EVLA Memo 242
On Determining Antenna Polarization with AIPS

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Abstract

We describe three ways to determine antenna polarizations ('D-terms') using AIPS. One of these – using the known polarization properties of 3C286 – is novel and is now available in AIPS.

1 Background

Accurate polarimetric imaging usually requires determination of the antenna cross-polarizations. This is especially important for the VLA's Cassegrain bands, where the wideband linear-to-circular polarizers result in significantly impure circular-basis signals.

Calibration of the antenna cross-polarization makes use of the correlations between the RCP and LCP signals. For the case where these leakages and sources polarizations are small (say, less than 15% each), and the antennas' azimuth axes are parallel, so that the parallactic angles for all are the same, we can write, presuming parallel-hand calibration is applied, and ignoring a factor of two

$$V_{r1l2} = [I(D_{lr1} + D^*_{rl2}) + e^{-i2\Psi_p}(Q + iU)]e^{i\phi_{rl}} \quad (1)$$
$$V_{l1r2} = [I(D_{rl1} + D^*_{lr2}) + e^{i2\Psi_p}(Q - iU)]e^{-i\phi_{rl}}. \quad (2)$$

In this expression, V_{r1l2} and V_{l1r2} are the complex visibilities provided by the correlator between the two antennas, I, Q, and U are the (generally) complex Stokes' visibilities, (which for an unresolved calibrator are real-valued), Ψ_p is the parallactic angle of the source, and the 'D' terms represent the leakages from the LCP to RCP (D_{lr}) and from RCP to LCP (D_{rl}) for the two antennas.

The phase term ϕ_{rl} represents the cross-hand phase: parallel-hand calibration removes all delays and phase offsets within the RR and LL channels separately, but is not sensitive to any phase or delay differences between the polarization channels. The cross-hand phase in these equations represents these quantities for the reference antenna. Note that the term $e^{i\phi_{rl}}$ is indistinguishable from the antenna rotation term $e^{-i2\Psi_p}$ represented by the parallactic angle. We can interpret the former term either as an instrumental rotation, or as a rotation of the complex polarization $Q \pm iU$.

We note that in these expressions, the cross-hand responses are the vector sum of two terms – the first represents the leakages of signals from one polarization channel to the other, is constant in time and proportional to Stokes' I. The second is the (desired) polarized signal which rotates in time with twice the parallactic angle. (Note that these equations are written in the antenna frame).

There are two well-known methods utilized by both AIPS and CASA to determine the antenna polarizations:

- Observe one of more calibrators over a wide range in parallactic angle. The method takes advantage of the differential rotation between the source polarized signal and the antenna cross-hand leakage, as shown in the equations above. Provided there is sufficient signal strength and change in differential rotation (i.e., change in parallactic angle), we can derive both the antenna leakage terms and source polarization. This method is the 'gold standard', as it makes no assumptions on the polarized flux of the calibrators.

- Observe a source with a-priori known/assumed zero polarization. In this case, the equations above become (omitting the cross-hand phase term for clairty):

$$V_{r1l2} = I(D_{lr1} + D^*_{rl2}) \quad (3)$$
$$V_{l1r2} = I(D_{rl1} + D^*_{lr2}). \quad (4)$$

With no source polarized signal, the cross-hand visibilities contain only the cross-hand leakages, and solution can be found with a single observation.

These two methods have been successfully utilized for many years. But they are not sufficient for one class of observing – a short observation without an unpolarized calibrator being included. It is clear from examination of the first pair of equations that an observation of a strong, polarized source with known polarization properties will suffice to determine the 'D' terms – all that needs to be done is to subtract the known polarized contribution (the rightmost term in the equation) from the observed visibilities, allowing the cross-polarization terms to be determined in the same way as that for the unpolarized case.

It has long been assumed this can be done, but has never been implemented or tested in AIPS nor (so far as we know) in CASA.

