MULTI-TONE PER BAND PULSE CAL

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1 The Pulse Calibration System

The pulse calibration system (also called the phase cal system) used in VLBI provides the information necessary to align the phases of different baseband channels as a function of time, removing the effects of any differences and fluctuations in the instrumentation. The pulse calibration system, in conjunction with the cable cal system, is also used to measure and correct for delay fluctuations between the feeds and the samplers, where the time code gets impressed on the data. In effect, application of the pulse cal phases moves the delay reference point from the sampler to the pulse cal injection point at the feed. The cable cal data can then be used to remove any fluctuations in the difference between this reference point and the maser. These delay corrections are especially important for geodesy and astrometry where delays measured in different directions are compared. The delays through the cable wrap can be a function of pointing position which would confuse the geometric solutions if not corrected.

The shift in the delay reference point when the pulse cal phases are applied is rather large, amounting to a significant fraction of a microsecond. Part of this shift is simply the signal travel time through the electronics and the hundred meters or so of cables. It is also dependent on the phase of the pulse cal generator relative to the station clock. Since that phase is neither controled nor measured, it introduces an additional delay of up to one half the pulse interval of 1 microsecond (usually) in either direction. This additional delay will be different at different stations and will change any time the pulse cal generator loses power. A delay shift of 1 microsecond causes a phase slope change of a turn across 1 MHz, or several turns across typical VLBA baseband channel bandwidths or between different baseband channels.

In past practice, one tone was measured in each baseband channel and this tone was used to align the channels and to remove fluctuations in the multi-band delay. The baseband channels were typically rather narrow. The single band delays were determined with fringe fitting, but no serious attempt was made to maintain the alignment of the single and multi-band delays through the small fluctuations measured with the pulse cal phases. Geodetic and astrometric solutions were based entirely on the multi-band delays — single band delays only had to be kept good enough to avoid signal loss.

The VLBA has much wider single bands than the Mark III system, but has fewer of them. For maximum sensitivity, it is important to align the phases both across the individual bands and between bands. Also, with the small number of bands, geodetic observations will be forced to use frequency sequences with small ambiguity spacings in the multi-band delays which must be resolved with the single band delays. For these reasons, the VLBA formatter has the capability to measure several pulse cal tones in each baseband channel. With at least 2 tones in each band, it is possible to shift the reference point for both single and multi-band delays to the phase cal injection point and to allign all phases.

The large and unknown (thanks to the pulse cal phase) delay shift involved in application of the pulse cal phases leads to significant problems with 2π ambiguities. In fact these problems caused enough confusion in the first attempts to apply the multi-tone per band pulse cal phases that it wasn't clear that the single and multi-band delays could be aligned with this system. In this memo, I try to show what the pulse cal phases are measuring and how to use them to align the single and multi-band delays.

2 Phase Madness

The block diagram on the next page shows the portions of a VLBA site system that are important for a discussion of the pulse cal phases. The delays through cables and electronics that are used in the equations below are marked. Consider the phases of the various signals, tones, LO's etc. in the system at a time t which is the time given by the clock written on the tape. All L.O.'s are assumed to be derived from a maser reference signal whose phase at the maser was zero at $t = -\tau_f \quad (t_{maser} = 0)$.

At the receiver, the data and pulse cal tone phases are:

$$\phi_d = \nu t + \phi_D \tag{1}$$
$$\phi_t = \nu_t(t - \tau_p - \tau_r + \tau_f) \tag{2}$$

In all of these equations, ϕ_d and ϕ_t are the data and pulse cal tone phases at the point in the system under discussion. They are different at different locations, but in the interest of avoiding excessive notational complication, they are not given extra subscripts.

