EVLA Memo 131
Measurements of C-Band EVLA Antenna Polarization

Rick Perley

May 18, 2009

Abstract

A simple method for determining absolute antenna cross-polarization is described. Observations using this method were taken at C-band and the results are shown. The wide-band EVLA circular polarizers have high cross-polarization, exceeding 5% at most frequencies on most antennas. However, orthogonality between the RCP and LCP outputs is maintained, resulting in baseline-based cross-polarization of typically 5%.

1 Introduction

The EVLA utilizes circularly polarized systems at all its frequency bands. Generation of circularly polarized signals requires combination of the orthogonal linear signal components provided by the horn with ±90 degree phase shifts – a process which cannot be done perfectly. The primary effect of imperfect circular polarizers is a coupling of the total intensity 'I' into the two cross-polarization correlations from which measures of linear polarization are derived. Typically, there is approximately equal signal from the leakage as there is in the desired linear polarization, so careful calibration of the cross-polarization is required in order to extract accurate linear polarization.

The EVLA project has established a goal of 5% cross-polarization for its circularly polarized receivers. Low cross-polarization is useful primarily to simplify calibration and imaging, as certain approximations can be taken in the determination of instrumental parameters, and in the subsequent inversion between the observed visibilities and Stokes visibilities.

The leakage signal appearing on any baseline is the sum of two complex antenna-based terms – because of this summation, it is not possible for an array like the VLA (where all antennas view the source with the same parallactic angle) to derive the antenna-based complex leakages. The usual procedure is to reference the derived values to an arbitrary standard – usually one 'reference' antenna for which the cross-polarization is taken to be zero, or the vector sum over all antennas. This procedure is generally sufficient for accurate corrections.

However, the laboratory engineering measurements of a feed system are always done on an antenna basis, and there is considerable confusion in comparing the on-sky baseline-based measurements with the laboratory antenna-based measures. To facilitate such comparisons, we have developed a simple method of deriving on-sky measures of the antenna polarization parameters.

2 Interferometer Response

In general, the four complex correlator products from any pair of arbitarily polarized antennas due to arbitarily polarized radiation is a weighted sum over the four Stokes visibilities, with the four coefficients of the sum being functions of the polarization states of the antennas involved. For unpolarized radiation from an unresolved source located at the phase tracking center as seen by two antennas whose parallactic angles are the same, the four equations (using a circular basis) are particularly simple:

$$V_{r_1r_2} = G_{r1}G^*_{r2}(1 + D_{r1}D^*_{r2})I \quad (1)$$

$$V_{l_1l_2} = G_{l1}G^*_{l2}(1 + D_{l1}D^*_{l2})I \quad (2)$$

$$V_{r_1l_2} = G_{r1}G^*_{l2}(D_{r1} + D^*_{l2})I \quad (3)$$

$$V_{l_1r_2} = G_{l1}G^*_{r2}(D_{l1} + D^*_{r2})I. \quad (4)$$

The four G terms represent the parallel-hand system gains, and are determined from the two parallel-hand correlations of a source of known flux density, where it is normally assumed that the product of the two D terms is negligible: $|D| << 1$, so that the product term between the two D's is ignored.

The four D terms represent the cross-polarization 'leakage' between the RCP and LCP channels for the two antennas concerned. These terms are defined in terms of the antenna's polarization properties by:

$$D_r = \tan\beta_r e^{2i\phi_r} \tag{5}$$
$$D_l = \tan\beta_l e^{-2i\phi_l}. \tag{6}$$

