass changes with high accuracy, better than 1%. Unfortunately, the way how the system was designed 40 years ago, it fell below the expectation. The fundamental flaw of the pc system is that it probes the coherent narrow-band signal for

Figure 4: **Pc phase (green)** and **pc amplitudes (blue)** superimposed. Pc amplitudes were scaled in order to fit the bounding box.

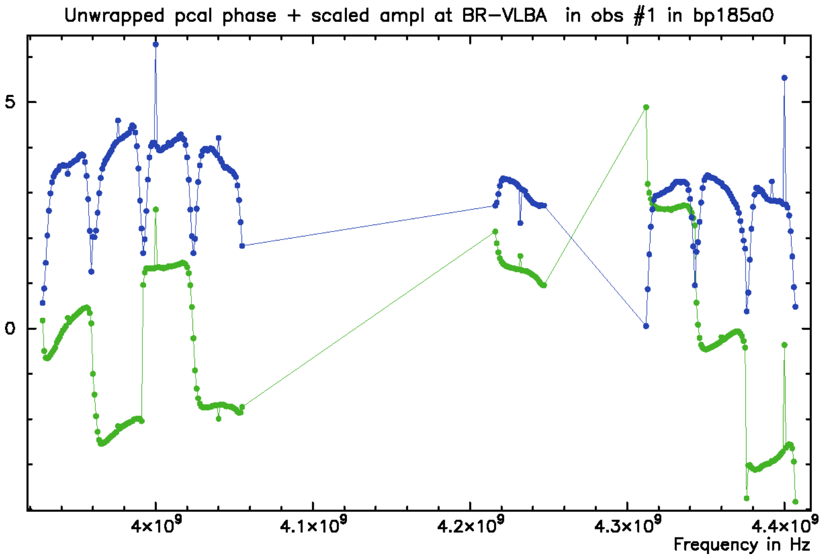
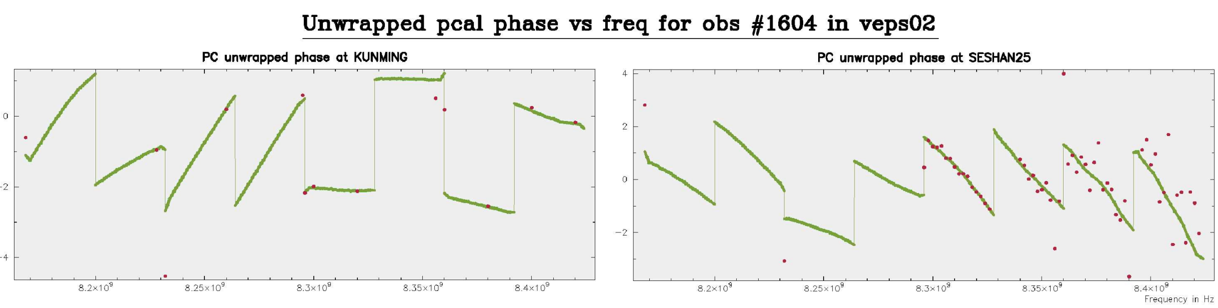


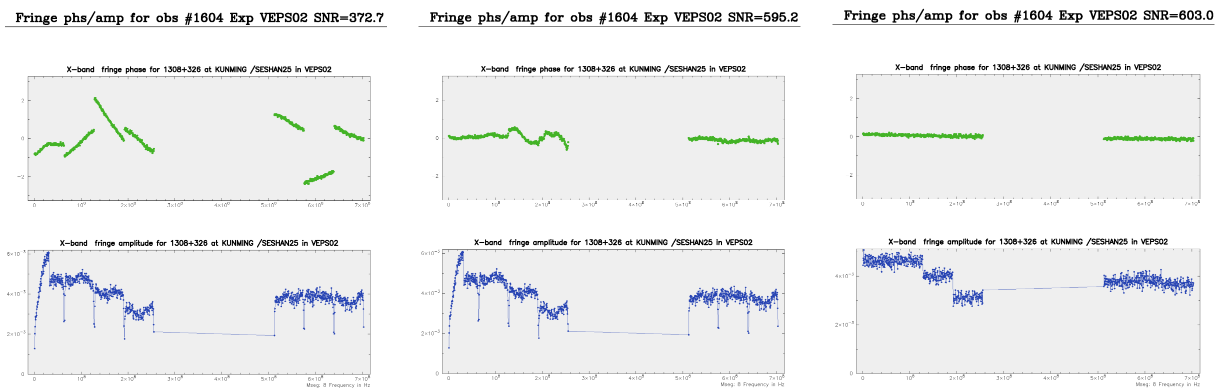
Figure 5: Pc phases cleaned for RFI and interpolated/extrapolated within each individual IF.