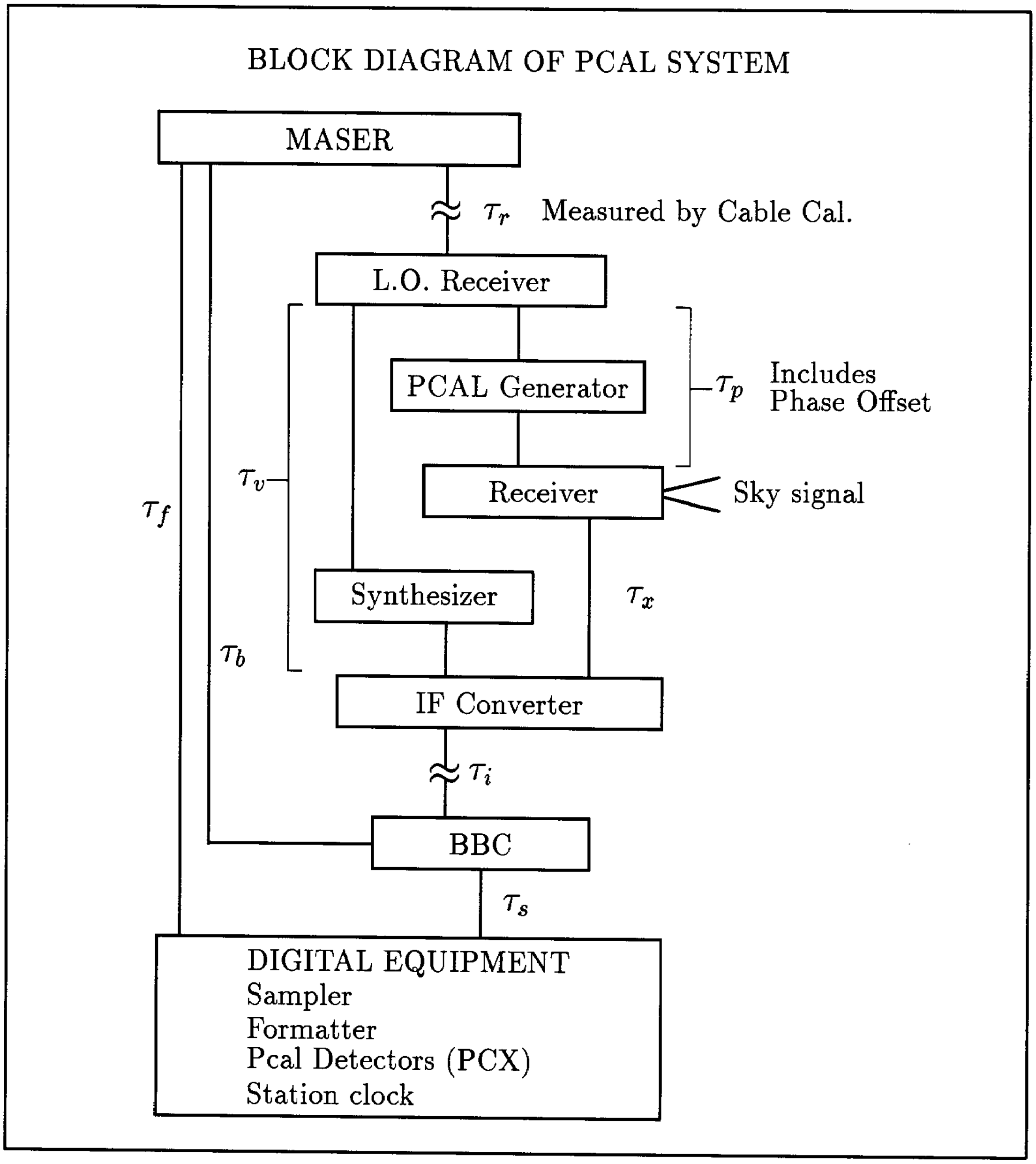
Note that the pulse cal tone phase lags the maser phase by the delay in the LO reference cable and by the delay through the pulse cal generator and associated cables. The large uncertain delay due to the undetermined pulse cal phase is in τ_p. Note also that the clock on the tape is delayed from the maser phase reference by an amount τ_f.

The phase of the first LO, which is generated in the synthesizer, at the point where it is mixed with the RF signal in the IF converter, is:

$$\phi_{LO} = \nu_{LO}(t - \tau_v - \tau_r + \tau_f) \tag{3}$$

The first LO is mixed with the signal that came through the receiver τ_x earlier. After the mix:

$$\phi_d = \nu(t - \tau_x) + \phi_D - \nu_{LO}(t - \tau_v - \tau_r + \tau_f) \tag{4}$$
$$\phi_t = \nu_t(t - \tau_x - \tau_p - \tau_r + \tau_f) - \nu_{LO}(t - \tau_v - \tau_r + \tau_f) \tag{5}$$



The baseband converter (BBC) phase is:

$$\phi_B = \nu_B(t - \tau_b + \tau_f) \tag{6}$$

Following this type of calculation, the phases at the sampler are:

$$\begin{aligned}\phi_d \;=\; & \nu(t - \tau_s - \tau_i - \tau_x) + \phi_D - \\ & \nu_{LO}(t - \tau_s - \tau_i - \tau_v - \tau_r + \tau_f) - \\ & \nu_B(t - \tau_s - \tau_b + \tau_f)\end{aligned} \tag{7}$$

$$\begin{aligned}\phi_t &= \nu_t(t - \tau_s - \tau_i - \tau_x - \tau_p - \tau_r + \tau_f) - \\ &\quad \nu_{LO}(t - \tau_s - \tau_i - \tau_v - \tau_r + \tau_f) - \\ &\quad \nu_B(t - \tau_s - \tau_b + \tau_f) \end{aligned} \tag{8}$$

The detected pulse cal tone phases are simply the sampled ϕ_t minus the detector phase which is $(\nu_t - \nu_{LO} - \nu_B)t$. Thus the output of a pulse cal detector is:

$$\begin{aligned}\phi_t &= \nu_t(-\tau_s - \tau_i - \tau_x - \tau_p - \tau_r + \tau_f) - \\ &\quad \nu_{LO}(-\tau_s - \tau_i - \tau_v - \tau_r + \tau_f) - \\ &\quad \nu_B(-\tau_s - \tau_b + \tau_f) \end{aligned} \tag{9}$$

If there are two tones in a band, the correction to the single band delay is the derivative of the tone phase with frequency, which can be obtained from the phase differences between two tones.

$$\begin{aligned}\frac{d\phi_t}{d\nu} &= \frac{(\phi_t^2 - \phi_t^1)}{(\nu_t^2 - \nu_t^1)} \\ &= -\tau_s - \tau_i - \tau_x - \tau_p - \tau_r + \tau_f \end{aligned} \tag{10}$$

Now we can obtain an expression for the data phase by substituting Equation 10 into Equation 7 and rearranging terms.

$$\phi_d = (\nu - \nu_{LO} - \nu_B)t + \phi_D + \phi_t + (\nu - \nu_t)\frac{d\phi_t}{dt} + \nu(\tau_p + \tau_r - \tau_f) \tag{11}$$

The uncorrected data set represents the correlations of data with phase ϕ_d at each site. What we would really like to correlate is data with phase $(\nu - \nu_{LO} - \nu_B)t + \phi_D$. Such data would not be subject to any offsets due to delays in the antenna systems. Rearranging terms in Equation 11 gives:

$$(\nu - \nu_{LO} - \nu_B)t + \phi_D = \phi_d - \phi_t - (\nu - \nu_t)\frac{d\phi_t}{dt} - \nu(\tau_p + \tau_r - \tau_f) \tag{12}$$

The term ϕ_t is the measured phase of one of the pulse cal tones, the one at ν_t. The derivative, $\frac{d\phi_t}{dt}$, is the phase slope determined from two or more tones within the band. Removing $\phi_t + (\nu - \nu_t)\frac{d\phi_t}{dt}$ from ϕ_d only leaves a term, $\nu(\tau_p + \tau_r - \tau_f)$, that looks like an overall clock offset if none of the delays involved are baseband channel dependent.