The angles ϕ_r and ϕ_l are the orientations of the major axes of the polarization ellipses for the REP and LEP ports, respectively, in the antenna reference frame. The angles β_r and β_l are defined as

$$\beta_r = \pi/4 + \chi_r \tag{7}$$
$$\beta_l = \pi/4 - \chi_l \tag{8}$$

and physically represent the deviation of the antenna polarization ellipticity from perfect circularity. The angle $\chi = \arctan(b/a)$ is a measure of the ellipticity of the antenna polarization ellipse in the antenna frame of reference. Left elliptical polarization has positive ellipticity ($\chi_l > 1$), right elliptical polarization is negative ($\chi_r < 1$). Low antenna cross-polarization means that $\beta \ll 1$. As defined above, both β_r and β_l are positive real quantities. It is easily shown that the ellipticity $\epsilon = b/a$ is related to the magnitude of the cross-polarization by

$$\epsilon = \frac{1-|D|}{1+|D|} \tag{9}$$

Let us now assume that calibration has been performed, and that the source has unit flux density: $S = 1$. Then the cross-polarized responses become

$$V_{r_1 l_2} = D_{r1} + D^*_{l2} \tag{10}$$
$$V_{l_1 r_2} = D_{l1} + D^*_{r2}. \tag{11}$$

The response for each baseline depends on the sum of two complex quantities, one from each of the two contributing antennas. Note that, being a sum of complex numbers, each cross-product can be as large as the sum of the absolute values of the cross-polarizations if the two leakage terms are oriented in parallel, or equal to zero if the absolute values are equal and the orientations opposite. This latter condition is termed 'orthogonality', as it corresponds to the two oppositely polarized ellipses being orthogonal.

Now suppose we are able to rotate one antenna by 90 degrees about an axis pointed towards the target source. This rotates the antenna polarization ellipse by the same angle for both polarizations, so that the antenna polarization ellipse angles become: $\phi \rightarrow \phi + \pi/2$. The cross-polarization responses are now, using equations (5) and (6):

$$V^R_{r_1 l_2} = D_{r1} - D^*_{l2} \tag{12}$$
$$V^R_{l_1 r_2} = D_{l1} - D^*_{r2} \tag{13}$$

where we have rotated antenna 2, and the superscript 'R' denotes the visibility observed when this antenna has been rotated.

If one makes a pair of observations, one with the antenna in the normal orientation, and the other with the antenna rotated by 90 degrees, the four resulting cross-hand visibility measurements can be trivially combined to provide the four complex 'D' terms:

$$D_{r1} = \frac{V_{r1l2} + V^R_{r1l2}}{2} \tag{14}$$
$$D^*_{l2} = \frac{V_{r1l2} - V^R_{r1l2}}{2} \tag{15}$$
$$D_{l1} = \frac{V_{l1r2} + V^R_{l1r2}}{2} \tag{16}$$
$$D^*_{r2} = \frac{V_{l1r2} - V^R_{l1r2}}{2} \tag{17}$$

This provides a straightforward way to determine the absolute antenna cross-polarizations.

3 Observations

It is not possible for the EVLA to rotate an antenna by 90 degrees while observing a source[1]. However, the receiver can be rotated by 90 degrees, as it is mounted to the horn by 8 bolts uniformly distributed around the flanges. Provided that the polarization impurity is dominated by the receiver and polarizer (and this is most surely the case), the cross-polarization can be determined by receiver rotation alone.

Observations were performed of the strong calibrator 3C84 with the receiver for antenna 8 rotated by 90 degrees on April 26, and with antenna 8's receiver in the normal orientation on April 30. The source 3C84 is well known for having negligibly small polarization. The array was in the 'B' configuration, for which the halo emission from 3C84 is largely resolved out. The two observations were made at the same hour angle to eliminate any residual parallactic angle effects. Observations were taken at 8 frequencies: 4385, 4885, 5385, 5885, 6385, 6885, 7385 and 7885 MHz in order to establish the frequency dependence of the cross-polarization over the entire C-band frequency span. Following basic editing, the data were calibrated using an arbitrary flux density of 1 Jy. Care was taken to ensure the normal correction for source parallactic angle was turned off, so the resulting values for the cross-polarization are in the antenna frame of reference.

