EVN Memo # 78

Calibration of VLBI Polarization Data

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The technique of imaging the linearly polarized emission from radio sources has long been routine for instruments such as the VLA. However, at VLBI scales, such observing has been historically limited to a small group of scientists, primarily at or associated with Brandeis University. With the advent of the VLBA, interest in polarization observing has dramatically increased, both with the VLBA and with the EVN. Apart from the scientific interest in studying the linearly polarized emission from sources, polarization observing has the additional benefit for EVN observers that the significant baseline errors introduced into the total intensity data by the instrumental polarization (*e.g.*, Massi *et al.* 1997; Massi & Aaron 1997) may be removed. This document is intended to provide a guide to the acquisition, processing, and imaging of VLBI polarization data.

1. Instrumental Polarization

Before discussing the observation and reduction of polarization data, let us review the issues related to linear polarization imaging. Suppose all the antennas in an array are sensitive to both right and left circular polarizations (RCP and LCP respectively). Then, there are four possible correlations on each baseline: $\langle LL^*(u,v)\rangle$, $\langle RR^*(u,v)\rangle$, $\langle RL^*(u,v)\rangle$, and $\langle LR^*(u,v)\rangle$ where the R refers to the response of the right circular feed L to the left circular feed and the pairs refer to the correlation between two antennas. I will usually drop the $\langle\rangle$ and * symbols and just write, for example, LL. The four Stokes parameters can be expressed as

$$
\begin{aligned}
LL(u,v) &= I - V \ , \\
RR(u,v) &= I + V \ , \\
RL(u,v) &= Q + \imath U = P \ , \\
LR(u,v) &= Q - \imath U = P^* \ ,
\end{aligned} \qquad (1)
$$

where $P \equiv pe^{2\imath\chi}$ is called the *complex polarization*, p is the polarized intensity, and χ is the electric vector position angle. Hence, the linear polarization properties of a source are determined from the correlation of RCP with LCP and vice-versa.

The ideal circular polarization receiver would respond to only one polarization, *e.g.*, LCP. However, real antenna feeds respond to both, introducing spurious polarization measurements called *instrumental polarization*. This can be expressed in two ways: the linear or D-term model, and the ellipticity-orientation model. Each of these are discussed below.

1.1. Linear model

Since a real circular polarization feed responds to its own polarization plus a small bit of the opposite polarization, we can model the complex voltage from each feed by a linear expression:

$$
\begin{aligned}
v_L &= G_L(E_L e^{\imath\phi} + D_L E_R e^{-\imath\phi}) , \\
v_R &= G_R(E_R e^{-\imath\phi} + D_R E_L e^{\imath\phi}) ,
\end{aligned} \tag{2}
$$

where G_L and G_R are the complex gains of the electronics of each feed, the "D" terms represent the leakage of RCP into the left feed and LCP into the right feed, ϕ is the parallactic angle, and the $e^{\imath\phi}$ terms represent the apparent rotation of an altitude-azimuth mounted antenna as it tracks the source (for an equatorially mounted antenna, the antenna does not rotate with tracking so the parallactic angle is taken to vanish). The observed correlations in terms of the Stokes parameters, assuming $V = 0$, then, are

$$
\begin{aligned}
R_1R_2 &= G_{1R}G_{2R}^* \left\{ I \left[e^{\imath(\phi_2-\phi_1)} + D_{1R}D_{2R}^* e^{-\imath(\phi_2-\phi_1)} \right] + D_{1R}P^* e^{\imath(\phi_2+\phi_1)} + D_{2R}^* P e^{-\imath(\phi_2+\phi_1)} \right\} , \\
L_1L_2 &= G_{1L}G_{2L}^* \left\{ I \left[e^{-\imath(\phi_2-\phi_1)} + D_{1L}D_{2L}^* e^{\imath(\phi_2-\phi_1)} \right] + D_{1L}P^* e^{-\imath(\phi_2+\phi_1)} + D_{2L}^* P e^{\imath(\phi_2+\phi_1)} \right\} , \\
R_1L_2 &= G_{1R}G_{2L}^* \left\{ P e^{-\imath(\phi_2+\phi_1)} + D_{1R}D_{2L}^* P^* e^{\imath(\phi_2+\phi_1)} + I \left[D_{2L}^* e^{\imath(\phi_2-\phi_1)} + D_{1R} e^{-\imath(\phi_2-\phi_1)} \right] \right\} , \\
L_1R_2 &= G_{1L}G_{2R}^* \left\{ P^* e^{-\imath(\phi_2+\phi_1)} + D_{1L}D_{2R}^* P e^{-\imath(\phi_2+\phi_1)} + I \left[D_{2R}^* e^{-\imath(\phi_2-\phi_1)} + D_{1L} e^{\imath(\phi_2-\phi_1)} \right] \right\} .
\end{aligned} \tag{3}
$$

These equations can be expressed in a matrix representation. Let us define $G_{\alpha\beta} = G_{j\alpha}G_{k\beta}^*$ where α and β can be either R for right or L for left, and $E_\pm = e^{\imath(\phi_k \pm \phi_j)}$. Then

$$
\mathrm{M}_{\mathrm{jk}}^{\mathrm{D}} = \begin{pmatrix}
G_{RR}E_- & G_{RR}D_{jR}D_{kR}^*E_-^* & G_{RR}D_{kR}^*E_-^* & G_{RR}E_- \\
G_{LL}D_{jL}D_{kL}^*E_- & G_{LL}E_-^* & G_{LL}D_{kL}^*E_+ & G_{LL}D_{jL}E_+^* \\
G_{RL}D_{kL}^*E_- & G_{RL}D_{jR}E_-^* & G_{RL}E_+^* & G_{RL}D_{jR}D_{kL}^*E_- \\
G_{LR}D_{jL}E_- & G_{LR}D_{kR}^*E_-^* & G_{LR}D_{jL}D_{kR}^*E_+^* & G_{LR}E_+^*
\end{pmatrix} \tag{4}
$$

so that

$$
\mathbf{F}_{jk}^{\mathrm{obs}} = M_{jk}^{\mathrm{D}} \mathbf{F}_{jk}^{\mathrm{true}} , \tag{5}
$$

where the Stokes parameters are written the vector form

$$\mathbf{F}_{jk} = \begin{pmatrix} RR_{jk} \\ LL_{jk} \\ RL_{jk} \\ LR_{jk} \end{pmatrix} \quad . \tag{6}$$

The uncorrupted visibilities are found by inverting the matrix M_{jk}^{D} on each baseline and at each integration time and multiplying this by the observed Stokes vector $\mathbf{F}_{jk}^{\mathrm{obs}}$.

If we assume that the leakage terms are small, we can ignore terms of order D^2. Since the fractional polarization of most sources is small, on the order of a few percent, we can also ignore terms of order DP. In other words, we only consider terms to first order in polarization:

$$\begin{aligned} R_1R_2 &= G_{R1}G_{R2}^* I e^{-\imath(\phi_{p1}-\phi_{p2})} \ , \\ L_1L_2 &= G_{L1}G_{L2}^* I e^{\imath(\phi_{p1}-\phi_{p2})} \ , \\ R_1L_2 &= G_{R1}G_{L2}^* \left\{ P e^{-\imath(\phi_{p1}+\phi_{p2})} + I \left[D_{L2}^* e^{-\imath(\phi_{p1}-\phi_{p2})} + D_{R1} e^{\imath(\phi_{p1}-\phi_{p2})} \right] \right\} \ , \\ L_1R_2 &= G_{L1}G_{R2}^* \left\{ P^* e^{\imath(\phi_{p1}+\phi_{p2})} + I \left[D_{R2}^* e^{\imath(\phi_{p1}-\phi_{p2})} + D_{L1} e^{-\imath(\phi_{p1}-\phi_{p2})} \right] \right\} \ . \end{aligned} \tag{7}$$

I emphasize here that Equations (3) are *exact* representations whereas Equations (7) are linear approximations.