The delay in the pulse cal system, τ_p, should have no such dependence, although it is possible that there is an offset between the two polarizations. It should also be constant, although there is some concern about the effects of the moderately large temperature fluctuations seen in the VLBA vertex rooms. In any case, there are no cables involved that are subject either to bending or to outside temperature fluctuations. This term does contain the large and arbitrary phase offset of the pulse cal system and so can have value between $\pm 1/2\mu$sec. This phase offset should be constant as long as the power and reference LO are not interrupted, but will be reset to a new arbitrary and unknown value when such an interruption occurs.

The delay up the LO reference transmission system, τ_r, is common to all baseband channels. It is subject to both cable bending and to long runs of cables in the outside air. However this delay, or at least its fluctuations, are measured by the cable cal system so corrections can be made.

Finally, the delay between the maser and the formatter clock τ_f involves short, stable cable runs in the controlled environment of the equipment room and should be stable. Note that, for this analysis, any offsets of sampler epoch are lumped into τ_s which drops out with the pulse cal phase subtraction.

3 Practical Application

The application of Equation 12 to correct VLBI data is reasonably straightforward. However there is a practical difficulty that must be overcome. The large apriori uncertainty in τ_p, the delay that is affected by the pulse cal phase, causes there to be 2π ambiguities in the single band delay correction, $\frac{d\phi_t}{dt}$. There are also 2π ambiguities in ϕ_t. In past practice, when only the ϕ_t correction was made, these ambiguities were of no concern because the baseband channel data were subject to the same ambiguity. The fringe fits were not affected, other than through the fact that this allowed the delay ambiguities in the multi-band delays that afflict geodetic data. If both single and multi-band delays are being aligned using the multi-tone per band system, the ambiguities must be resolved.

One way to resolve the ambiguities is to do separate single and multi-band fringe fits on a strong calibrator. Then examine all of the possible combinations of ambiguities in the single band delay and the multi-band delay for the best match. If care is taken to be sure that the single band delay correction for each baseband channel is on the same ambiguity (the program that finds the deravitive should enforce this), then all of the data can be fitted for one single band delay, which should simplify the process and improve the SNR. Once the ambiguities have been resolved on a strong source, they are likely to remain constant over the entire experiment.

In the future, it is likely that 3 tones per band will be measured, one near each end and one separated from one of the others by the minimum 1 MHz spacing. This will either simplify or eliminate the need for ambiguity resolution. Also, it may eventually be possible to either force the phase of the pulse cal generators on the VLBA or measure that phase. That would significantly simplify processing.

In a practical application, there is an additional concern which should be taken into account. The phase slope change required by the pulse cal corrections can be very large — amounting to several turns across typical VLBA baseband channels. Literally forcing such a large phase slope on the data will complicate further processing and display. Eventually the phase slope would be taken back out by the fringe fitting step at which time it gets ascribed to a delay (probably clock) error. Therefore, it is a good idea to take out an arbitrary constant delay at the time the pulse cal calibration is made so that the residual phase slopes are nearly flat. This delay can be the result of a rough fringe fit on a calibrator. This step allows the use of a narrow fringe fitting window for weaker sources and improves the understandability of displays of bandpass spectra.

4 An Example

There are three pages of plots attached to this memo which show an example of calibration of a data set using 2 tones per band. These plots are cross correlation bandpasses on reference baselines made with a modified version of `plotbp`, the bandpass plotting program in the sniffer, the package use to examing VLBA correlator output. The program modifications were specific for the data used for this demonstration. The general ability to calibrate observations awaits a new AIPS task being written for that purpose. The test was done on experiment BB14, which just happened to be what was available at the time. Each baseband channel is 8 MHz wide and there are 4 channels in each circular polarization. The channels abut each other in frequency. The measured pulse cal tones were at 0.49 MHz and 7.49 MHz within each band.

The first page shows the uncorrected data. On this page, the channel order is such the the RCP and LCP data from the same frequency are adjacent to each other. On the other two pages, the channels have been reordered to place the 4 RCP channels before the 4 LCP channels. In the uncalibrated data, there are significant differences between the phase slopes in each individual band and there are phase jumps between bands. Without some sort of phase calibration, fringe fitting would have to be done separately on each band and the single and multi-band delays would have to be treated separately.

The second page shows the data after the pulse cal phases have been applied, but before the ambiguities have been resolved. Note that no pulse cal data were available for the VLA (station Y). Straight application of the pulse cal data introduced large phase slopes which made detection of phase jumps at baseband channel boundaries (the dashed vertical lines) difficult. Therefore, all data from a baseline were flattened by removing a single phase slope that was crudely derived by differencing adjacent spectral channels in the first baseband channel. For many baselines, the initial choice of ambiguity was correct as shown by the well aligned phases between baseband channels. However, for others, the single band delays have clearly been well aligned with each other, but the multi-band delay is different as indicated by the phase jumps between baseband channels. Note that, with 7 MHz between tones within each channel and 8 MHz between channels, it is possible for rather small phase jumps between channels to be the result of incorrect ambiguity choices.