2 Implmentation into AIPS

We have implemented this third method into AIPS, and have tested the results. There is however one complication due to the presence of the cross-hand phase in initial equation pair. The known 'Q' and 'U' values are referenced to the astronomical frame, while the equations shown are in the antenna reference frame – the (unknown) value of ϕ_{rl} needs to be accounted for before the correct 'D' values can be determined. In AIPS-language, the program RLDIF, using a source of known E-vector position angle, must be run before PCAL – this is inverse to normal procedure which requires calculation of the D-terms before the phase offset between the polarization channels is applied.[1]

To implement this third method, AIPS had to be modified to permit the cross-hand phase to be solved for before the cross-hand polarization is determined. For this reversal to be effective, it is necessary that the source used for RLDIF be strongly polarized with known polarization properties – so the (Q±U) term is known and is larger than the I(D1 + D^*2) term. The calibrator 3C286 (J1331+3030) meets these requirements, and was chosen for the tests described below. The polarized properties of 3C286 are well known, as shown in the recent paper by Perley et al. ApJS **283**,82 (2026).

3 The Observations

Testing this proposed new procedure requires an observation which allows all three polarization calibration methods to be run. Such an observation is found in the recent Cygnus-A transient monitoring program – 26A-487. This is a six-hour observation including numerous scans of a point-calibrator J2007+4029, a pair of scans on 3C286, and a single observation of J0319+4130 (3C84) – the 'canonical' unpolarized calibrator. These observations were taken on 28 March 2026, and bands X through Q. We selected X-band for this analysis.

Parallel-hand calibration was done by standard methods using the source 3C286 for flux density and bandpass calibration. The polarization calibration followed three parallel methods:

1. Use all the observations of the three calibrators – J0319+4130, J1331+3030, and J2007+4029 – to determine both the antenna D-terms and the calibrator polarizations.

2. Use the single observation of 3C84 (J0319+4130), presuming its intrinsic polarization is zero.

3. Use the known polarization of 3C286 (J1331+3030). AIPS now knows the Stokes Q and U values for this source for frequencies between 530 MHz and 49 GHz. Invoking the OPTYPE = CPOL option in the task SETJY will fill the SU table with I, Q, and U values for all frequencies in the database.

The first two methods allow use of the standard procedures:

1. RLDLY to find the cross-hand delay,

2. PCAL to find the cross-polarizations and (for the first path) calibrator polarizations,

3. RLDIF to rotate these solutions to the astronomical frame, using a source of known EVPA.

For the third method, the latter two operations are reversed in order – one of the goals of this excercise is to judge the effectiveness of this reversal.

Following these calibrations, images of the three calibrators were made in the three Stokes' parameters I, Q, and U. For this, we used spectral window #20, at a frequency of 10.423 GHz.

[1] Alternatively, the determination of ϕ_{rl} could be made as part of the polarization calibration program PDIF, since both Q and U are known. However, AIPS is not at present able to do this.