At the time of these observations, eight EVLA antennas were equipped with the new wide-band ortho-mode transducers (OMTs): 2, 3, 8, 9, 15, 21, 24 and 28. One of these, antenna 15, was not available both days, so the results below are provided for the remaining seven. All other EVLA antennas were equipped (temporarily) with old style VLA polarizers. Polarization results for these, and the remaining unconverted VLA antennas (6, 7, 10, 12, 20, 22) were derived at 4385 and 4885 MHz.

4 Results

The antenna polarizations for all available antennas are shown in Figures 1 and 2 for 4385 and 4885 MHz. The

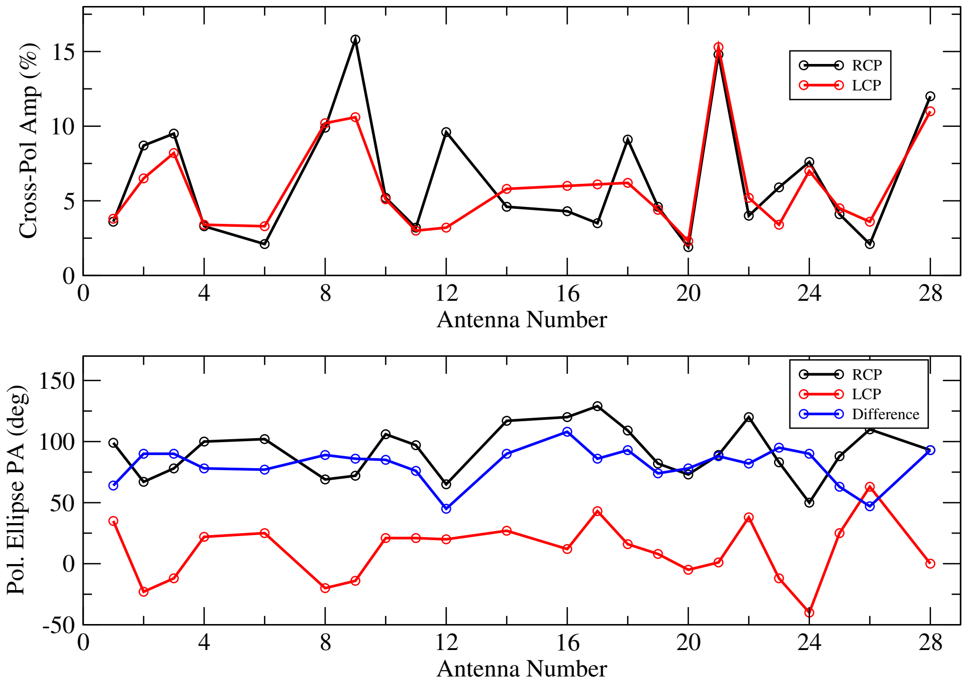

Figure 1: The absolute cross-polarization of the VLA and EVLA antennas at 4385 MHz. The top panel shows the cross-polarization amplitudes $|D| = \tan\beta$ in percent. The EVLA antennas equipped with wideband polarizers (2, 3, 8, 9, 21, 24 and 28) all have notably higher polarization than the antennas equipped with the old-style narrow band VLA polarizers. The orientations of the antenna polarizations are shown in the lower panel. The blue trace shows the difference, indicating that the polarization ellipses are generally closely orthogonal.

[1]One can rotate it by 180 degrees by observing 'over the top' for sources of sufficiently high elevation – however, this is not useful for determining polarization as the polarization ellipse is reflection-symmetric about its principal axes.

first plot shows that the typical polarization for antennas equipped with the old narrow-band VLA polarizers is about 5MHz. The polarization is considerably higher for the new wide-band polarizer-equipped EVLA antennas. The lower panel of this figure shows the orientation of the antenna polarization ellipses. The blue trace in the figure is the orientation difference, which is close to 90 degrees for all antennas. Figure 2 shows that at 4885 MHz, the antenna polarizations for the old-style narrow-band polarizers are very small indeed – typically 1%. The quadrature relation is retained, although with the low polarizations, the noise in the phase differences is much higher. It is to be noted that the behavior of the VLA polarizers is exactly as expected – they were designed to give good purity between 4500 and 5000 MHz. The higher values noted at 4385 MHz are no surprise.