The third page shows fully corrected data. For all baselines except that to the VLA where there was no pulse cal data, the phases have been very nicely aligned both within baseband channels and between them. It is clear that now a fringe fit could be made for a single delay that would apply to single and multi-bands and that would work for both polarizations. This should significantly increase the sensitivity that can be achieved easily. Basically, after this calibration, it is reasonable to treat all of the spectral channels in a polarization as if they were in one IF.

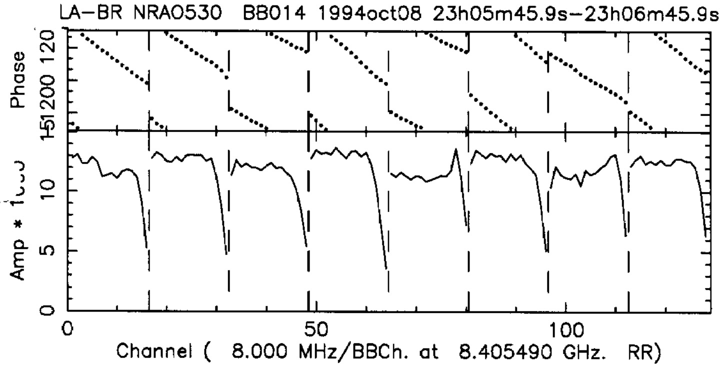
Note that there are small, but significant curvatures in some of the phase bandpasses over the full 32 MHz covered by this experiment. This curvature is not corrected by the pulse cal system. I am not sure what causes it, but suspect that it is something in the optics of the antenna which is not probed by the pulse cal system. This effect is worst on LA-SC.

Note also that there is a phase offset between the RCP and LCP channels (the break between the upper and lower halves of the spectra plotted). We hope that that offset is constant in time and can be used to calibrate the R-L phase difference and hence the absolute position angle of polarization on the sky. It should only depend on a few short pieces of cable and waveguide in the receiver so there is hope that it will be constant over long periods of time.

5 Summary

It has been demonstrated both mathematically and empirically that the multi-tone per band phase cal can be used to align the all of the phases in a polarization in a VLBI observation. After such calibration, the single and multi-band delays are equal and only one delay need be found with fringe fitting. Application of such calibration effectively shifts the point of delay reference from the sampler to the pulse cal injection point, or to the maser if cable cal calibration is done. This calibration should significantly simplify the downstream processing of multiple baseband channel data. It will also allow the use of single band delays to constrain multi-band delays for geodesy using the VLBA's rather limited number of baseband channels.