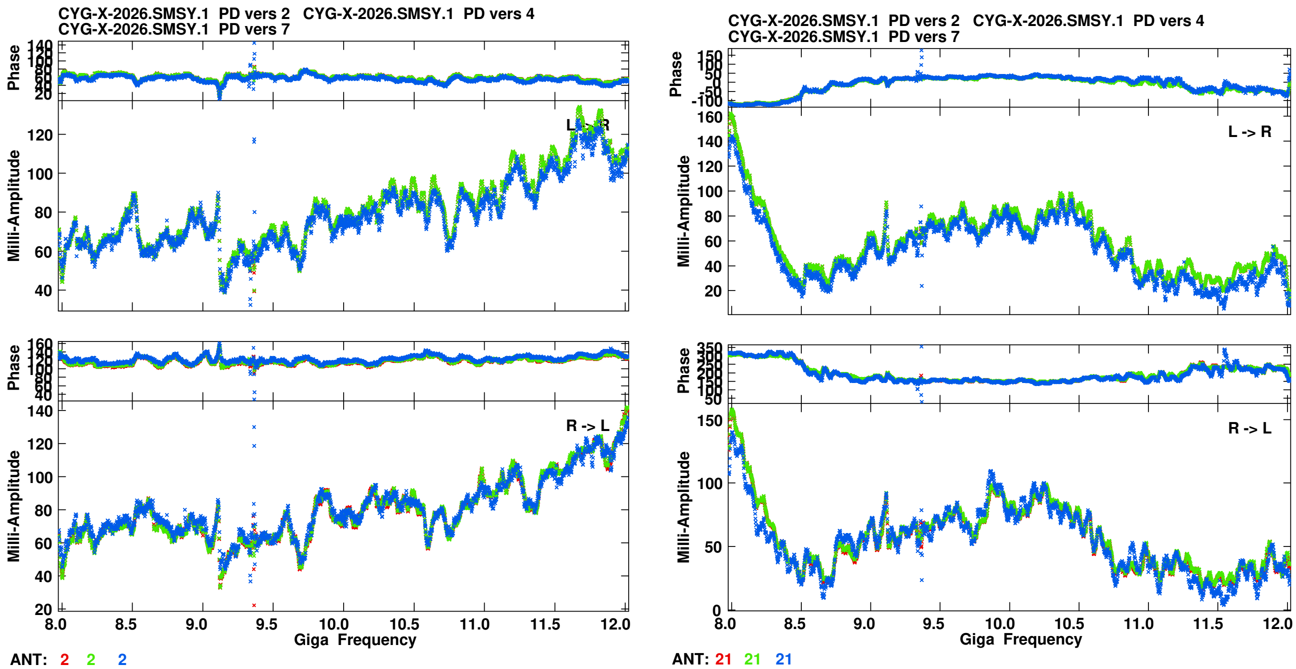

Figure 1: The resulting D-terms for ea02 (left) and ea21 (right), spanning all frequencies. The narrow plot shows the phase in degrees, the wider one the amplitude, in milli-fractional polarization. The red trace shows the result from Method 1, the green trace for Method 2, the blue trace for Method 3.

4 Results

The derived D-term parameters for ea02 and ea21 are shown in fig 1. These are typical for all antennas in the array. The solutions for the three methods are barely separable, differing by typically 0.2 percent, and no more than 0.5 percent. The red and blue traces are nearly identical – the green one (3C84 with assumed zero polarization) is slightly offset, possibly because the source has a small polarization.

The values for the polarized properties of the three calibrators are given in the following table. SPW20 was used for this, at a frequency of 10.423 GHz. Examination of the Q and U images gives important information.

	J2007+4029			J1331+3030			J0319+4130		
	I	EVPA	%Pol	I	EVPA	%Pol	I	EVPA	%Pol
Method1	2.51	75.03	2.86	4.24	32.95	12.40	54.1	15.8	0.08
Method2	2.51	75.06	2.91	4.24	32.94	12.44	54.1	-	<.03
Method3	2.51	75.03	3.04	4.24	32.92	12.44	54.1	-61	0.61

Methods 1 and 2 give about the same residual noise for the three sources: ∼0.16 mJy for J2007+4029, ∼0.40 mJy for J1331+3030 and J0319+4130. Method 3 however, while giving similar residuals for J2007+4029 and J1331+3030 to those from Methods 1 and 2, gave considerably worse residuals for J0319+4130 – more than ten times higher, with easily visible residual structures. Evidently, for a source this strong, with fractional polarization so low, the polarization calibration errors have dominated.

5 Discussion

There are only trivial differences between the solutions for the three methods. Method 2 (assumes 3C84 has zero polarization) is slightly displaced upwards in the R -> L leakages, possibly because it has an intrinsic polarization of ∼0.5% as shown in the table in Method 1. The red (Method 1) and blue (Method 3) traces in the plot are nearly indistinguishable.

The fractional polarizations are the same within 0.1% for the two standard calibrators, while the electric vector position angles (EVPA) are the same to better than 0.05 degrees. These values are comparable to error estimates made through propagation of the residuals in the map images. There is a notable difference in the fractional polarizations for the supposedly unpolarized calibrator 3C84 – about 0.5%. However, the fractional polarization for this source is very low, while the flux of the source is quite high – 54 Jy. Method 1 shows the true fractional polarization of this source is not zero, but at 0.08% it is certainly low enough for Method 2 to be expected to work.

We conclude that the three methods are equally valid for polarization calibration, but note that Method 1, which makes no assumptions about the polarization properties of the calibrators (other than they are not high) is always to be preferred. Based on the degraded Q and U images of the unpolarized calibrator 3C84 - J0319+4130, Method 3 should not be employed for sources with very low polarization – 1% or less.