1.2. Ellipticity-Orientation Model

An alternative model for the antenna response is to assume that each feed responds to elliptical polarization, which is conceptually identical to the linear model. Following Cotton (1992), we parameterize the response as

$$G = \hat{\mathbf{e}}_x \left[\cos\theta \cos(\phi+\chi) - \imath \sin\theta \sin(\phi+\chi) \right] + \hat{\mathbf{e}}_y \left[\cos\theta \sin(\phi+\chi) + \imath \sin\theta \cos(\phi+\chi) \right] \ , \tag{8}$$

where $\hat{\mathbf{e}}_x$ and $\hat{\mathbf{e}}_y$ are unit vectors, θ is the feed ellipticity, χ is the orientation of the ellipse, and ϕ is the parallactic angle. The response of a given interferometer can then be written

$$\begin{aligned} F_{jk}^{\mathrm{obs}} &= g_j g_k^* \{ RR_{jk} \left[(\cos\theta_j + \sin\theta_j)\, e^{-\imath(\phi_j+\chi_j)} \right] \times \left[(\cos\theta_k + \sin\theta_k)\, e^{\imath(\phi_k+\chi_k)} \right] \\ &+ RL_{jk} \left[(\cos\theta_j + \sin\theta_j)\, e^{-\imath(\phi_j+\chi_j)} \right] \times \left[(\cos\theta_k - \sin\theta_k)\, e^{-\imath(\phi_k+\chi_k)} \right] \\ &+ LR_{jk} \left[(\cos\theta_j - \sin\theta_j)\, e^{\imath(\phi_j+\chi_j)} \right] \times \left[(\cos\theta_k + \sin\theta_k)\, e^{\imath(\phi_k+\chi_k)} \right] \\ &+ LL_{jk} \left[(\cos\theta_j - \sin\theta_j)\, e^{\imath(\phi_j+\chi_j)} \right] \times \left[(\cos\theta_k - \sin\theta_k)\, e^{-\imath(\phi_k+\chi_k)} \right] \} \ , \end{aligned} \tag{9}$$

where $F_{jk}^{\rm obs}$ is the observed correlation. For example, RR would be found by using the gains g_j and g_k as well as the feed parameters θ and χ for the right circular feeds of each antenna. The effects of phase calibration are given by $g_R = e^{-\imath(-\phi-\chi_R+\chi_R^{ref})}$ and $g_L = e^{\imath(-\phi-\chi_L+\chi_L^{ref}+\chi_{R-L})}$ where χ_{R-L} is the right-left phase difference.

As in § 1.1, the above equation can be written as a matrix equation. Let us define the following symbols:

$$
\begin{aligned}
\hat{G}_{\alpha\beta} &= g_{\alpha j} g^*_{\beta k} \ , \\
S_{\beta k} &= \cos\theta_{\beta k} + \sin\theta_{\beta k} \ , \\
D_{\beta k} &= \cos\theta_{\beta k} - \sin\theta_{\beta k} \ , \\
E_{\beta k} &= e^{\imath(\chi_{\beta k}+\phi_k)} \ ,
\end{aligned}
$$

$$
\mathrm{M_{jk}} = \begin{pmatrix}
\hat{G}_{RR} S_{Rj} E^*_{Rj} S_{Rk} E_{Rk} & \hat{G}_{RR} D_{Rj} E_{Rj} D_{Rk} E^*_{Rk} & \hat{G}_{RR} S_{Rj} E^*_{Rj} D_{Rk} E^*_{Rk} & \hat{G}_{RR} D_{Rj} E_{Rj} S_{Rk} E_{Rk} \\
\hat{G}_{LL} S_{Lj} E^*_{Lj} S_{Lk} E_{Lk} & \hat{G}_{LL} D_{Lj} E_{Lj} D_{Lk} E^*_{Lk} & \hat{G}_{LL} S_{Lj} E^*_{Lj} D_{Lk} E^*_{Lk} & \hat{G}_{LL} D_{Lj} E_{Lj} S_{Lk} E_{Lk} \\
\hat{G}_{RL} S_{Rj} E^*_{Rj} S_{Lk} E_{Lk} & \hat{G}_{RL} D_{Rj} E_{Rj} D_{Lk} E^*_{Lk} & \hat{G}_{RL} S_{Rj} E^*_{Rj} D_{Lk} E^*_{Lk} & \hat{G}_{RL} D_{Rj} E_{Rj} S_{Lk} E_{Lk} \\
\hat{G}_{LR} S_{Lj} E^*_{Lj} S_{Rk} E_{Rk} & \hat{G}_{LR} D_{Lj} E_{Lj} D_{Rk} E^*_{Rk} & \hat{G}_{LR} S_{Lj} E^*_{Lj} D_{Rk} E^*_{Rk} & \hat{G}_{LR} D_{Lj} E_{Lj} S_{Rk} E_{Rk}
\end{pmatrix} , \tag{10}
$$

where the indices α and β can be R for the right feed or L for the left feed. Then the relation between the true correlations and the observed correlations can be written as a simple matrix equation:

$$
\mathbf{F}_{jk}^{\rm obs} = M_{jk} \mathbf{F}_{jk}^{\rm true} \ . \tag{11}
$$

1.3. Limitations on the Correction for Instrumental Polarization

In the preceding sections, we've expressed the effects of, and, hence, correction for, instrumental polarization as a matrix operating on a four element vector of correlations. This means that full correction for the instrumental polarization, regardless of model, requires all four correlations to be present. For VLBA data, this does not present much of a problem as all stations provide dual polarization receivers. EVN observers are not afforded this luxury. Many EVN telescopes only have single polarization receivers. Furthermore, some of the worst telescopes in terms of instrumental polarization, *e.g.*, Onsala with a D-term of $\sim 25\%$ at $\lambda 6$ cm, only have single polarization receivers. Hence, only partial corrections can be made.

2. Observational Considerations

Proper imaging of linear polarization introduces two additional aspects of data processing over the standard data reduction: calibration of instrumental polarization and of the absolute position angle of the electric field. Each of these presents special considerations for the observing, which are discussed below.

2.1. Instrumental Polarization Calibrator

Let us consider the requirements for an instrumental polarization calibrator. The most obvious is that

- The source must be sufficiently strong in total intensity that we may detect the instrumental polarization, which is proportional to the total intensity. This refers not only to the integrated flux, but to the VLBI scale flux.

The most straightforward way to determine the instrumental polarization parameters of the telescopes in an array is to observe an unpolarized source. In that case, the measured polarization is simply that of instruments. However, we see from Equations (3) that the instrumental polarization terms rotate with parallactic angle in a different way from the source polarization terms. This allows us to separate the effects of source and instrumental polarization. For purposes of illustration, let us consider the linear approximation model of Equations (7). Then, following Roberts, Wardle, & Brown (1994), we may write, for example,

$$\frac{R_1 L_2}{R_1 R_2} \propto M_{12} e^{-2\imath\phi_2} + D_{1R} e^{+2\imath\phi_{12}} + D_{2L}^* \ , \tag{12}$$

where $M_{12} \equiv P_{12}/I_{12}$ is the fractional polarization on the baseline and $\phi_{12} \equiv \phi_1 - \phi_2$. So, for an unpolarized source ($M = 0$) and assuming both telescopes to have an altitude-azimuth mounting, the ratio of cross-hand to parallel-hand visibilities will track a circle in the $u - v$ plane, with the center determined by one D-term and the radius of the circle determined by the other. For a polarized source, the center of the circle will also rotate in the complex plane. The rotation of these vectors is determined by the parallactic angle variation at each station. Hence, a second requirement for a polarization calibrator is that

- It must be observed over a large range of parallactic angle at each station.

Unless the calibrator polarization structure is known prior to observation, we must make some assumption about M. Usually, one makes the *similarity assumption*, that M is a constant in the $u - v$ plane. This condition is trivially satisfied for a polarized point source and for an unpolarized, resolved source. However, if the source is of fairly simple structure, we may model the total intensity as a collection of point or gaussian components, each of which satisfy the similarity assumption. So,

- The calibrator source must be of fairly simple structure on VLBI scales, especially if it is both resolved and polarized.

