# EVLA Memo 135
# Further EVLA Polarizer Stability Measurements

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**Abstract**

Following on from EVLA Memo 134, further measurements were made of the stability of EVLA cross-polarization characteristics. Observations and analysis were performed at C, K, Ka and Q bands over an 11 hour period. In general this short-term analysis showed variations in the polarization leakage parameter estimates that were consistent with the thermal noise errors inherent in those estimates. That is, the stability is better that the thermal noise limits of the tests. The upper limit on the variability ranged from about $10^{-3}$ at C band to $10^{-2}$ at Q band. Although the tests of most of the antennas reached this thermal noise limit, there are a small number of miscreant antennas. Some of these have system sensitivity that was much poorer than a the norm for the array.

This memo also reports on an analysis of long term stability at C and K bands for observations 5 weeks apart. Although the deduced variability was above the sensitivity limit, the variation was typically $< 10^{-3}$ at C band and $\sim 2 \times 10^{-3}$ at K band. We looked for and found no evidence that moving an antenna has an effect on its polarimetric stability.

Antenna 21 at C band and antenna 13 at K band are antennas which have the poorest stability, both short-term and long-term. Antenna 4 at C band also shows poor stability. However it has a VLA-style polarizer that is scheduled for replacement. Antenna 11 at Q band appears to have poor stability.

## 1 Introduction

With similar motivation and approach to the tests described in EVLA Memo 134, observations were made of the source 1800+784 at several frequencies in C, K, Ka and Q on 02 June 2009. The observing frequencies and antennas used are given in Table 2. The standard VLA continuum observing mode with a bandwidth of 50 MHz was used. The observation cycled around all the frequencies, typically making an observation of one minute at each frequency setting every half hour. The observation was for 11 hours mainly in the night (approximately 4:00 to 15:00 UT or 22:00 to 09:00 local summer time). Observing conditions were good with clear skies and low wind. Reference pointing was performed regularly: the pointing solutions showed a slow, smooth change with time. Flagging and baseline-dependent calibration was performed in AIPS. Additional flagging and the remaining calibration and analysis were performed in Miriad. The source 1800+784 is a good point source. We have assumed a flux density of 2.3 Jy at 4300 MHz, rising to 2.5 Jy at 7800 MHz, and then remaining flat at 2.75 Jy at all frequencies above 18000 MHz. It is also modestly polarized: there is 2.8% linearly polarized emission up to about 30000 MHz, and then this rises to about 3.7% at 48000 MHz. Solving for and accounting for the linear polarization was an integral part of the calibration process used for these observations.

A notable difference with the work presented in EVLA Memo 134 and this one is that this memo is broader in frequency coverage, but shallower in sensitivity. Because the calibrator used in Memo 134 was a factor fo $\sim 5$ stronger and because there were fewer frequencies and so more integration time per frequency, the polarization measurements of Memo 134 are about an order of magnitude more sensitive than those presented here.

## 2 Short term variability

Using the $\approx$ 11-hour observation, an overall solution was found for the leakages and the source polarization. Using this source polarization, leakage solutions were computed every 30 minutes. Each solution interval typically contained only a few minutes of integration time at each frequency. For each solution, we found "normalization terms" so minimize any difference from the overall solution[1]. The RMS variation in the leakages for each antenna from the overall solution was then found. This is given in Figure 1. This gives the RMS of the variation in the real and imaginary parts. Points are shown for the best, the median and the 80th percentile antenna as well as the worst antenna. The worst antenna is numbered on the plot.

This variation must be compared with the expected uncertainty in the leakage term solutions resulting from system noise. Appendix I gives an approximate analysis of this uncertainty and finds

$$\sigma_{\mathrm{d}}^2 = \frac{1}{N}\frac{\sigma_{\mathrm{c}}^2}{I^2}.$$

Here $N$ is the number of antennas and $\sigma_{\mathrm{d}}^2$ and $\sigma_{\mathrm{c}}^2$ are the variance of the real or imaginary parts of the leakages and correlation data respectively. These variances will integrate down with the number of time slices that go into forming the polarization calibration.