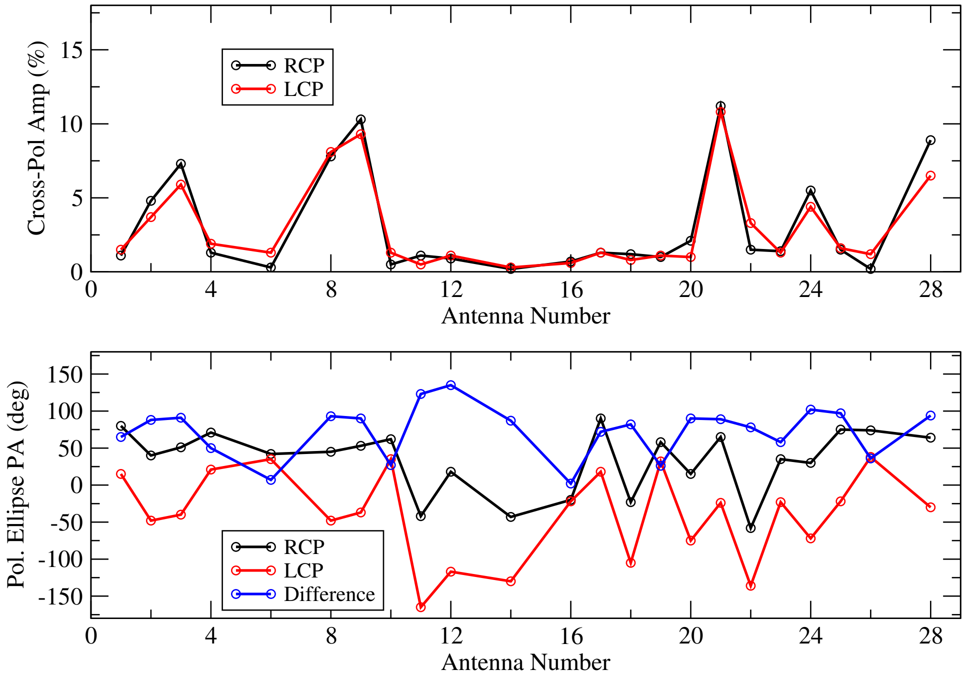

Figure 2: The same as in Fig. 1, but for 4885 MHz. The antennas equipped with the narrow-band VLA polarizers show excellent purity. The new wide-band polarizers (on antennas 3, 4, 8, 9, 21, 24 and 28) are notably less pure.

Orthogonality is a useful characteristic. If the polarization ellipse of the RCP of one antenna is equal and orthogonal to the LCP of the other, equations (10) and (11) show that the cross-polarized leakage signals will be exactly cancelled out. Even if the ellipticities and not exact and/or the orthogonality not perfect, a considerable reduction in the cross-polarization baseline response can be obtained. Hence, even if the antenna polarizations are poor, acceptable cross-polarization can be obtained if this phase relationship can be established.

Figure 3 shows the frequency dependence of the cross-polarization for the seven working EVLA antennas equipped with the new wide-band OMTs. The general trend of higher polarization at the edges and lower in the middle is clear, and matches the trends seen in the lab. However, the absolute values of the polarization are higher than expected from lab measurements. Polarization orthogonality is a valuable characteristic, so we show in Figure 4 the difference between the RCP and LCP ellipse position angles for the seven tested antennas. There is only one discrepant antenna – antenna 2 whose LCP orientation is notably different at high frequencies. However, the effect of this is small, as the antenna polarization is very low.

The effectiveness of the quadrature relation in reducing cross-polarization can be notable. In all cases, the baseline-based measures of the cross-polarization seen in these data are less than the typical antenna cross-polarizations, and in many cases, less than 3%, despite the component antennas having polarization of 10% ore more.