If the calibrator is resolved and polarized, each model component must satisfy the source strength condition.

The unpolarized source OQ 208 has been shown to be useful at frequencies between 1.45 and 8.4 GHz for calibrating the instrumental polarization (Aaron 1996). The source 3C 84 is a very powerful radio source (VLA core flux of 40 Jy or more at 5 GHz) and is also unpolarized. With the Brandeis software, this source has been frequently used for this purpose. However, it shows a very complicated structure at VLBI scales (*e.g.*, Vermeulen, Readhead, & Backer 1994) and is heavily resolved on most baselines, which makes it difficult to properly self calibrate and fairly weak on longer baselines. With the processing described in § 3, the source must be self calibrated to remove the gain terms, so one must devote much more time to observing 3C 84 than to OQ 208 to properly image the source with high fidelity, which is quite inefficient. More recently, Leppänen, Zensus, & Diamond (1995) have had success using 3C 273, 3C 279, and 3C 345 for VLBA instrumental polarization calibration at higher frequencies.

2.2. Position Angle Calibrator

The position angle of the polarized emission is determined from the phase of the cross-hand data. This phase is affected by the phase difference between the right and left hand gain terms. Therefore, we conclude that polarization imaging requires this difference to be constant in time; a time dependent phase difference will introduce a time dependent term in the cross hand phases. Inspection of Equations (3) show that the parallel hand data are insensitive to an arbitrary phase difference between the right and the left, indicating that self calibration will not ensure this stability by correcting for a variable phase difference. So, polarization observations are limited to wavelengths shorter than about $\lambda 20$ cm. At longer wavelengths, the ionospheric Faraday rotation, which is manifested in a time variable right-left phase difference, becomes appreciable. As the parallel hand data and calibration provides no information about the absolute phase difference between the right and left systems, special calibration must be performed to determine the absolute difference and, thereby, the electric vector position angle.

For instruments like the VLA and MERLIN, 3C 286 is typically observed as its electric vector position angle is known to be 33°. So, one simply aligns the 3C 286 data with this value. At low frequencies, *e.g.*, 1.6 GHz, and with sufficient short $u-v$ spacing coverage, one may use 3C 286 directly with VLBI. In this approach, one forms a polarization image of the source, measures the integrated polarization from the total Q and U CLEAN'd flux, and rotates the integrated position angle to align with the expected value of 33°. For higher frequencies, 3C 286 is too difficult to image without extensive observing time. However, if it is known that the polarized emission from a source arises entirely in the VLBI scale structure, one may align the integrated VLBI polarization with the polarization measured at some other instrument, *e.g.*, the VLA. BL Lacertae objects frequently satisfy this condition (*e.g.*, Gabuzda *et al.* 1992; Cawthorne *et al.* 1993; Gabuzda *et al.* 1994). The object OJ 287 has been commonly used at λ6 cm as a position angle calibrator. Perhaps a better source is $1823 + 568$, which is brighter than OJ 287, in both total intensity and linear polarization. A restriction on this source is that, on VLA scales (*e.g.*, O'Dea, Barvainis, & Challis 1988), the source shows a strongly bent jet and should, therefore, only be used with the VLA at high resolution. Both of these sources may also be used to calibrate the instrumental polarization.

3. Data Processing

In this section, I will discuss the calibration of polarization sensitive VLBI data, both from the Mark III and VLBA correlators. Throughout, I will only consider processing with the $\mathcal{AIPS}$ software package of the NRAO. The calibration steps will be demonstrated by data from a λ6 cm global Mark III VLBI experiment (epoch 1992.24, network designation GR2) and from a λ6 cm VLBA experiment (epoch 1995.23, designation BA8). The processing path for VLBA and Mark III correlator output differs only in the reading of data into $\mathcal{AIPS}$.

An alternative reduction path is provided by the Brandeis software package, which provides facilities for amplitude calibration, polarization calibration (in the linear approximation, Equations 7), and imaging as well as model fitting routines that allow simultaneous fitting of total intensity and complex polarization. See, for example, Roberts, Wardle, & Brown (1994) for a description of the Brandeis software. The package was originally written for data from the Mark III correlator, but software to convert between FITS format and Brandeis format is currently being developed. The Brandeis software package is maintained by Dr. Denise Gabuzda of the Lebedev Physical Institute who may be contacted at gabuzda@sci.lpi.ac.ru.

3.1. Reading the correlator output

3.1.1. Mark III correlator

The $\mathcal{AIPS}$ task MK3IN reads data from the tape made by the Mark III correlator and Bonn or Haystack. To run MK3IN, the user must prepare a text file containing information about the experiment. For example, the experiment file used for the GR2 observation is

```
STATIONS='MEDICINA','EFLSBERG','WESTBRKA','JODRELL2','HAYSTACK',
'NRAO_140','VLBA_NL','VLBA_LA','VLA','VLBA_PT','VLBA_KP',
'VLBA_OV'
DOPOL=1
STOKES='RR','LL','RL','LR'
FREQCODE='R','L','r','l'
/
```

This lists the 12 antennas used in the experiment, whose names must be identical to those used at the correlator, and tells the task to accept all four correlations. This will allow $\mathcal{AIPS}$ to read the stations in any order desired. Other parameters are possible in this file, but not generally needed.

On the Mark III correlator, data are frequently correlated more than once, meaning there may be several entries on the distribution tape for the same time stamp and baseline. Only one of these may be used in the data processing. Along with the data tape, the user should have obtained a set of ASCII files from the correlator, called A-files, containing the results of the online fringe fitting for all data correlated. Concatenate these files into one and place the single file in a place where $\mathcal{AIPS}$ may read it. The task AFILE will read this file, select the scans that are to be read according to the criterion chosen by the user, and write a text file that will be used by MK3IN to choose the appropriate data. Set OPCODE='EDIT'; the APARM(1) parameter controls how the scans are chosen. A value of 1 means that the most recently correlated data will be used, 2 means the scans with the highest quality factor will be used, 3 means that the scans with the highest signal to noise ratio will be used, and 4 means that scans with the most data will be used.

Once these two files, the MK3IN experiment file and the output of AFILE, are prepared, MK3IN may be used to read the data. The reference date for the experiment must be specified. The CL table increment, specified by APARM(1), should be chosen short enough to adequately track changes in the instrumental gain. This should be less than or equal to the fringe fitting solution interval desired. An interval of 1 minute is likely to be sufficient. Set APARM(6)=2. If the observation recorded both upper and lower sidebands, *i.e.*, mode A or B, you may specify APARM(7)=1 to store each sideband as a separate frequency channel, or IF. Otherwise, each sideband will be stored in the same IF and the user must use the task SBCOR to correct for the phase difference between upper and lower sidebands on VLBA and Mark IV recording terminals. Data should be stored in compressed format, unless disk space is in abundance. The remaining adverbs may be set to default values.

After the data has been read into $\mathcal{AIPS}$, additional processing must be done before the data may be calibrated. The data from the Mark III correlator is not in time-baseline order as required by the calibration and imaging tasks. To rectify this, run the task UVSRT. The default antenna table created by MK3IN has all antennas with an alt-az mounting. This can be fixed with TABPUT, setting PIXXY=n,5,1 where n is the antenna number in the AN table. Index the data set with

INDXR (don't create a new CL table since the original table has the phase cal information). Since the original CL table will now have many redundant entries, run TAMRG.

A final problem of the CL table is that not every time stamp will have an entry in the initial or merged table, which will cause data to be flagged whenever calibration is applied. To see these entries, print the CL table with PRTAB. You will see many entries in the REAL and IMAG columns as 'INDE'. These values must be filled in. If the phase cal information in the CL table is to be applied to the data (see § 3.2 for a discussion of whether or not to apply this calibration), write the CL table to a disk file with TBOUT (with DOCRT=132). The UNIX command SED can be used with (the format must be exact)

```
s/\'INDE\'          \'INDE\'        /  1.000000E+00   0.000000E+00/
```

on the text file to fill in the 'INDE' entries with a gain of 1 and phase 0. The filled in table can be read with TBIN. If the phase cal information is not to be used, run CLCOR with OPCODE='PCAL' and CLCORPRM=0 instead of editing the file manually. This will simply set all phase entries to 0°. At this point, the data and CL table are *finally* ready to use.