However, the delay shift resulting from pulse cal caibration can be large and, because the phase of the pulse cal is not forced or measured, can vary a lot from one antenna to another and one experiment to another (or even within an experiment if there is a power failure). This large delay shift leads to the complication of needing to resolve ambiguities which will complicate processing. A third tone per band and/or fixing or measuring the pulse cal phase at the antenna would be a big help.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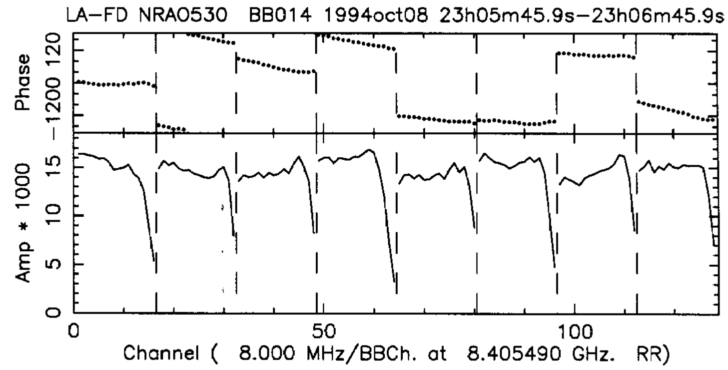
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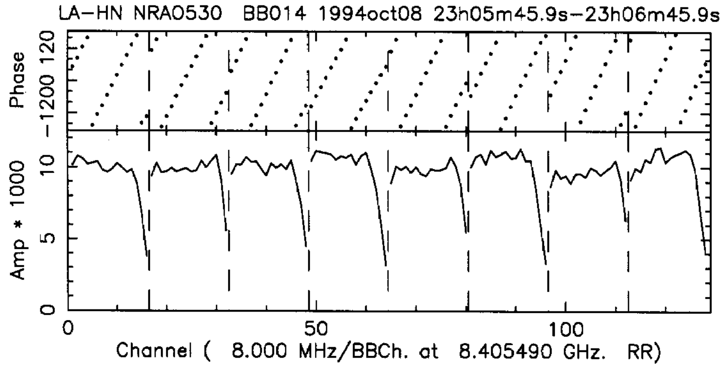
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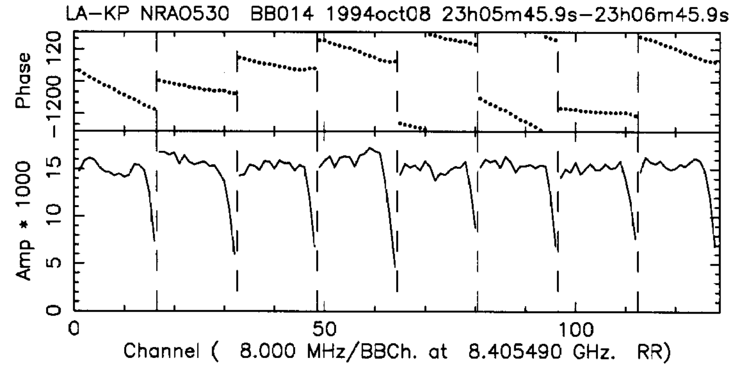
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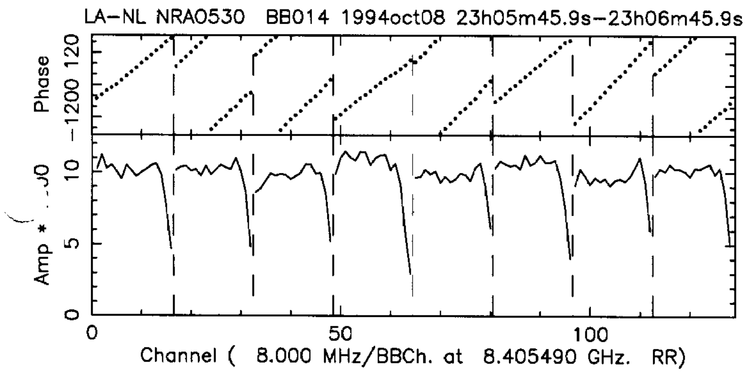
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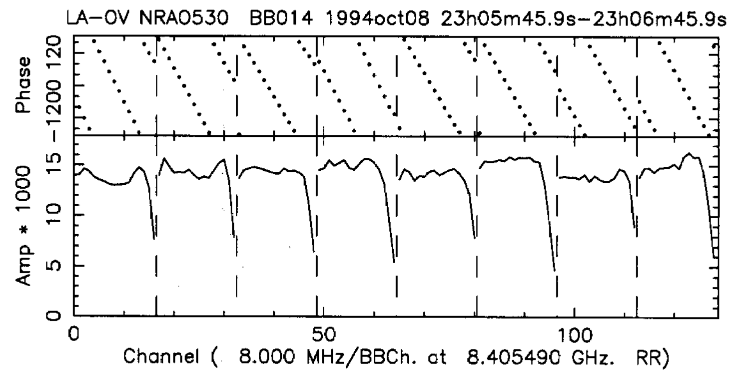
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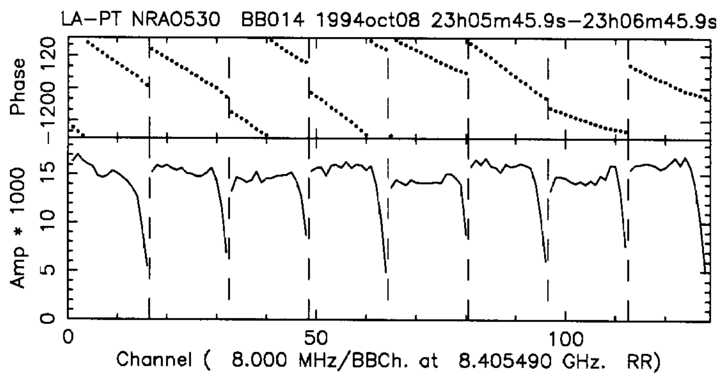
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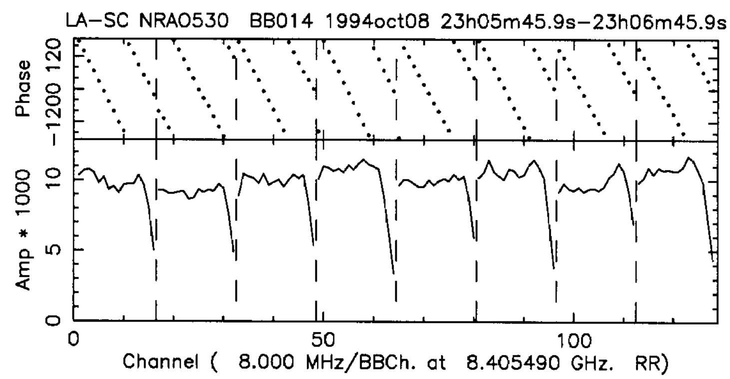
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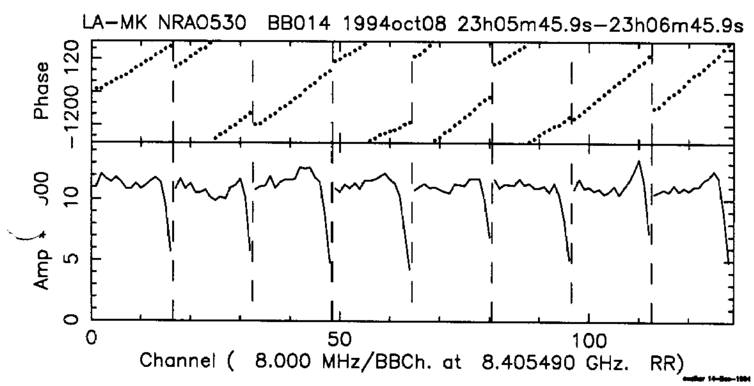
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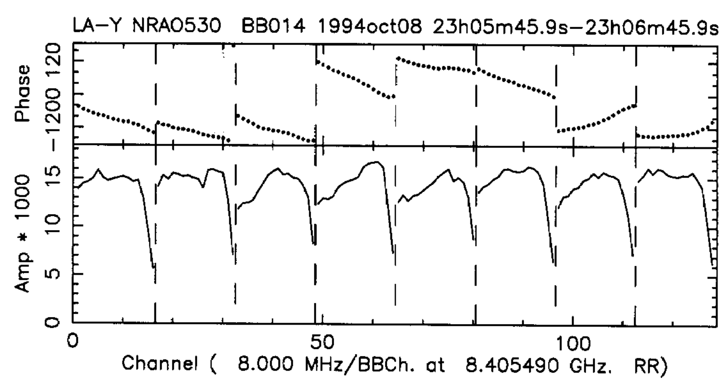
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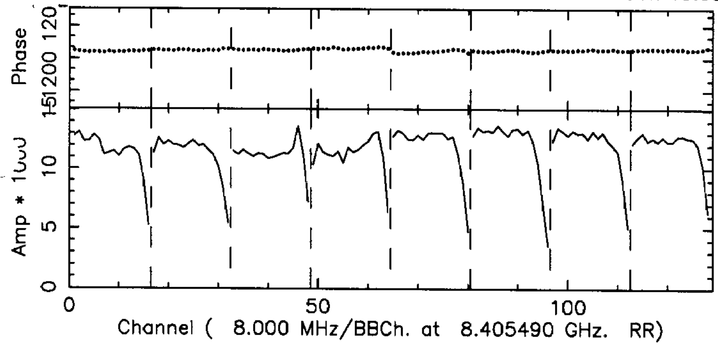

