Calibrating the Electric Vector Position Angle with the VLBA Pulse Calibration System

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1 Introduction

The calibration of the electric vector position angle (EVPA) in polarization VLBI observations has been traditionally based on independent observations of calibrator sources, often with the VLA. Not only do such observations require a lot of telescope time, but they greatly complicate scheduling and data reduction. Such observations are also an inaccurate way to calibrate the EVPA: comparison of measurements made at very different angular scales (with the VLA and the VLBA, for example) is very prone to errors since in many cases such instruments are sensitive to different emission. Even if many calibrators are used, it is difficult to get an EVPA calibration that is reliable to better than 10 degrees or so.

The calibration of the EVPA is equivalent to finding the absolute phase difference between the RCP and LCP gain systems. After parallel-hand fringe fitting, this phase difference is the same as the RCP–LCP (or R–L) gain phase difference at the antenna that was used as the reference. It will be shown in this document that instead of calibrating this phase difference "externally" using an astronomical source, it can also be calibrated "internally" with the pulse calibration system. The main question that will be answered here is whether the relative phase of RCP and LCP branches of this system remains sufficiently stable over months, or even years.

To answer this question, three 22 GHz VLBA experiments covering a period of ~1.5 years were used to obtain the absolute or "intrinsic" R–L phase differences in the pulse calibration systems at all VLBA sites. The intrinsic phase can be determined by (1) taking the difference of the RCP and LCP PCX (phase cal extractor) phase measurements for two tones (low and high) in a given baseband; (2) reducing the phase difference to the lower band edge frequency by using the slope (R–L delay difference) deduced from the two tones; (3) correcting for the R–L phase contribution that occurs between the feed and the sampler, which can be found by taking the difference of RCP and LCP gain phases that were applied to *fully* calibrate the data in AIPS. Here full calibration means that the absolute R–L gain phase difference was determined and corrected for using a method independent of the PCX system—for example, with an astronomical calibrator source.

When the intrinsic values for the PCX R-L phases have been determined (and found sufficiently stable for this purpose), they can be used to obtain an independent calibration of the EVPA. In section 2, the level of stability of the intrinsic PCX R–L phases is demonstrated. Section 3 discusses ways to calibrate the EVPA with the PCX. Recommendations to implement an effective scheme for EVPA calibration at the VLBA are given in section 4.

2 Results

The main results from the three experiments are given in Tables 1–4. The experiment on 13 June 1994, BL007, is chosen to serve as the reference epoch, because it is likely to have the most accurate external R–L gain phase calibration. The calibration was based on the measurements of a single strongly polarized spectral feature (linearly polarized flux density 170 Jy) in the water maser W51M with both the VLBA and the VLA. The time delay between the two observations was 5 days and there was no ambiguity in the identification of the observed polarized emission. The VLA EVPA (or A–C phase) calibration was obtained from the VLA primary calibrator 3C286. I am confident that the accuracy of the EVPA calibration in BL007 is better than 5 degrees.

In TP002 (2 May 1994), the R–L calibration was obtained by transferring it from BL007 via the phases of the *D*-term (instrumental polarization parameters of the antennas) solutions. In this process the *D*-term phases, which have the R–L gain phase offset in them, were compared and the best estimate of this offset was used to rotate the R–L phase in TP002.

Calibration for BL028 (24 January 1996) was obtained by comparing VLA and VLBA measurements of three continuum sources. From the scatter in the values given by different sources, I estimate that the accuracy of this calibration is unlikely to be better than 10 degrees in EVPA.

The columns in Tables 1–4 are as follows (all values in degrees):

(1) The R-L phase difference of the calibration tones averaged over the experiment and reduced to the lower band edge (R-L phase slope is available from the two tones within a baseband).

(2) The average R–L gain phase (for the given IF) applied in AIPS, corrected with the estimated error in the external R–L phase calibration (see below).

(3) The sum of (1) and (2), or calibrated PCX R–L phase. This value is intrinsic to the pulse calibration system at each site.

(4) The difference of the calibrated PCX phase from the value measured in BL007. If no BL007 value is available for a given station, then TP002 is used as the reference.

The extra correction in the R–L gain phase (column 2) was determined by requiring that the mean of column (4) should be zero. This correction was 2.1 degrees for TP002 and 15.6 degrees for BL028. The large value required for BL028 was not a surprise, since the expected accuracy of the external calibration in this experiment was low.

The most important result is that the phase residuals in column (4) are small. The three exceptions (Kitt Peak, Los Alamos and Hancock, see Table 5) all appear to have had their receivers replaced between BL007 and BL028, which naturally randomizes the intrinsic PCX R–L phase. This means that the intrinsic PCX stability at all sites over a period of ~1.5 years has been better than 7 degrees. As will be discussed in the next section, this allows calibration of the EVPA to within 1 degree or so.

Comparison of Tables 3 and 4 shows that the differences of the intrinsic PCX R–L phases between two channels separated by 8 MHz are small, but not zero. These reflect the R–L delay differences in the pulse calibration systems. So, to properly characterize the system, also its intrinsic R–L delay should be determined from measurements made at well-separated frequencies in a given frequency band.

3 The EVPA calibration path

In principle, PCX measurements at the fringe fitting reference antenna only are sufficient to calibrate the R–L phase in an experiment. Exactly this happens if the PCX measurements are applied the "standard" way (using the task PCCOR in AIPS before fringe fitting): *in the R–L phase calibration*, only the PCX measurement from the reference antenna is used in this case. The result is a correctly calibrated data set, provided that the PCX system at that particular station worked correctly and was accurate.