3.1.2. VLBA correlator

Reading data from the VLBA correlator is much simpler than the process described in § 3.1.1. The task FITLD is used. Data from the VLBA correlator comes on DAT tape (by default) in several FITS format files. A CL table will be created when these files are read in. The size of this table is controlled by the adverb CLINT, which sets the time interval in this table. As discussed in § 3.1.1, a 1 minute interval is usually sufficient. Because of the size of the files, which are much larger than files out of the Mark III correlator (usually 16 channels per IF instead of 4 for the Mark III data and 2 second averages rather than 4 or more seconds for the Mark III), the data must be written in compressed format (DOUVCOMP=1). The most important adverb in FITLD is DIGICOR, which applies corrections to the data as it is read in to compensate for losses arising from the correlation of digitized signals rather than analog. This is done by setting DIGICOR=1. As many tape files as possible should be concatenated into one disk file, to make book-keeping easier.

When reading data that are all at one frequency, the remaining adverbs can be set to default values. For multi-frequency data, additional steps must be taken. In principle, $\mathcal{AIPS}$ can process multiple frequencies in the same file, each frequency labeled by a unique FREQID which can be selected in most tasks. However, for book-keeping reasons, each frequency should be saved in a separate file. This can be done in two ways. Adverbs SELBAND and SELFREQ can be specified to choose each frequency separately. This necessitates running FITLD multiple times, one for each frequency. Since digital corrections require computations for every visibility, every channel, and every time stamp, this can result in a lot of extra time reading the data. If one has plenty of disk space, the other alternative is to run FITLD once, saving all frequencies in the same file. Then run the task UVCOP to copy out each FREQID into a separate file. This saves CPU time since FITLD is only run once, but requires a lot of extra disk space since the result is effectively two copies of the same data on disk at the same time.

Before proceeding, the flagging table provided by the online monitoring system at the VLBA stations should be read with the task UVFLG. Little editing of the text file should be required before running this task.

3.2. Antenna Phase Cal

While the telescopes are observing, a signal of known strength and phase, called the instrumental phase cal, is injected into the signal path. This allows the observer to align the various IF's in phase. For data from the Mark III correlator, the phase cal information is recorded in the initial CL table created by MK3IN. For the VLBA correlator, the phase cal data are written to a text file which much be extracted from the NRAO log file. This file is read by the task PCLOD, which will create a PC table. (Eventually, this table will be attached to the data at the correlator and PCLOD will not be necessary.) The task PCCOR is used to write a solution (SN) table, which is applied to the calibration with the task CLCAL.

As discussed in § 2.2, the stability of the right-left phase in the calibration is essential to the success of a VLBI polarization observation. At all stages of phase calibration, this stability must be checked. The phases of the phase cal data should be plotted in each IF as a function of time, and evaluated for consistency. If the behavior of the signal varies significantly across the band, or do not show stability in the $R - L$ phase, set the phases to zero with the task CLCOR. We may determine appropriate phase cal values from the data itself (§ 3.4.1), though this assumes the phase cal does not change in time. The phase cal information for the reference antenna should be good at all times since the phase cal information keeps track of any drift in the right-left phase difference and removes it.

3.3. Correction for parallactic angle

As we saw in Equation (3), the parallactic angle of the source at each antenna contributes to the phase of the observed correlations. The effect is to rotate the visibilities in the complex plane as a function of time, as in Figure 1a. To correct for this effect, the task CLCOR is used. The important adverbs are OPCODE='PANG' and CLCORPRM=1. Before running CLCOR, use LISTR to list the parallactic angles, checking the values to make sure they are right. Then plot the phase of RR/LL before and after applying the parallactic angle correction. This plotting can be done with VPLOT. The phase after applying the correction should be constant in time on all baselines, as in Figure 1b.

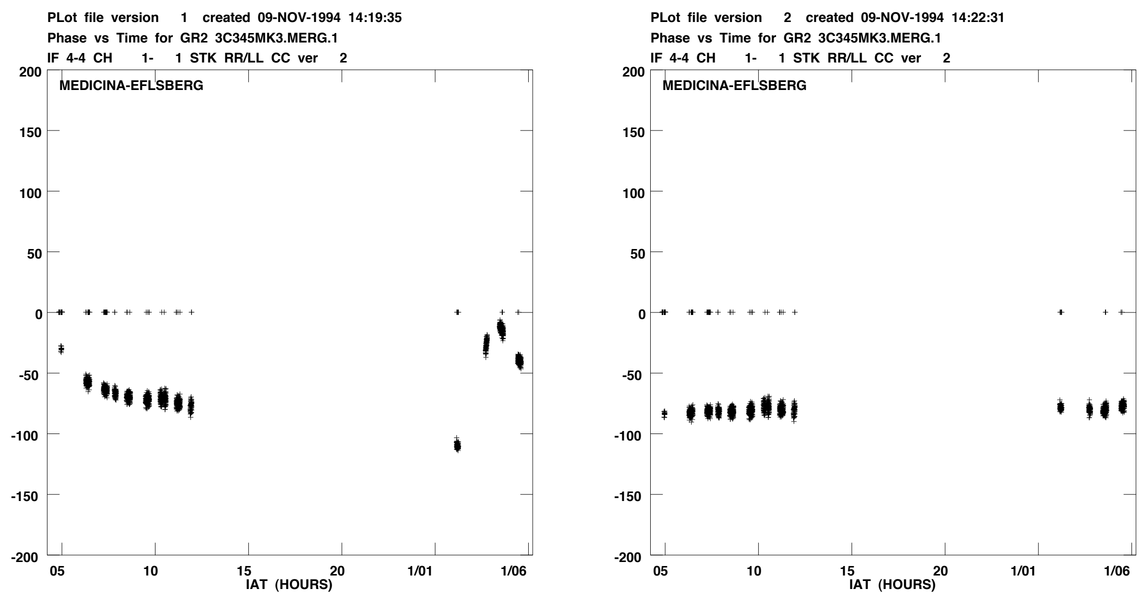

Fig. 1.— A plot, using the task VBPLT, showing the phase of RR/LL as a function of time for one channel on the Medicina-Effelsberg baseline of 3C 345 from GR2. (a) The parallactic angle correction has not been applied and the phases are seen to rotate smoothly with time. (b) The parallactic angle correction has been applied and the phase rotations seen in a have been corrected; the phase is now constant.

3.4. Fringe Fitting

The fringe fitting step for a dual polarization observation is done in three steps: manual phase cal, global fringe fitting, and calibration of the right-left delay.

3.4.1. Manual Phase Cal

We discussed the antenna generated phase cal in § 3.2. This information will enable us to align the phases between the individual IF's. If this calibration is not applied to the data, the manual phase cal step must be run. The antenna phase cal may still leave some residual delay across the band, in which case the manual phase cal should also be run. Choose a segment of data, say 2 minutes long, on a strong source where all the antennas provide data. Run the task FRING with APARM=2,0,0,0,0,1 and DPARM=1,2000,100,t_{int} where t_{int} is the integration time out of the correlator. The rates determined should be set to zero in the resultant SN table with the task SNCOR. Apply this solution to the entire data set and plot the phase across the band on all baselines for the time segment chosen to do the fringe fitting as well as a few others. If this step has been done properly, the phase should be constant across each IF, as in Figure 2*b*. This calibration should be run on a strong source and the solution table derived should be used for all other sources.

If no scan is exists for which all stations are present, choose two scans, writing the resultant solutions *to the same table*, obtaining only one solution for each station. When this calibration is applied, any antenna for which there is no solution will be flagged for the entire experiment.