calibration of the broadband incoherent signal. The latter signal is mainly insensitive to the RFI environment inside the station, while the pc signal is distorted by the leakage of signals generated by the electronics that are fed from the same H-maser. This problem was known for 40 years. The ability of the DiFX correlator to extract all pc tones just highlighted the problem and allowed us to investigate it in details. Attempts to get rid of spurious signals in pcal take significant efforts and often do not bring satisfactory results. **In general, artifacts of the pc pose a stronger problem than the the bandpasses instability, the system is supposed to calibrate**. When we see systematic changes in residuals, more often than not they are are caused by the pc, and a removal of the pc from the analysis chain eliminates the problem. The pc system may suddenly die and, if used, may ruin a healthy experiment. The dead pc is responsible for what we call "red rain" (see Figure 9) that can be found in a number of IVS databases.

The VLBA system is very stable, but may suffer from jumps related to power reset. Usually a jump in pcal give an analyst a warning to search for a possible break in the bandpass and/or a clock break. In some cases the pcal absorbs the jump — the data with the pc applied are jump

Figure 6: Fringe plots. *Left:* no pc, no bandpass applied. *Center:* the pc model computed by analyzing all the tones is applied. No bandpass is applied. *Right:* no pc is used, the complex bandpass is applied. The bandpass was derived from cross-correlated data.



free, and in other cases the data still have a jump. I recommend to compute complex bandpass on top of the applied pcal. Cases when using the pc degrades results are rare. I recollect several experiments when the pc amplitude was low and as a results, the pc phase was unstable.

For non-VLBA systems the use of pcal is problematic. Experiments with significant variations of pc phases raise a concern and should be checked whether the changes seen in pc are seen in visibility phases. The straiforward test is to compte the bandpass and process the experiment with and without pc applied. Abrupt changes are often seen in visibility phases, while slow drift or a jitter are usually intrinsic to pc itself. To tell the truth, I do not remember cases when phase-cal showed no jumps and using pcal improved fringe fitting and/or astrometry-geodesy results. In the era of digital BBC we do not expect drifts in the electronics. Potentially, the pc can determine delay variations in the cable that brings the signal from the pc injection point to the BBC, but it is unclear whether this help in data analysis.

Another merit of using pc is to use its amplitudes as a proxy to system temperature. If the system temperature measurements are missing or corrupted by the RFI, the pc amplitudes cleaned for spurious signals and averaged over IFs can be successfully used to fill the gap.

5 Conclusion

The pc system, contrary to its name, should not be considered as a calibration system for VLBI visibilities, since the response of VLBI hardware to a coherent narrow-band signal is different than the response to the wide- band incoherent signal, and these differences are in general greater than the effects the pc system is supposed to measure. It rather should be considered as a diagnostic tool that monitors changes in the data acquisition terminal. The ability of the DiFX and SFXC correlators to extract all the pc tones greatly expands the capability of this monitoring tool.

Figure 7: Fringe plots. *Left:* no pc, no bandpass applied. *Right* the pc model computed by analyzing all the tones is applied. No bandpass is applied. Only the first 3 IFs are shown.