Figure 1 also shows the RMS uncertainty in the leakage solutions resulting from system noise. Determining this requires a measure of the term $\sigma_{\mathrm{c}}^2/I^2$. We have estimated this from the RMS value of the closure phase of the data[2]. We have also compared this closure-phase-based estimate of $\sigma_{\mathrm{c}}/I$ with a value derived from nominal system parameters at C band. We find excellent agreement assuming a post-correlator SEFD of 340 Jy, a noise bandwidth of 35 MHz and a source flux density varying between 2.3 and 2.5 Jy.

Considering the results in Figure 1, it is apparent that the best, median and 80th percentile antennas show quite similar apparent RMS leakage term variability. These are also similar to the uncertainty in the leakages that would result purely from system noise. Given the approximations made in deriving the latter, and some additional "second order" considerations, it appears likely that all the apparent variation seen in the leakages of most antennas is simply measurement error. That is, the sensitivity of these observations have provided an upper bound only on the variability of the leakages on most antennas.

Although the RMS leakage term variability is consistent with the measurement noise on most antennas, at many frequencies there are a small number of errant antennas. Table 1 summarizes some information about these outlier antennas. In several instances the issue appears to be abnormally poor sensitivity of the receiver system (either temporarily or throughout the observation) resulting in the error in the leakage determination being much larger than the norm at that frequency. In one instance it may be caused by a bad reference pointing solution. There are two instances at K band where there is a brief and apparently real change in leakage. There remain two other instances where there is no apparent cause (antenna 4 at C band, but this has a VLA-style polarizer; antenna 3 at Ka band).

# 3 Long term variability

In order to check the long term stability of the antenna leakages between observations made at different epochs, it is useful make a comparison of the data here with the leakage solutions given in EVLA Memo 134. Those data, which were at C and K band only, were observed on 26 April (i.e. 5 weeks prior to the observations of this memo). As there was an array re-configuration between the two epochs, it is also of interest so see whether moving antennas has an effect on the polarimetric response.

The observations taken on 02 June were of 1800+784 and those on 26 April were of 0319+415. These two sources are quite different in that one moves slowly across the northern sky, whereas the other traverses a wider range of azimuth and elevation, and transits close to the zenith.

Between the two observing epochs, two C band receiver systems, on antennas 8 and 18, underwent significant engineering changes. On antenna 8, the C-band receiver was rotated by 90°. This was because of an accidental misorientation of the receiver when it was originally installed. On antenna 18 the C-band receiver polarizer was converted from a VLA to an EVLA system. These changes are expected to significantly change the polarimetric response of the antennas. Indeed, we found this to be so. Consequently the C-band data for these two antennas have been excluded from the following analysis.

Of the remaining antennas available at 4385 and 4885 MHz, 9 antennas moved, 12 antennas were fixed and one was unavailable at the earlier epoch.Of the other C-band frequencies, where only EVLA-compliant receivers

[1]For the VLA (and similarly for other interferometer arrays) for a source that is weakly polarized and of unknown position angle, there is a degeneracy in determining the leakage solutions. The leakage solution is insensitive to a complex offset being added and a phase term being applied uniformly to the R leakages, and the conjugates of these two terms being applied to the L leakages. Clearly when analyzing solutions for variability, it is important to 'normalize' out this degeneracy.

[2]Assuming a pure point source, a high signal-to-noise ratio and provided decorrelation within a correlator dump cycle does not occur, then the expected variance of the closure phase, in radians, is $3\sigma_{\mathrm{c}}^2/I^2$.