3.4.2. Full Fringe Fitting

The full fringe fitting step is next. The goal is to derive the single band and multi band delays as well as the residual fringe rates and remove them from the data. Figure 3*a* shows a scan of data before the fringe fitting. Set APARM=2,0,0,0,2,1 and choose appropriate values for DPARM and SOLINT. Make sure to set DPARM(7)=1. This will prevent FRING from re-referencing the phases when using a secondary reference antenna. This re-referencing must be done, but allow CLCAL to do it; FRING does not implement the re-referencing properly.

Since a major concern in calibrating cross hand data is that the right-left phase difference remain constant at the reference antenna, plot the phase difference of each dual polarization antenna from the resultant solution table. If the difference is not constant for all stations, check your solution intervals, delay and rate windows, or phase cals and try again. Sometimes, large phase differences are unavoidable, but jumps in phase difference should be as few as possible. The variation of $R-L$ phase is a somewhat subtle problem. If the $R-L$ phase at a station other than the reference is varying, this will manifest itself in the plot for that station, but no other. Global fringe fitting

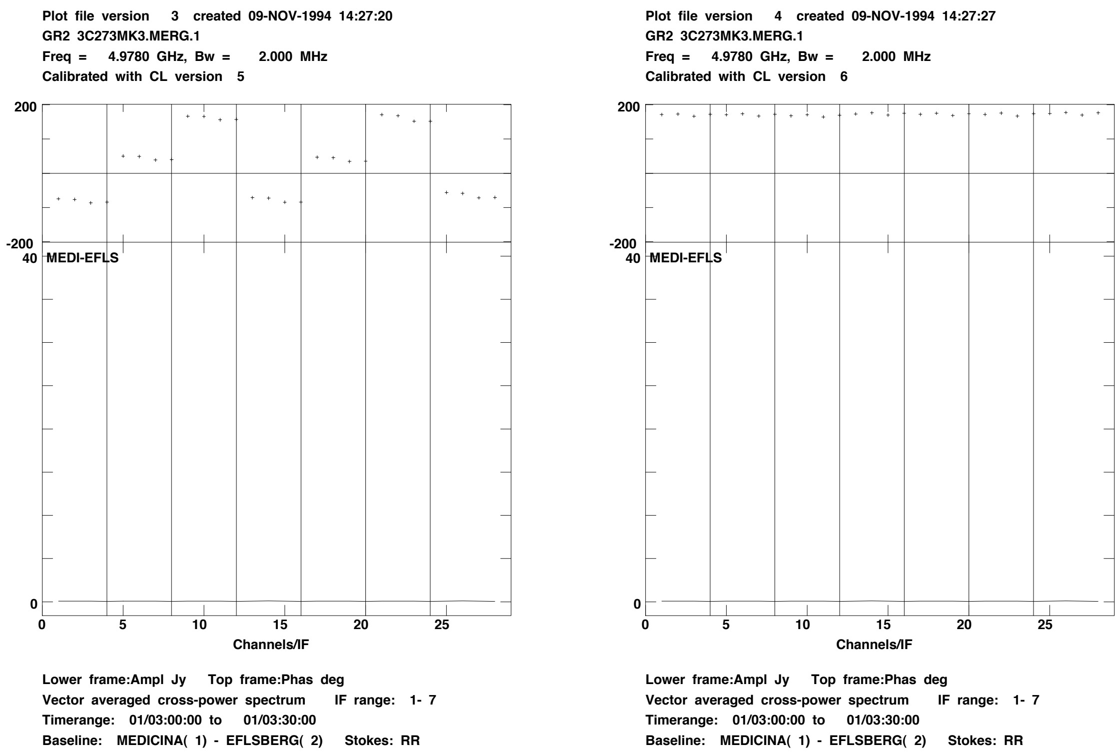

Fig. 2.— A plot, using the task POSSM, showing the vector averaged RR visibility across the band for one scan on the Medicina-Effelsberg baseline from the GR2 data on 3C 273. (a) The manual phase cals have not been applied. We see significant variation of phase from IF to IF. (b) The manual phase cals have been applied. The phase variation across each IF has been removed. For this particular scan, the phase variation across the entire band has also been removed. In general, that will not be true; such variation will be corrected with full fringe fitting.

as done here will correct for this variation at the station, and the calibrated polarization data are usable. However, if the variation is at the reference station, all antennas will show the same fluctuations. In this case, a new reference station is required, and the fringe fitting must be run again. In short, if the fluctuations are systematic, choose a new reference station and perform the fringe fitting again. Otherwise, accept the solutions.

In some experiments, the reference antenna may not be present in all scans. One must control the sequence of antennas used as the reference antenna to ensure that only those with stable $R-L$ phases are used. Starting with the 15APR97 release of $\mathcal{AIPS}$, the adverb SEARCH is provided which does precisely this. Set APARM(9)=1 and fill in the SEARCH array with a sequence of antennas to be used as reference antenna, in order of preference. For earlier releases of $\mathcal{AIPS}$, the ANTWT parameter may be used to control the sequence of reference antenna, with the higher weight antennas being preferred. The messages produced by FRING will report which antenna is being used as the reference.

The task SNSMO can be used to smooth and clip the derived delays and rates. This is especially important for VLBA data, where the first few visibilities on each baseline could be noise, resulting in a large rate which will be interpolated to adjacent points, giving large slopes of phase versus time where there hadn't been before fringe fitting. Smoothing should be done for each source separately because adjacent solutions on different sources could be very different.

To apply these solutions to the data, use the task CLCAL. The task CLCAL will interpolate between solutions to find values to put in each entry in the CL table. This could mean interpolating between solutions on different sources, which could have wildly different delays and rates. This will corrupt data at the beginning and end of scans. To avoid this, use INTERPOL='SELF', which forces $\mathcal{AIPS}$ to only use solutions on the source in question for the interpolation.

Once the solutions are properly smoothed, apply them to the data and plot the phase of the parallel hand data for all scans, making sure that the phases are nearly constant over moderate (say, a few minutes) time and across the band. Figure 3*b* shows the same data as before with the fringe fitting solution applied. The intent of fringe fitting is to make the phases vary slowly enough that the visibilities can be averaged in time and frequency to give a smaller, more manageable data set. The purpose is *not* to do detailed phase calibration. Soon the data will be averaged across each IF (not across the band until after the instrumental calibration has been applied) and for a short time (say, 10 seconds).

3.4.3. Right-Left Delay Difference–CROSSPOL

Finally, any right-left phase and delay difference variation across the band needs to be removed. The procedure CROSSPOL is used to determine any residual delay in the reference antenna and remove it. Choose a two minute segment of data on one baseline to the reference antenna. The cross hand fringes need to be strong so using a strongly polarized, bright source on a baseline with large

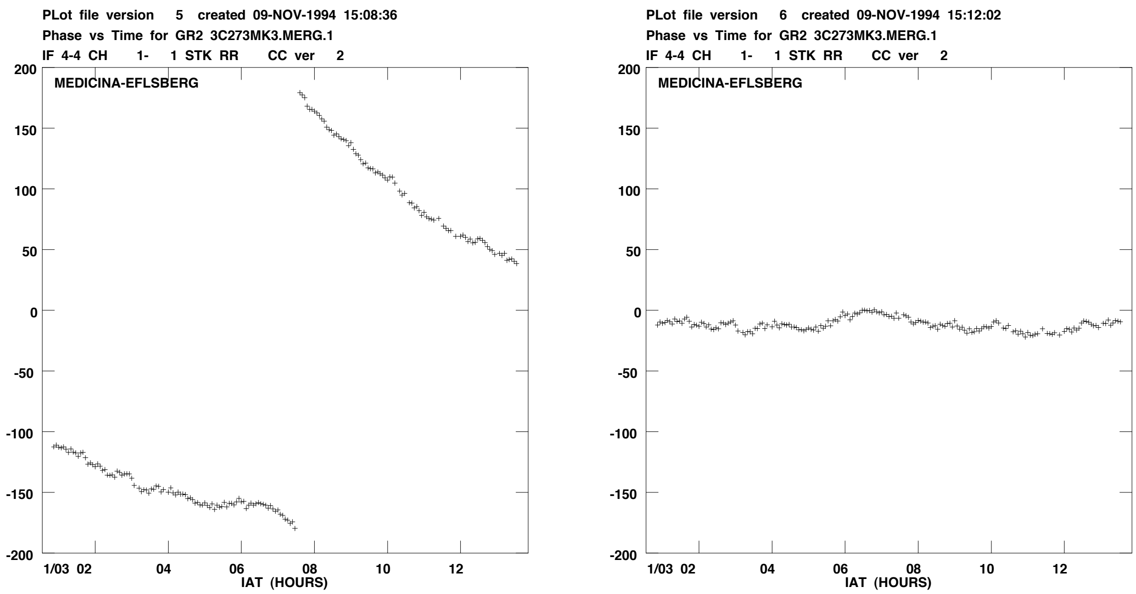

Fig. 3.— The same data as in Figure 2, with the phase of one channel plotted against time. (*a*) The full fringe fitting solution has not been applied and the residual phase rate is readily apparent. (*b*) The full fringe fitting solution has been applied. The residual rate has been removed and the phase is reasonably steady for the duration of the scan. The data can now be averaged in time to reduce the size of the data set.