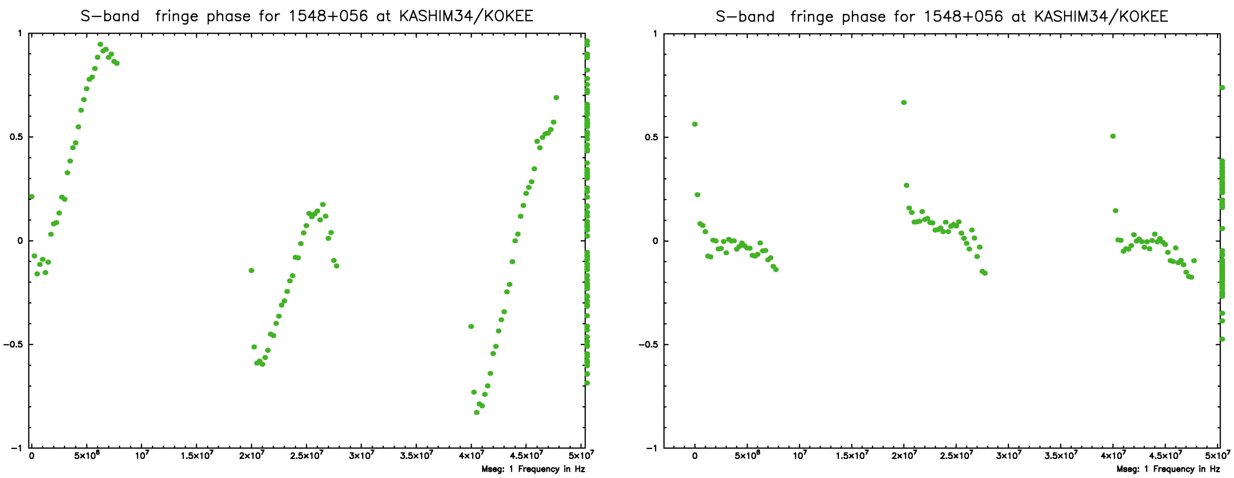


Figure 8: Fringe plots. *Left:* no pc, no bandpass applied. *Right* the pc model computed by analyzing all the tones is applied. No bandpass is applied. Only the first 4 IFs are shown.

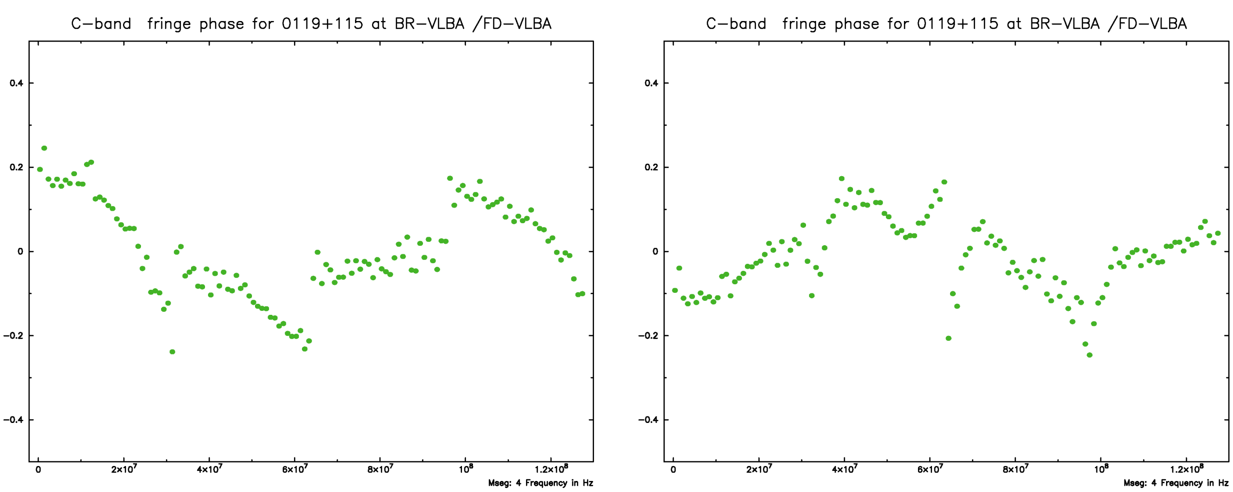


Figure 9: Pcal system at KATH12M suddenly died during CRF87. The correlator extracts always pc phases and amplitudes, but when the pc is dead, they are just noise. *Left:* the pc was applied for KATH12M. All the points processed with dead pc have to be deselected. The plot resembles red rain. *Right:* the same experiment, but processed without using pc at KATH12M. The red rain is gone.