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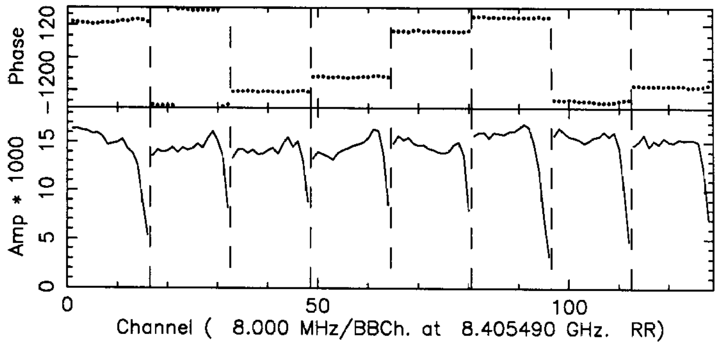

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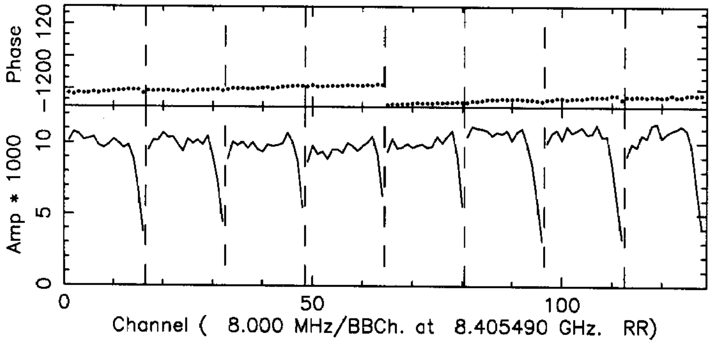

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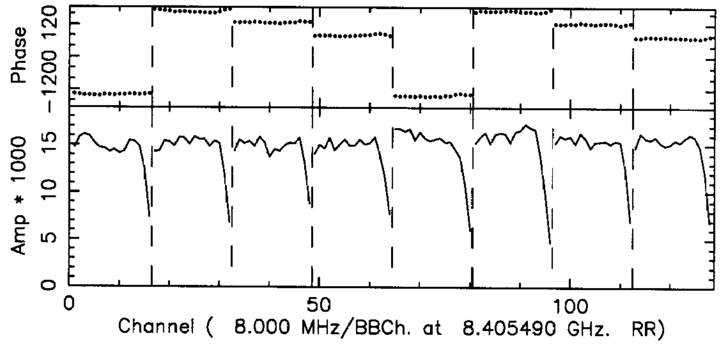

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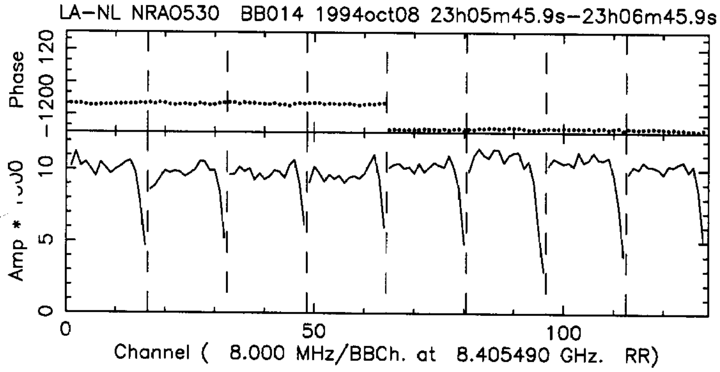

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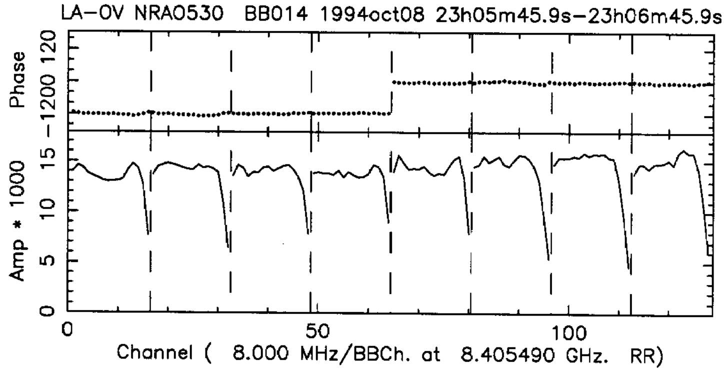