"D"-terms is best. For example, using data for 3C 273 on the Effelsberg-Medicina baseline is very good. If the D-terms are large, an unpolarized source like 3C 84 works well also. The CROSSPOL adverbs should be set as for the full fringe fitting. The resulting table should be applied to all sources. For Mark III data sets, CROSSPOL should not do much since the phase cals will remove the relative phase differences across the band. For VLBA data set, even those with phase cal data applied, the effect of CROSSPOL will be obvious, flattening the cross hand phase across each IF and aligning the phase across the band. (This discrepancy has to do with how $\mathcal{AIPS}$ stores the phase cal data in Mark III data and VLBA data. For Mark III, the data for each antenna is stored in the CL table directly. For VLBA data, the phase in the CL table for the reference antenna must always be 0 so what is actually written is the difference between the phase cal at each antenna and that at the reference antenna. This latter procedure throws away the information about the relative phase difference at the reference antenna.) Figure 4 shows RL data from a λ6 cm VLBA data set before and after the results of CROSSPOL.

3.5. Amplitude Calibration

Amplitude calibration for VLBI data sets is done using the tasks ANTAB and APCAL. A very large text file needs to be created outside of $\mathcal{AIPS}$, containing the system temperatures and gain curves of each antenna. This file will be read by ANTAB to create a TY (system temperature) table. APCAL reads the TY table and produces an SN table which can be applied to the calibration by CLCAL. APCAL can also perform opacity corrections to the gain curves, but the details will not be discussed here. This table is shipped as part of the log file for VLBA data sets. The EVN has begun providing its users with an ANTAB-ready system temperature file as well. Contact Fredrik Rantakyro (frederik@astbo1.bo.cnr.it) for further information. Errors in these tables have frequently arisen as the system is developed, so carefully check the system temperatures provided by the EVN with the telescope log files.

The system temperature section is just a list of temperatures and the times at which they were measured. For the GR2 data, the Effelsberg system temperature section looked like

```
TSYS EFLSBERG FT=1. TIMEOFF=26.0
INDEX ='R1','L1','R2','L2','R3','L3','R4','L4','R5','L5','R6','L6','R7','L7'/
086 06:12 47 43 47 43 47 43 47 43 48 43 48 44 48 43
086 07:09 47 43 47 44 47 43 47 43 47 43 48 45 48 43
086 07:30 52 48 52 48 52 47 52 47 52 47 53 49 52 48
086 07:44 36 34 37 34 36 34 36 34 36 34 37 35 36 34
086 08:23 48 44 48 44 49 44 49 44 49 44 49 45 49 44
```

The INDEX adverb is used to specify the polarization of each value entered. For the file prepared at the VLBA correlator, the index string is not provided, and must be added by hand.

After the system temperatures have been entered in the file for all antennas, the gain curves must be entered. For the VLBA antennas this information is found in the vlba_gains.key file obtained from the AOC public FTP area. Gain curves from other antennas are supplied by the stations in various formats and are entered in the file. At this time, an effort is underway to accurately and systematically determine the antenna gain curves for all of the EVN stations.

Once the gain curves are entered for all antennas, copy the file to a directory accessible by $\mathcal{AIPS}$ and run ANTAB and APCAL. Use SNPLT to plot the system temperatures for each antenna, flagging bad calibration points. This flagging step is important since $\mathcal{AIPS}$ will interpolate between all entered values to get the amplitude for each time stamp. High values will cause problems with some data as a result. The resultant SN table should be applied to the cumulative calibration with CLCAL, again using interpolation mode 'SELF' to avoid interpolating between gain values from different sources.

Other tests of the amplitude calibration can be done. For example, use VPLOT to plot the amplitude of RR/LL as a function of time. This should be close to unity for all baselines. If one antenna shows a consistently low or high value of RR/LL, you can scale either the right or left gain curve to compensate (either with the DPFU in the ANTAB text file or by using the task CLCOR). Another test would be to plot the amplitude of the parallel hand data as a function of $u - v$ distance. If data to one antenna is consistently low or high, scale the gain curve of that antenna to fix it. Such testing will make the hybrid mapping stage much easier and faster.

3.6. Bandpass Calibration

The data stream at each antenna is passed through a filter to select the appropriate bandwidth. The response of this filter is not a uniform function of frequency. Hence, the amplitude of the visibility function will not be uniform across an IF, as shown in Figure 5*a*. Averaging the data in frequency in the presence of such non-uniformity will introduce baseline errors into the data, which cannot be calibrated out, reducing the data and resultant image quality. The task BPASS will calibrate the bandpass response and correct for it via a BP table. The end result is the amplitudes being flat across the band, as in Figure 5*b*.

To run BPASS, choose a scan of data on a strong source, *e.g.*, 3C 84 or 3C 273. Set BPASSPRM(10)=2, BPASSPRM(11)=2, and the others to 0. Apply the full calibration: amplitude, fringe rates, and delays. Calculate one solution for the entire scan. Apply this BP table to all sources by setting DOBAND=1 and BPVER=1 in all subsequent tasks.

3.7. Applying the full calibration

To apply the full calibration to the data, use the task SPLIT as one would for VLA data. This creates a single source format file which is then self calibrated and imaged. SPLIT can also be used to average across each IF and across the band, if so desired.

There are a few things to note about applying the full calibration. Before any self calibration or instrumental polarization calibration has been applied, average the data across each IF, but not in frequency. This means setting APARM(1)=1. Set APARM(2) equal to the integration time of the data out of the correlator. This enables $\mathcal{AIPS}$ to apply baseline amplitude corrections to the data to compensate for having averaged the data in frequency and time in the presence of residual delays and rates. Optionally, one may set APARM(4)=1 to calibrate the data weights. The effect of this is to divide the weights by the amplitude calibration factor. This way, the effects of bad or noisy antennas are reduced. To reduce the size of the data set, and to increase the signal to noise of the visibilities, the data should be averaged in time, say, to 10-15 seconds.

If the instrumental polarization parameters have already been determined (§ 3.8), they should *not* be applied at this point. Within the $\mathcal{AIPS}$ calibration scheme, the instrumental gain terms must be removed from the data before the instrumental polarization can be applied. This means the data must be reasonably well self calibrated before applying the D-terms. For this reason, the data should not be averaged across the entire band; full averaging in frequency should be done only after correction for instrumental polarization. Applying the polarization calibration is described in § 3.8.1.

3.8. Polarization Calibration

Both the linear (§ 1.1) and ellipticity-orientation (§ 1.2) are implemented in $\mathcal{AIPS}$, the former with the task LPCAL, the latter with the task PCAL. As the linear model is simpler to understand, to solve for mathematically, and more accurate, we will only consider it.