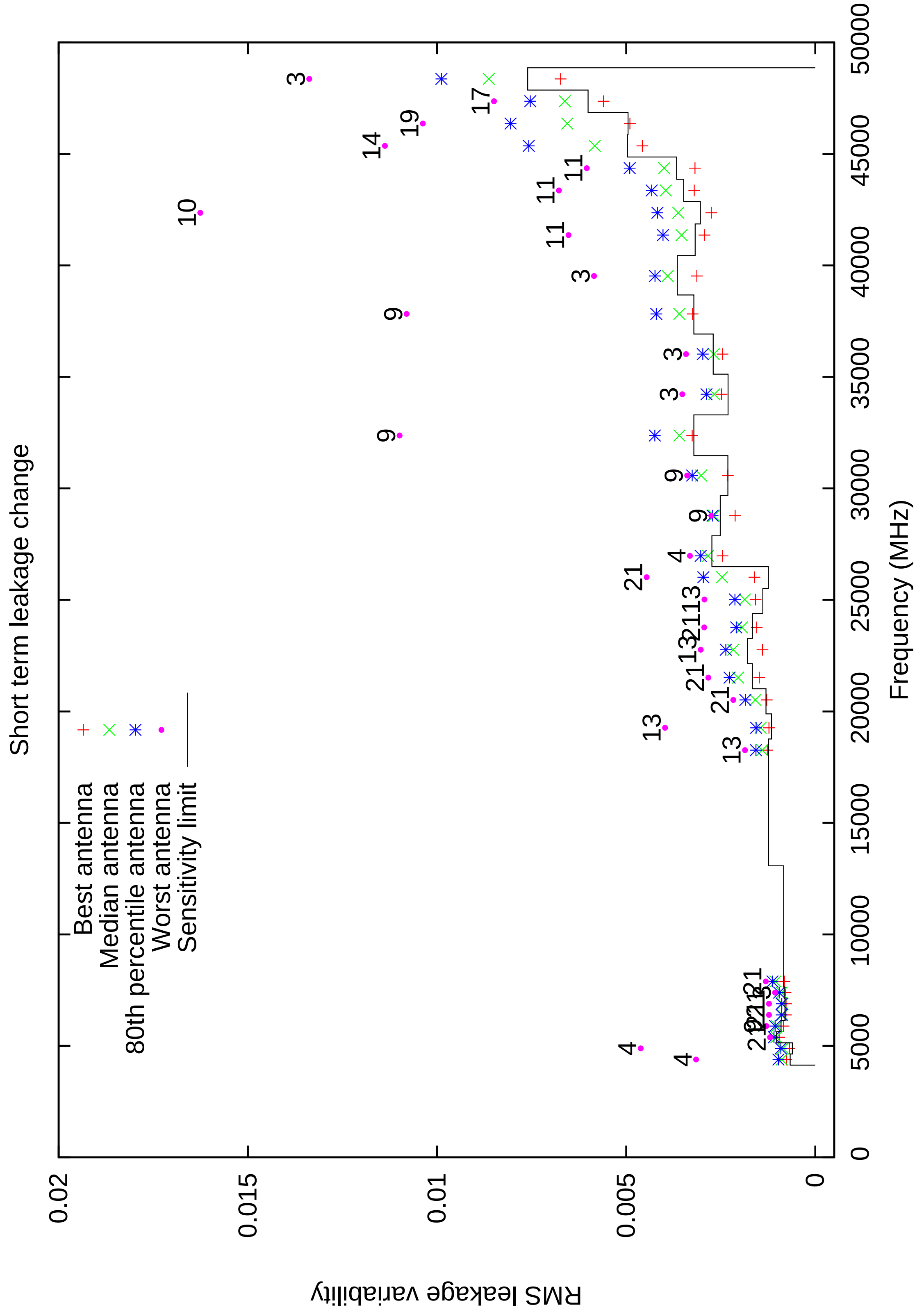


Figure 1: Short-term variations in the leakage terms. This plot shows the RMS variation of the leakage terms around their mean as a function of frequency. The best, median, 80th percentile and worst antennas are shown. The worst antenna is also numbered. Also shown is a line representing the RMS variation that is expected from the thermal noise limit.