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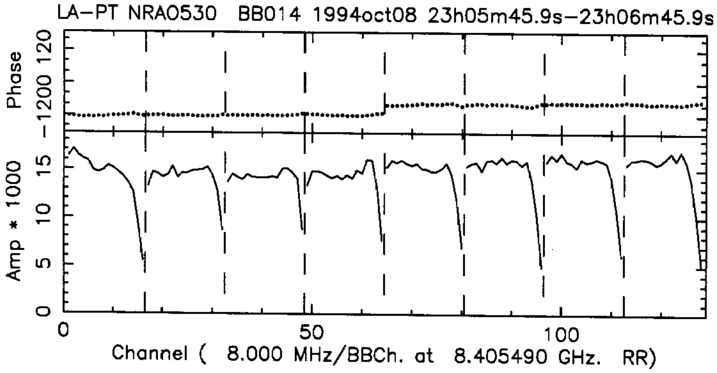

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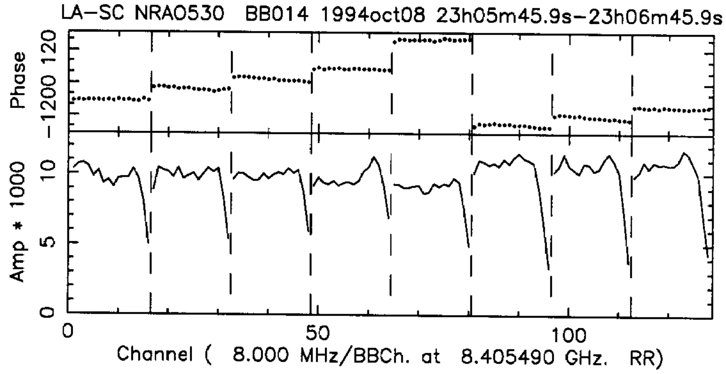

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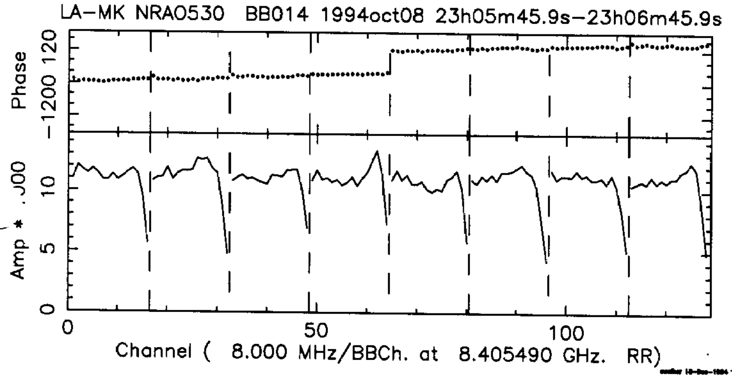

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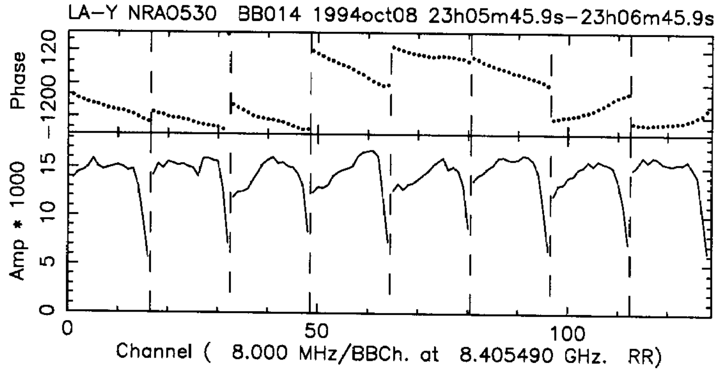

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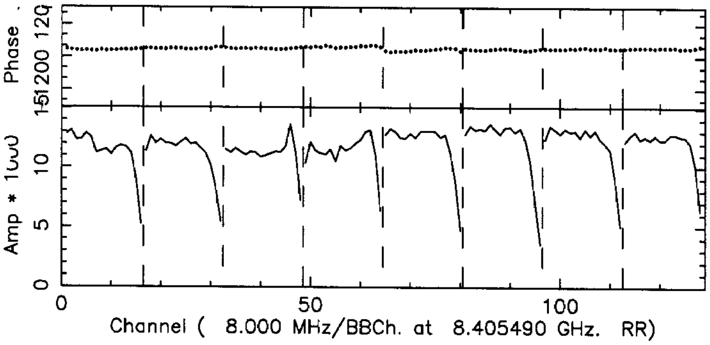

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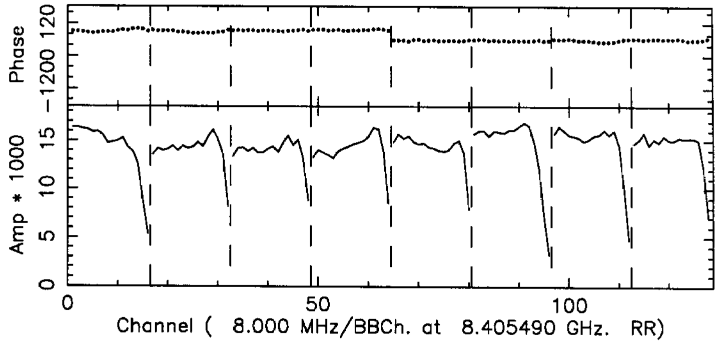

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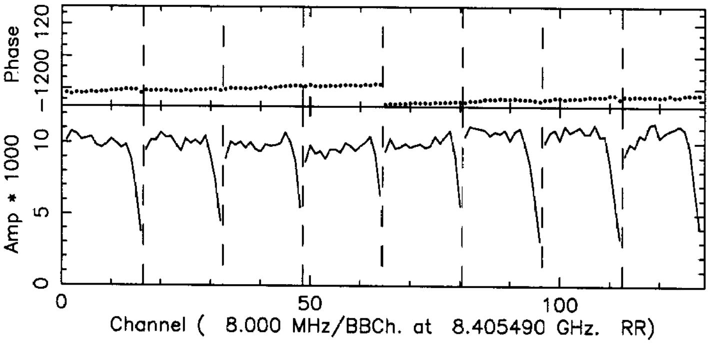