To start with, one must fully self calibrate the data on the polarization calibrator source. Make a multi-source format $u-v$ data set using the task MULTI and index with INDXR. One must also provide LPCAL with a model of the source total intensity structure. If the calibrator is unpolarized, simply provide a CLEAN'd map with a single CC table. If the source is polarized and resolved, the single CC table must be separated into several tables, each representing one model component. This may be achieved with the task CCEDT. Place boxes (with TVBOX) around each of the regions you wish to call a component. This will set the NBOX and CLBOX adverbs. The procedure BOX2CC will calculate the CCBOX and NCCBOX adverbs in CCEDT. Set NCCBOX to $-$NBOX. This ensures that the CLEAN components from each region are saved as a separate CC table. Alternatively, one may model fit the $u-v$ data with a small set of point and gaussian model components and save each in a separate CC table.

The inputs to LPCAL are set as follows. The CALSOUR name must be provided, even though there is only one source in the file. The default message level will give both the D-terms determined and the polarization of each model component. Set NMAP to be the number of fields used for imaging the calibrator source, usually 1. Set IN2VER to be the first CC table to be used and NCOMP to be the number of CC tables in each field to use for the source model. The task will modify the antenna table (AN), storing the D-terms for each IF.

$\mathcal{AIPS}$ does not provide powerful methods of verifying the solutions generated by LPCAL. If the calibrator source is unpolarized, then the corrected cross-hand visibilities should cluster at the origin of the complex plane. This can be examined by plotting the normalized visibilities, RL/RR, RL/LL, LR/RR, LR/LL, in the complex plane with and without applying the polarization with the task VPLOT. Figure 6 shows the RL/RR visibility in the complex plane before and after applying the polarization calibration for the GR2 data set on the Medicina-Effelsberg baseline. The D-term for Medicina for this experiment is around 15% and for Effelsberg around 10% so the instrumental contamination is easily seen. For VLBA stations, D-terms are only a few percent or less. Bad data points should be flagged and LPCAL run again.

If the calibrator source is polarized, one should verify that the polarization of each model component is consistent between IF's, in both amplitude and phase. One should also make an image of the calibrator source, verifying that the polarization structure is consistent with that that was solved for. The noise in the Q and U images should be as low as in the total intensity image, if not lower; residual systematic errors will raise the noise. Using an unpolarized source as a calibrator is preferable as the source polarization is known *a priori* and may be compared with the results of the calibration.

When a satisfactory solution has been obtained, apply the calibration as described in § 3.8.1. The data may now be averaged fully in frequency. If the full, non-linear corrections are made so that the parallel hand data or modified, further self calibration on the resultant data should be performed before averaging in frequency, especially if the D-terms are large.

3.8.1. Applying the Instrumental Polarization Calibration

To apply the instrumental polarization calibration to the data, again use the task SPLIT, setting DOPOL to some positive value. For $\mathcal{AIPS}$ releases up to and including 15OCT96, DOPOL is simply a boolean adverb, controlling whether or not the polarization calibration is to be applied. Starting with the 15APR97 release of $\mathcal{AIPS}$, the DOPOL parameter takes on a broader meaning in the case of the linear model (§ 1.1). DOPOL=1 means to correct for instrumental polarization in the linear approximation model, *only* in the cross hands. DOPOL=2 means to do the full non-linear correction, including parallel hands, with appropriate approximations being made in the case that not all four correlations are present (see § 1.3). DOPOL=3 means to do the full non-linear correction, but to only use visibilities where all four correlations are present and to flag the remaining data.

3.9. Position Angle Calibration

The only remaining calibration is that of the absolute position angle of the polarization, which was discussed in § 2.2. Fully self calibrate the data on the calibrator, correcting for instrumental polarization. Make a total intensity map and compare the integrated flux ΣI with the VLA value. These should be very close, except when 3C 286 is used as a calibrator, providing a good check on the absolute flux calibration of the VLBI data. Then, form a polarization image recording the total Q and U fluxes. The integrated polarized flux, $p_{\rm int} = \sqrt{(\Sigma Q)^2 + (\Sigma U)^2}$, should agree with the polarized flux measured from the VLA data The right-left phase calibration term φ_{RL} is found from the expression

$$\varphi_{RL} = 2\chi_{\rm true} - \tan^{-1}\left(\frac{\Sigma U}{\Sigma Q}\right) \ , \tag{13}$$

where $\chi_{\rm true}$ is the polarization position angle of the source determined from the VLA data. This calibration is applied to the data with the task CLCOR. Set OPCODE='POLR', STOKES='L', and CLCORPRM=φ_{RL} (a value must be provided for all IF's). As this calibration will also rotate the D-terms, the file on which this calibration is run must have the AN table with the D-terms present, unless the instrumental polarization calibration has already been applied; CLCOR will make the appropriate rotation and rewrite the AN table.

4. Self Calibration and Imaging

There are several options for the self calibration and imaging of VLBI data. Within $\mathcal{AIPS}$, one may use the standard combination of CALIB and IMAGR. Alternatively, one may use the SCMAP task, which combines self calibration and deconvolution, running several cycles before determining the final calibration. $\mathcal{AIPS}$ will derive gain curves for the RR and LL data separately. As in all other phase calibration steps, make sure the $R-L$ phase is stable.

An alternative to the $\mathcal{AIPS}$ tasks is to use the DIFMAP program of the Caltech package (ftp://phobos.caltech.edu/pub/difmap/difmap.html). This is a very powerful program, which allows fast processing of the data. In DIFMAP, a model of the source is gradually built, and removed from the $u-v$ data. There are two primary limitations to the use of DIFMAP with dual polarization VLBI data. First, in the standard release, one may form Stokes I only for visibilities with both RR and LL. This is a significant problem for EVN data in which many telescopes have only one hand of polarization. I have implemented a new Stokes parameter within DIFMAP, Stokes PI, which will form I if only one parallel hand correlation is present. This is only, at present, implemented in my private version of DIFMAP at the MPIfR and at Brandeis University.

Second, DIFMAP does not solve for gain curves for R and L, but for I. This means that any gain difference between RR and LL *must* be completely removed before any processing can be done. The Brandeis package provides software to solve for the $R - L$ gain differences and to correct for them. Moellenbrock (1997) designed an $\mathcal{AIPS}$ procedure that would also perform this calibration. However, the simplest means of circumventing this limitation to DIFMAP is to build a good model for source within DIFMAP, using perhaps only one parallel hand if appreciable gain differences are expected, read this model into $\mathcal{AIPS}$, and perform phase and amplitude self calibration on this model. This will remove the gain differences and the resultant data may then be read into DIFMAP and a full self calibration and editing may be done.

Final images, regardless of the software used for self calibration, should be made with the $\mathcal{AIPS}$ task IMAGR. The total intensity image is made as one would make an image from VLA data. For the linear polarization image, there are two options. In Equations (1), we expressed the Q and U parameters as combinations of the RL and LR correlations. If all the visibilities in the $u - v$ data have both cross hand correlations, one may simply form Q and U normally with IMAGR and make each image as one would for VLA data. If, however, many of the antennas have only a single polarization, this will result in significant data flagging. We also expressed the complex polarization P directly in terms of the cross hand correlations in Equations (1). With this formulation, we may form the complex polarization map directly, and perform a complex CLEAN on this. This is implemented within $\mathcal{AIPS}$ via a combination of the procedure CXPOL, which forms dirty Q and U maps using the MX task, and the task CXCLN, which performs the complex CLEAN. CXCLN is based on APCLN, rather than IMAGR or MX, so the full field is not CLEAN'd; make sure the field size is sufficient to contain all features of the source. The dimensions and orientation of the restoring beam must be provided. One way of making a P beam is to combine the Q and U beams created by CXPOL to form the intensity beam. The restoring beam is a Gaussian fit to the center of the P intensity beam. A second peculiarity of CXCLN is that a CLEAN box *must* be provided.

For VLBA data sets, experience has shown that nearly all the visibilities have all four correlations. Hence, one need not use the complex CLEAN procedure, but rather use IMAGR to make Q and U images in the standard way. This is not to say that one cannot use the complex CLEAN for VLBA data.