| Frequency (MHz) | Bad Antennas | Notes |
|---|---|---|
| 4385, 4885 | 4 | The leakages of antenna 4 drifted over the course of the observation. Note that antenna 4 is a VLA-style receiver. |
| 4385 – 7885 | 21 | Across C band, antenna 21 is the least stable antenna except at for antenna 4 at 4385 and 4885 MHz. However it is only marginally less stable than the other antennas. |
| 18265 – 26015 | 13, 21 | At 19265 MHz, antenna 13 shows a single time period where the leakage changes significantly. This can be seen in the raw data before calibration. Antenna 21 at 26015 MHz shows a similar single time period where there is a significant leakage change. |
| 26975 – 39525 | 9,3 | Antenna 9 had a factor ≈4 poorer sensitivity at 32375 and 37825 MHz than the other antennas. These frequencies were observed simultaneously. Possibly this is an instance of poor tuning. Antenna 3 shows general poorer leakage term stability. It is not caused by a lack of sensitivity in the solution process. |
| 41365 – 48365 | 11, 10, 14, 19, 3 | Antenna 11 shows general poorer leakage stability. It is not caused by a lack of sensitivity in the solution process. At 42365 MHz, antenna 10 shows a single time period where there is a significant leakage change. This may be related to a poor reference pointing solution. At 45365 MHz, there was an issue with the sensitivity of the L receiver on antenna 14 for a brief period. The R receiver on antenna 19 showed poor sensitivity at 46365 MHz throughout the observation. The L receiver on antenna 3 showed poor sensitivity at 48365 MHz throughout the observation. |

Table 1: Notes on antennas with large leakage term variability.

could be used, 4 antennas moved and 2 were fixed. At K-band frequencies, 9 antennas moved, 9 antennas were fixed and one was unavailable during the earlier epoch.

To compare the polarimetric calibration from the two epochs, we have determined the ‘normalization terms’ between the two sets of leakages using only the nominally stable antennas. This was done to avoid possibly corrupting the normalization terms by polarimetric changes of the moves or engineering work. However, after taking this precaution, we found *no* evidence that moving an antenna modified its polarimetric response. Indeed the largest changes were seen on antennas that were nominally ‘stable’ (we do not attribute this to anything but small number statistics). Figure 2 plots the RMS change of each antenna, as well as numbering the antenna number of the worst point at each frequency. This also shows the sensitivity-imposed limit in variability: the observed variability of the leakage solutions is well above the sensitivity limit. Note that this is unlike the short-term variability results, where the observed variability was near the sensitivity limit. We conclude that the changes between the two epochs is real and not an artifact of limited sensitivity.

A notable feature in Figure 2 is that there is markedly poorer stability at 6385 MHz. Various checks of the data and leakage solutions gave no insight into the cause of this. It is not a case of a single band antenna or baseline, nor are the data or calibration at this frequency remarkable compared with neighboring frequencies. We have no explanation for this abnormally poor performance.

At K band, antenna 13 is the least stable between the two epochs. It also showed poor short term stability in the earlier section, although the variability was smaller over the shorter period. This is clearly a system with poorer stability. Similarly at C band, antenna 21 shows the poorest long term and short term stability. Although antenna 4 showed extremely poor short-term stability, its change over 5 weeks is no worse than its change over 11 hours.

## 4 Analysis and conclusions

This memo is a follow-up to EVLA Memo 134: its motivations is similar. In particular, the analysis here shows that the short term ($\sim$ 11 hours) polarizer stability for most antennas at C, K, Ka and Q bands is near or better