5 Discussion

The antenna cross-polarization is higher than desired. However, this is not a critical issue – defined as one requiring a new design – unless the cross-polarizations are also unstable. High cross-polarization will require

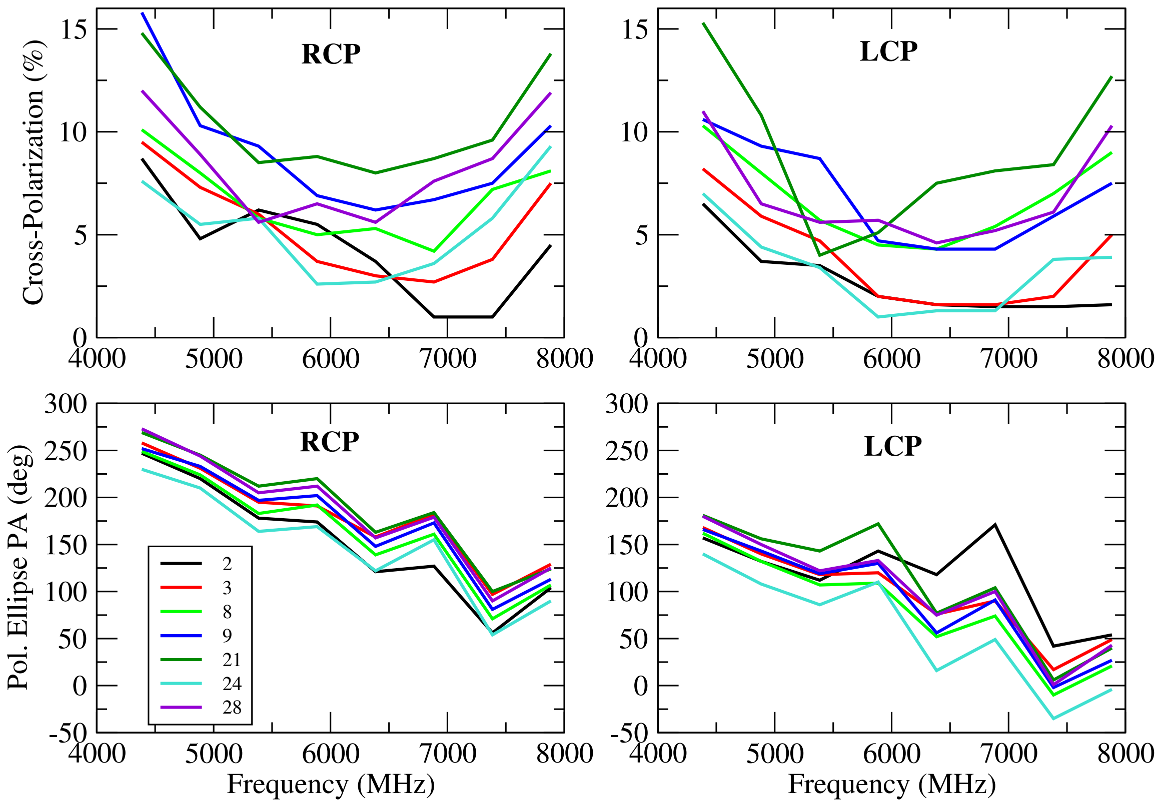

Figure 3: The upper panels shows the absolute cross-polarizations for all seven functioning EVLA antennas equipped with wide-band OMTs for RCP (left) and LCP (right). The lower panel shows the orientations of the polarization ellipses. The differences between RCP and LCP are close to 90 degrees for all antennas.

a more involved calibration process, especially if high dynamic range is also required in addition to accurate polariimetry. But as long as the cross-polarizations are stable, they can be measured and the appropriate corrections made to the visibility data. Preliminary observations appear to show that the cross-polarizations are indeed very stable – the results will be in an upcoming memo by Perley and Sault.