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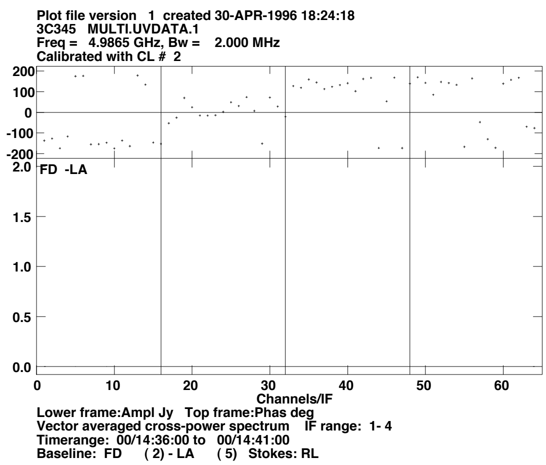

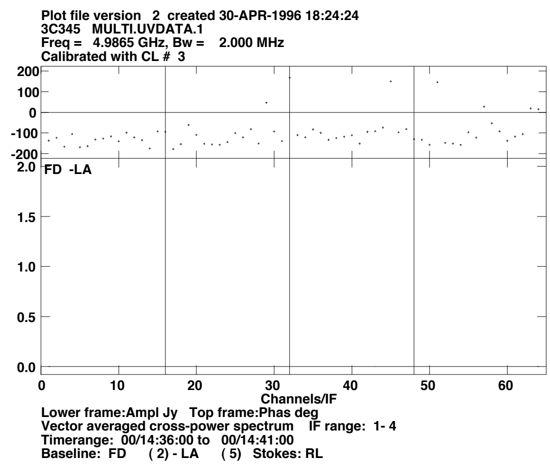

Fig. 4.— A plot, using the task POSSM, showing the vector averaged RL visibility across the band for 5 minutes of data on the source 3C 345 at $\lambda 6$ cm on the FD-LA VLBA baseline from the BA8 data set. (a) The CROSSPOL solution has not been applied. The data in each IF have a different phase. (b) The CROSSPOL solution has been applied. The RL phase is now constant across the band. The absolute phase has not be calibrated, but the differences between IF's have removed so that only one right-left phase difference need be determined.

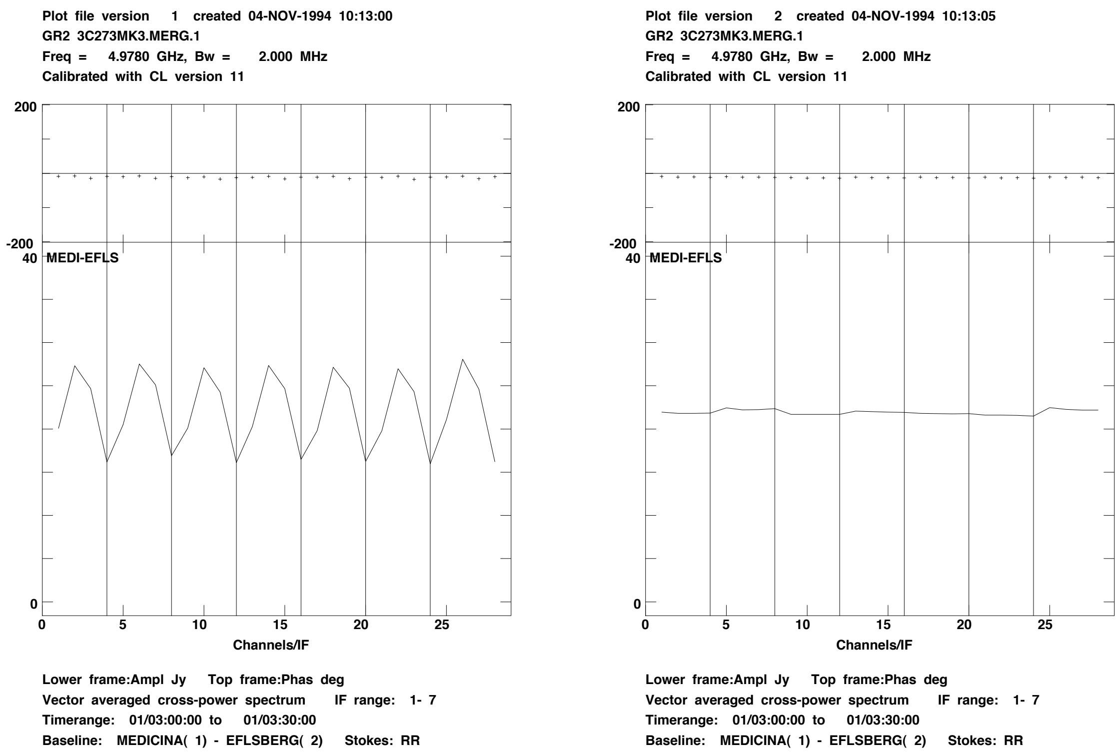

Fig. 5.— A plot, using the task POSSM, showing the same GR2 data as before after applying the fringe fitting and amplitude calibration. (*a*) The band pass calibration has not been applied. A sawtooth pattern in the amplitude is readily apparent. (*b*) The band pass calibration has been applied. The sawtooth pattern has been corrected so that the visibility amplitude across the band is flat.

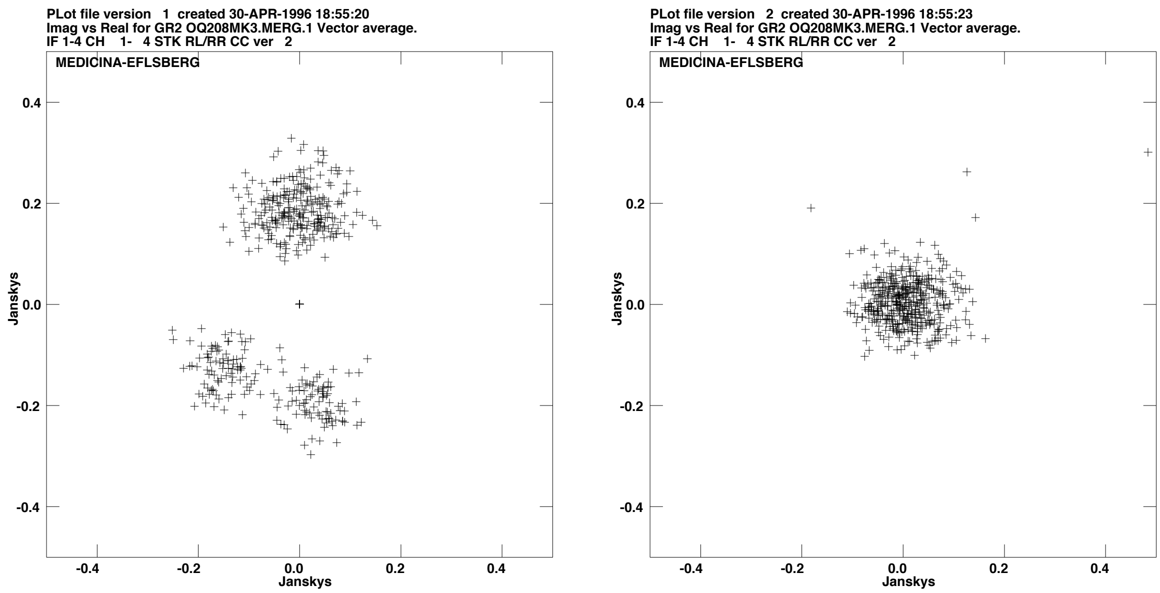

Fig. 6.— A plot, using the task VPLOT, of the RL/RR visibility in the complex plane on the source OQ 208 for the Medicina-Effelsberg baseline in GR2. (a) No instrumental calibration has been applied. The visibility is seen to lie on a circle offset from the origin. This is due to the antenna D-terms providing spurious polarization measurements which rotate in the complex plane because of the parallactic angle variation at each antenna. (b) The instrumental calibration has been applied. The visibilities are now seen to be very close to the origin, implying that OQ 208 is unpolarized. Averaging these data in time will greatly reduce the noise.