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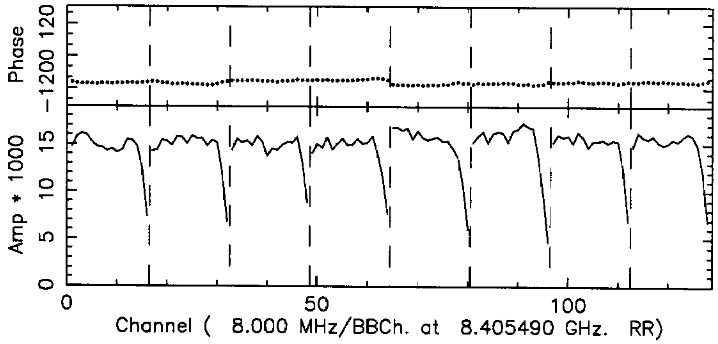

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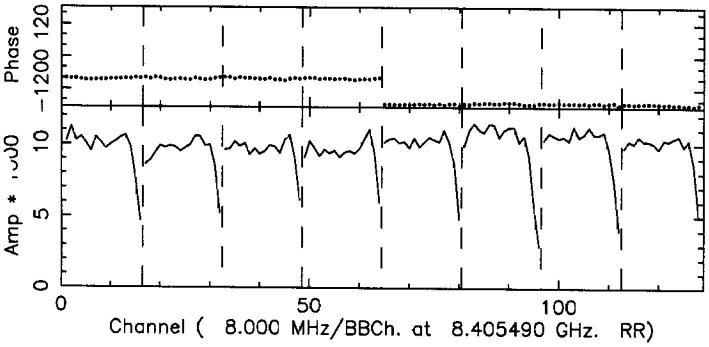

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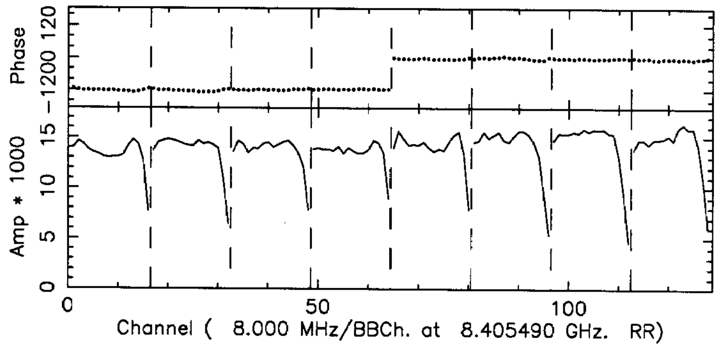

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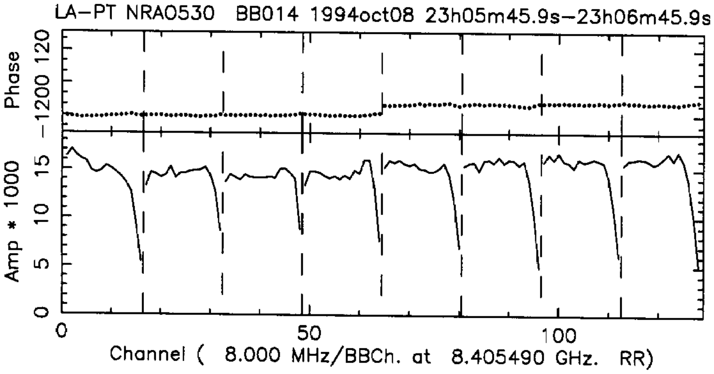

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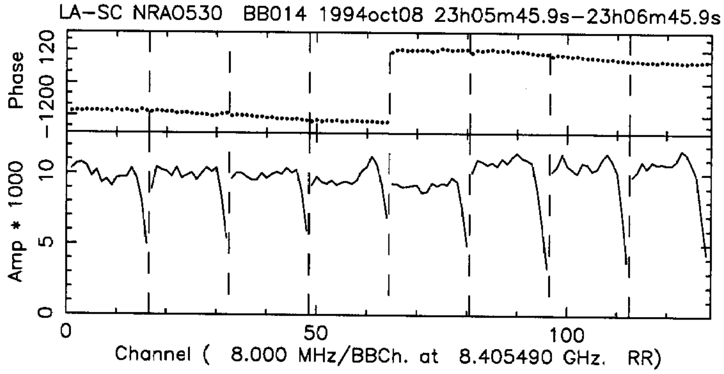

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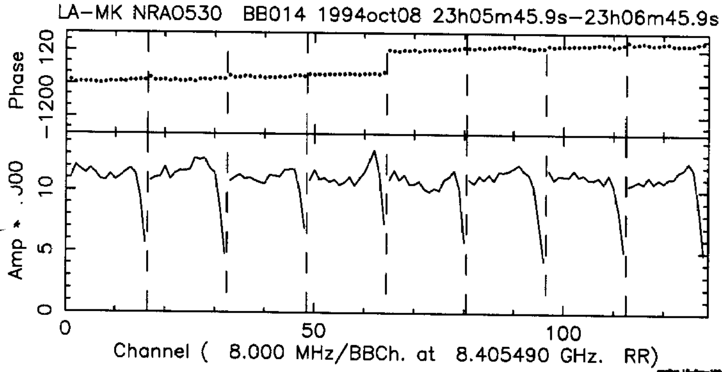

LA–Y NRAO530 BB014 1994oct08 23h05m45.9s–23h06m45.9s