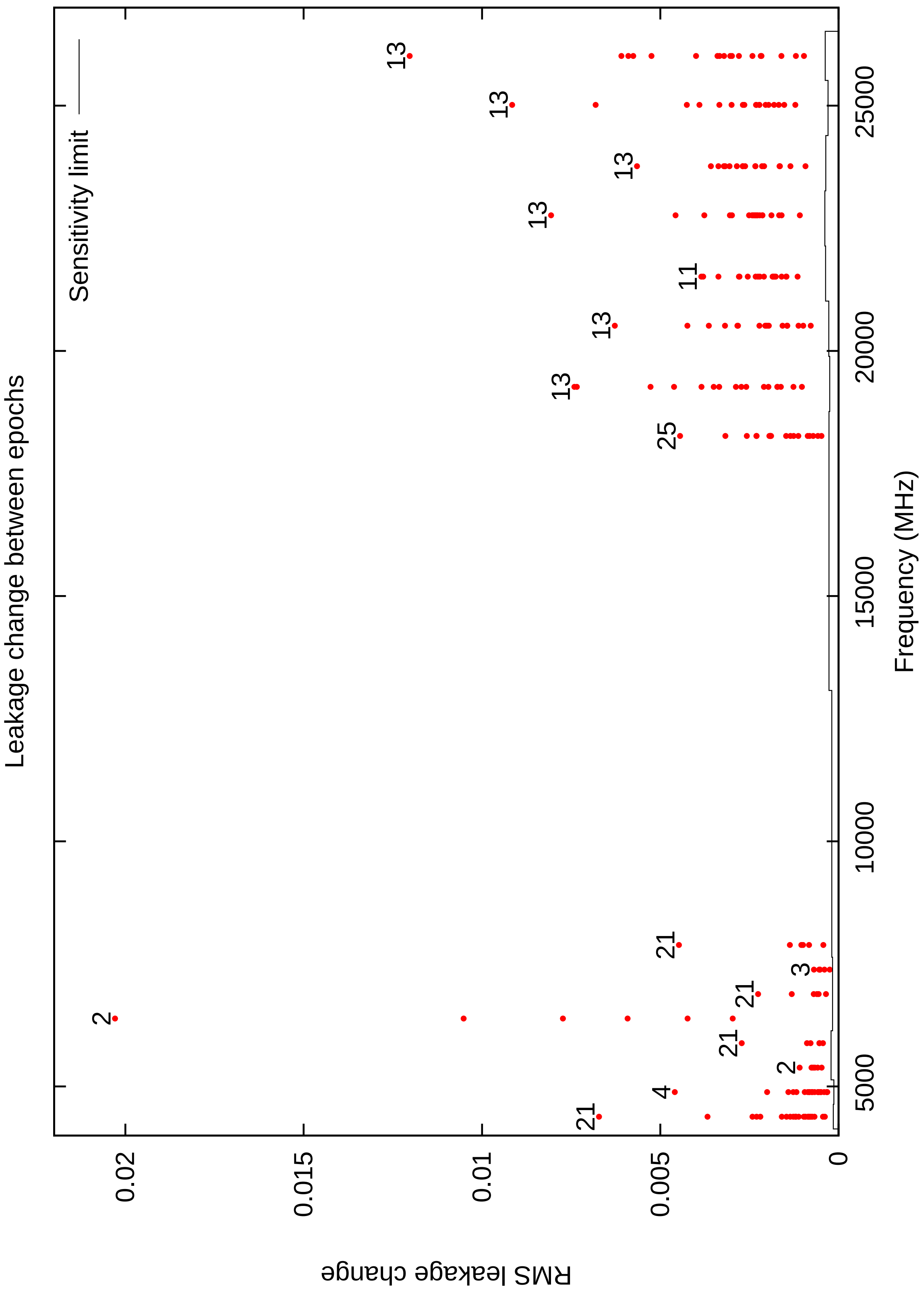


Figure 2: Long-term variations in the leakage terms. This plot shows the RMS variation of the leakage terms around their mean as a function of frequency. All antennas are shown. The antenna of the worst point at each frequency is given.

than the level set by the measurement accuracy of this experiment. The upper limit on the variability ranged from about $10^{-3}$ at C band to $10^{-2}$ at Q band. This stability is sufficient to enable accuracy in on-axis fractional linear polarization of better that 0.1% in a 12-hour integration.

This memo also reports on an analysis of long term stability at C and K bands for observations 5 weeks apart. Although the deduced variability above the sensitivity limit, the variation was typically $< 10^{-3}$ at C band and $\sim 2 \times 10^{-3}$ at K band. We looked for and found no evidence that moving an antenna has an effect on its polarimetric stability. This bodes well for an approach where polarimetric 'reference images' of better than 1% polarimetric purity are made from short observations using a database of leakages that the observatory maintains and periodically updates.