The existence of orthogonality in the antenna polarizations is not an accident, and must clearly be a property of the quadrature hybrid used to perform the 90 degree phase shifts needed to convert the native linear output of the OMTs to the desired circular polarizations. Providing amplitude balance is maintained, orthogonality is preserved in an imperfect quadrature hybrid if the differential phase shifts in the diagonal elements of the hybrid remain at 180 degrees. For example, if the 'H' port phase shift to the 'L' port output is 91 degrees, orthogonality is retained if the 'V' port phase shift to the 'R' port is -89 degrees.

The author thanks Bob Hayward for the discussions on polarization measurements which led to this work.

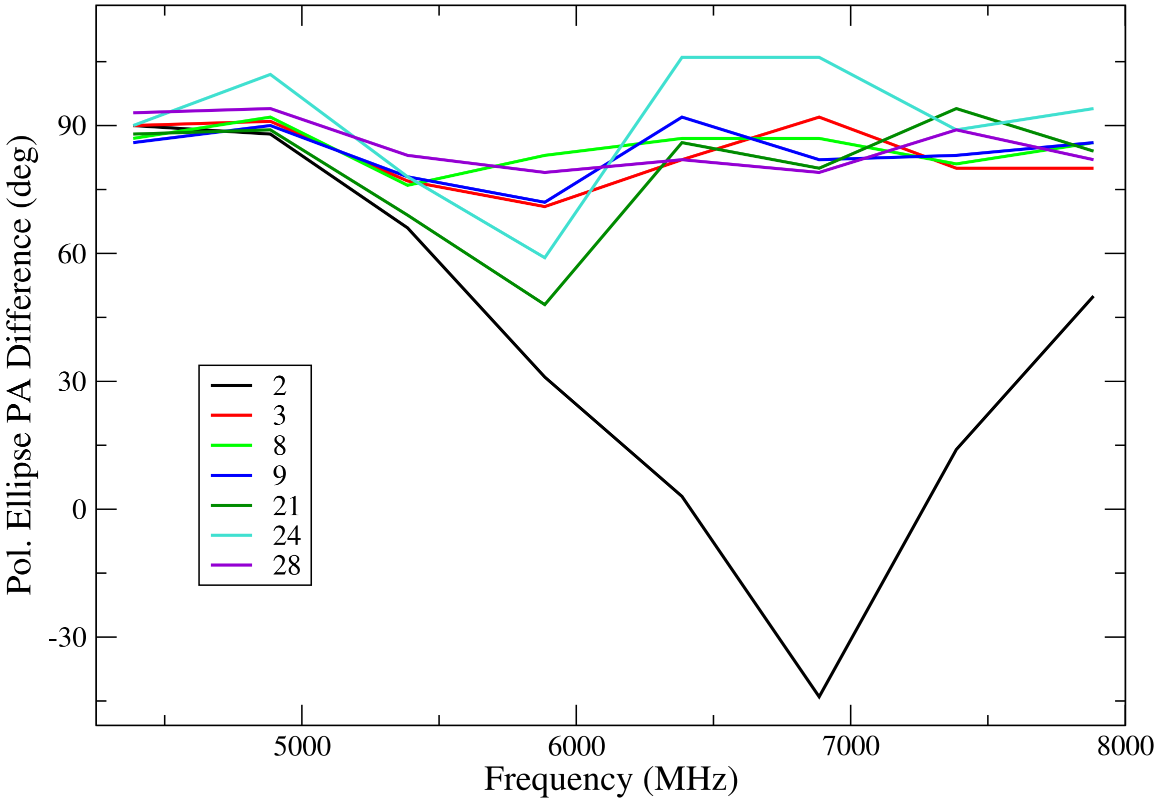

Figure 4: Showing the orthogonality of the EVLA antenna polarization ellipses. Except for antenna 2 (whose polarization at the higher frequencies is very low), the differences are close to 90 degrees, enabling acceptably low leakages in the cross-polarization baseline-based correlations.