Better accuracy and reliability in R–L phase calibration can be achieved if PCX measurements from all stations are used. Probably the easiest way to implement this is as follows: 1) apply the PCX measurements with the AIPS task PCCOR; 2) fringe fit the parallel hands; 3) refine the fringe fit solutions. In the third step the R–L phase difference residuals of the fringe fitting solutions are studied and the mean over all antennas is made zero by adding a small overall R–L gain phase correction. The R–L residuals should be small, since the application of PCX phases before fringe fitting have removed the offsets w.r.t. the reference station—only the scatter in the PCX measurements is reflected by the fringe fitting solutions. Taking the average of the PCX measurements this way tends to cancel the errors and significantly more accurate calibration should result. Considering the scatter in column (4) of Table 3, it should be easy to attain an accuracy of 2 degrees in R–L phase, which means an accuracy of 1 degrees in the EVPA. No other current means of EVPA calibration can deliver such accuracy. One additional advantage of this approach is that the easily measurable scatter between antennas gives an estimate of the EVPA calibration accuracy.

As a prerequisite to this scheme, the PCX systems have to be externally calibrated so that they properly calibrate the absolute R–L gain phases at the antennas. This calibration, which is equivalent to finding the intrinsic PCX R–L phases, can be done in the way discussed in sections 1 and 2. Step 3 could be implemented by creating a new AIPS task that reads the SN table from FRING and modifies the R–L phase difference.

4 Conclusions and recommendations

It has been demonstrated that the VLBA pulse calibration systems show excellent R–L phase stability at 22 GHz over a period of 1.5 years. It is likely that better or same level of accuracy can be achieved at lower frequencies, where the pulse cal is likewise injected into the RF prior to any active components in the signal path. Unfortunately, this is not the case at 43 GHz, where the injection occurs only after the first frequency down-conversion. Therefore, I conclude that at 22 GHz and lower frequencies, an accurate internal calibration of the EVPA is possible with the VLBA pulse calibration system.

In order to implement a routine EVPA calibration scheme based on the pulse calibration system, I recommend the following:

1. A regular program for the external (or astronomical) calibration of the intrinsic PCX R–L phases at all relevant frequency bands should be initiated. This could be integrated into the semi-annual calibration run of the VLBA.

2. Tables containing the intrinsic PCX R–L phases and delays (or alternatively, the R–L phases at multiple frequencies within each band) should be maintained and regularly updated. These tables would be used to calibrate the information in the PC table, either when the table is created (preferable) or when the user applies the table to the data.

3. An AIPS task that reads the fringe fitting phase solutions and refines the R–L gain phase should be written. Such a task would allow the full accuracy of this method to be achieved.

Table 1: TP002 IF#1: 22223.49 MHz (02/05/1994). All values in degrees.

Antenna	Raw PCX phase (1)	Gain phase (2)	Intr. PCX phase (3)	TP2–BL7 (4)
BR	4.0	−9.1	−5.1	–
FD	–	–	–	–
HN	99.3	158.3	−102.4	+0.7
KP	177.9	110.7	−71.4	−0.5
LA	−115.8	−103.0	141.2	+1.9
MK	−15.2	8.4	−6.8	–
NL	80.8	−88.5	−7.7	+0.1
OV	–	–	–	–
PT	−142.7	118.6	−24.1	−1.0
SC	−107.0	47.4	−59.7	−1.0

Table 2: BL007 IF#1: 22220.49 MHz (13/06/1994)

Antenna	Raw PCX phase (1)	Gain phase (2)	Intr. PCX phase (3)
BR	–	–	–
FD	−28.8	155.1	126.3
HN	−120.2	17.1	−103.1
KP	110.4	178.7	−70.9
LA	−112.0	−108.7	139.3
MK	–	–	–
NL	85.9	−93.7	−7.8
OV	145.6	48.7	−165.7
PT	−136.1	113.0	−23.1
SC	−77.4	18.7	−58.7

Table 3: BL028 IF#1: 22225.49 MHz (24/01/1996)

Antenna	Raw PCX phase (1)	Gain phase (2)	Intr. PCX phase (3)		BL28–BL7 (4)	
BR	162.9	−166.3	−3.4		+1.7	
FD	42.6	83.1	125.7		−0.6	
HN	173.6	−25.2	148.4		−108.5	(3)
KP	108.6	43.1	151.7		−137.4	(1)
LA	12.2	−86.4	−74.2		+146.5	(2)
MK	−108.8	98.2	−10.6		−3.8	
NL	152.9	−158.0	−5.1		+2.7	
OV	−134.2	−31.2	−165.4	(4)	+0.3	
PT	124.0	−139.2	−15.2		+7.9	
SC	−113.8	55.1	−58.7		0.0	

Table 4: BL028 IF#2: 22233.49 MHz (24/01/1996)

Antenna	Raw PCX phase (1)	Gain phase (2)	Intr. PCX phase (3)		BL28–BL7 (4)	
BR	141.6	−146.2	−4.6		+0.5	
FD	−144.8	−83.1	132.1		+5.8	
HN	−61.0	−151.0	148.0		−108.9	(3)
KP	137.2	14.1	151.3		−137.8	(1)
LA	79.5	−153.9	−74.4		+146.3	(2)
MK	54.2	−65.3	−11.1		−4.3	
NL	−141.6	136.7	−4.9		+2.9	
OV	−121.4	−48.4	−169.8	(4)	−4.1	
PT	76.5	−95.7	−19.2		+3.9	
SC	161.0	139.3	−59.7		−1.0	

Table 5: Comments for tables 3 and 4. Source: vlba_gains.key

1)	KP	24/04/95	New receiver
2)	LA	12/09/95	New receiver
3)	HN	17/11/95	Dramatic change in Tcal (probably new receiver)
4)	OV	29/03/96	New receiver → PCX phase has to be re-calibrated