There are a small number of miscreant antennas. The polarimetric solutions on some antennas was compromised by intrinsic system sensitivity that were several factors worse than other antennas. This was particularly an issue with some antennas at Q band. Antenna 21 at C band and antenna 13 at K band are antennas which have the poorest stability, both short-term and long-term. Antenna 4 at C band also shows poor stability. However it is a VLA-style polarizer that is scheduled for replacement. Antenna 11 at Q band appears to have poorer polarizer stability.

The long term stability analysis also showed a significant leakage change for observations at 6385 MHz. This change is anomalous and remains unexplained.

| | 1 | | | | 5 | | | | | 10 | | | | | 15 | | | | | 20 | | | | | 25 | | | 28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4385 | ○ | ● | ● | ○ | | ○ | ○ | ● | ● | ○ | ○ | ○ | | ○ | ● | ○ | ○ | ● | ○ | ○ | ● | ○ | ○ | | ○ | ○ | | ● |
| 4885 | ○ | ● | ● | ○ | | ○ | ○ | ● | ● | ○ | ○ | ○ | | ○ | ● | ○ | ○ | ● | ○ | ○ | ● | ○ | ○ | | ○ | ○ | | ● |
| 5385 | | ● | ● | | | | | ● | ● | | | | | | ● | | | ● | | | ● | | | | | | | ● |
| 5885 | | ● | ● | | | | | ● | ● | | | | | | ● | | | ● | | | ● | | | | | | | ● |
| 6385 | | ● | ● | | | | | ● | ● | | | | | | ● | | | ● | | | ● | | | | | | | ● |
| 6885 | | ● | ● | | | | | ● | ● | | | | | | ● | | | ● | | | ● | | | | | | | ● |
| 7385 | | ● | ● | | | | | ● | ● | | | | | | ● | | | ● | | | ● | | | | | | | ● |
| 7885 | | ● | ● | | | | | ● | ● | | | | | | ● | | | ● | | | ● | | | | | | | ● |
| 18265 | ● | ● | ● | ● | | | | ● | ● | | ● | | ● | ● | ● | ● | ● | ● | | | ● | | ● | ● | ● | ● | | ● |
| 19265 | ● | ● | ● | ● | | | | ● | ● | | ● | | ● | ● | ● | ● | ● | ● | | | ● | | ● | | ● | ● | | ● |
| 20515 | ● | ● | ● | ● | | | | ● | ● | | ● | | ● | ● | | ● | ● | ● | ● | | ● | | | ● | ● | ● | | ● |
| 21515 | ● | ● | ● | ● | | | | ● | ● | | ● | | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | | ● | ● | | ● |
| 22765 | ● | ● | ● | ● | | | | ● | ● | | ● | | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | ● | ● | ● | | ● |
| 23765 | ● | ● | ● | ● | | | | ● | ● | | ● | | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | | ● | ● | | ● |
| 25015 | ● | ● | ● | ● | | | | ● | | | ● | | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | ● | ● | ● | | ● |
| 26015 | ● | ● | ● | ● | | | | ● | ● | | ● | | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | | ● | ● | | ● |
| 26975 | | ● | ● | ● | | | | ● | ● | | | | | | ● | | | | | | | | | | ● | | | |
| 28775 | | ● | ● | ● | | | | ● | ● | | | | | | ● | | | | | | | | | | ● | | | |
| 30575 | | ● | ● | ● | | | | ● | ● | | | | | | ● | | | | | | | | | | ● | | | |
| 32375 | ● | ● | ● | ● | | | | ● | ● | | | | | | ● | | | | | | | | | ● | ● | | | |
| 34225 | ● | ● | ● | ● | | | | ● | | | | | | | ● | | | | | | | | | ● | ● | | | |
| 36025 | ● | ● | ● | ● | | | | ● | | | | | | | ● | | | | | | | | | ● | ● | | | |
| 37825 | ● | ● | ● | ● | | | | ● | ● | | | | | | ● | | | | | | | | | ● | ● | | | |
| 39525 | ● | ● | ● | ● | | | | ● | ● | | | | | | ● | | | | | | | | | ● | ● | | | |
| 41365 | ● | ● | ● | ● | | | | ● | ● | | ● | | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | ● | ● | ● | | ● |
| 42365 | ● | ● | ● | ● | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | | ● |
| 43365 | ● | ● | ● | ● | | | | ● | ● | | ● | | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | ● | ● | ● | | ● |
| 44365 | ● | ● | ● | ● | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | | ● |
| 45365 | ● | ● | ● | ● | | | | ● | | | ● | | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | ● | ● | ● | | ● |
| 46365 | ● | ● | ● | ● | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | | ● |
| 47365 | ● | ● | ● | ● | | | | ● | ● | | ● | | ● | ● | ● | ● | ● | ● | ● | | ● | | ● | ● | ● | ● | | ● |
| 48365 | ● | ● | ● | ● | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | ● | ● | | ● |
| Moved | | ⋆ | | ⋆ | ⋆ | | | | ⋆ | | | | | ⋆ | ⋆ | ⋆ | | | | | ⋆ | ⋆ | ⋆ | ⋆ | | | | |
| No April data | | | | | | | C | K | | | | | | | | | | | | | | | | | | | | |
| Eng. change | | | | | | | | C | | | | | | | | | | C | | | | | | | | | | |

Table 2: The antennas and frequencies used in the observations on 02 June. The closed and open circles (● and ○) indicates antennas with EVLA and VLA polarizers respectively. Also shown are three rows indicating the antennas that were moved between the two epochs (marked by ⋆), where no data were available at the earlier epoch (symbol C and K for the respective bands) and where receiver systems underwent engineering change between epochs (symbol C for C band).

## Appendix I: Error variance of leakage terms

Here the error variance resulting from system noise of the real or imaginary part of the polarization leakage terms is derived. In doing this, a point source is assumed. We ignore the effect of the polarized emission of the source in determining the error variance: assuming that the source is no more that the typical few percent polarized, its effect on the error variance will be negligible. Similarly the terms that are quadratic with leakage can be ignored: they, too, have negligible effect on the error variance. Finally the antenna gain is ignored: this is effectively a normalization term that drops out of the analysis. Then for the pq visibility (RL or LR) on baseline $i-j$, we have

$$V_{\mathrm{pq},ij} \approx (d_{\mathrm{p},i} + d^*_{\mathrm{q},j})I$$

or

$$\frac{1}{I} V_{\mathrm{pq},ij} \approx d_{\mathrm{p},i} + d^*_{\mathrm{q},j}$$

It is terms of this type that provide the best sensitivity to the leakages, and which will dictate the sensitivity that is achieved in solving for the leakages. For $N$ antennas, summing over the $N-1$ such equations containing $d_{\mathrm{p},i}$ gives

$$\begin{aligned} \frac{1}{I}\sum_j V_{\mathrm{pq},ij} &= \sum_j (d_{\mathrm{p},i} + d^*_{\mathrm{q},j}) \\ &= (N-1)d_{\mathrm{p},i} + \sum_{j\neq i} d^*_{\mathrm{q},j} \end{aligned}$$

In computing the variance, we make the approximation that the error in each leakage term, $d$, is independent. This is an incorrect assumption, but we justify it by noting it will affect the result by a factor of only order $1/N$. Taking the variance of the above equation, and assuming that all antennas have the same sensitivity, we have

$$\frac{(N-1)\sigma_{\mathrm{c}}^2}{I^2} = (N-1)^2\sigma_{\mathrm{d}}^2 + (N-1)\sigma_{\mathrm{d}}^2$$

or

$$\sigma_{\mathrm{d}}^2 = \frac{1}{N}\frac{\sigma_{\mathrm{c}}^2}{I^2}.$$

Here $\sigma_{\mathrm{d}}^2$ and $\sigma_{\mathrm{c}}^2$ are the variance of the real or imaginary parts of the leakages and correlations respectively. These variances will integrate down with the number of time slices that go into forming the polarization calibration.