BIMA MEMO No. 43

Polarization Switching for the BIMA array

M.C.H. Wright, 15-Dec-95

The BIMA array receivers each have a single linear polarization. Polarization Switching is required in order to obtain polarization observations. This memo explores efficient switching cycles.

For linear polarization measurements we wish to sample LL, LR, RL, and RR, where L and R designate the sense of circular polarization for a pair of antennas. The interferometer response, F, to polarized emission is

$$\begin{aligned} F(LL) &= F(I) + F(V) \\ F(RR) &= F(I) - F(V) \\ F(LR) &= F(Q) + jF(U) \\ F(RL) &= F(Q) - jF(U) \end{aligned}$$

where I, Q, U, and V are the Stokes parameters (e.g. Fomalont & Wright, 1974). If there is no circular polarization, V=0, and either LL or RR measure the total intensity I. Both LR and RL are required to measure the linear polarization since LR and RL uv-data are not Hermitian. With dual polarization receivers and 4 x nants(nants-1)/2 correlators it would be possible to obtain all 4 combinations of L and R simultaneously for all baselines in an array with nants antennas. Although it is possible in principal to use the 4 spectral windows in the BIMA correlator to sample the 4 polarizations, with a single polarization receiver we must time multiplex the polarization observations. The array is currently being outfitted so that each antenna can be switched between L and R circular polarization. Since the mechanical switching takes a few seconds, we seek efficient switching cycles. To sample all combinations on all baselines would take 2**nants combinations of L and R on each antenna. This is not compatible with good uv sampling, so we must compromise.

One possibility, suggested by John Lugten, is to use Walsh functions to switch the polarizations. A Walsh function of length 16 provides orthogonal series for switching the polarization on up to 15 antennas. A complete polarization cycle takes 16 integrations, which may be too long for good uv sampling on long baselines. With the 9-antenna array we can use higher Walsh sequencies, which cycle through all polarization on most baselines in fewer than 16 integrations, as noted by John. Walsh function switching takes no account of how many baselines simultaneously observe total intensity, which may be a problem for calibration. We could add cycles to simultaneously observe total intensity, although this makes the complete cycle longer.

Another possibility is to switch the polarizations in groups with a common polarization. With Ng groups there are 2**Ng combinations, of polarizations, but the number of baselines which sample all 4 polarizations is reduced as Ng gets smaller. For the current 9-antenna array, 3 groups of 3 antennas provides a reasonable compromise as illustrated in Table 1.

Table 1. Polarization switching for 9-antenna array

cycle	antennas in group			baselines in group					
	A	B	C	AB	AC	BC	A	B	C
	3	3	3	9	9	9	3	3	3
1	L	L	L	LL	LL	LL	LL	LL	LL
2	R	L	L	RL	RL	LL	RR	LL	LL
3	L	R	L	LR	LL	RL	LL	RR	LL

4	L	L	R	LL	LR	LR	LL	LL	RR
5	R	R	L	RR	RL	RL	RR	RR	LL
6	R	L	R	RL	RR	LR	RR	LL	RR
7	L	R	R	LR	LR	RR	LL	RR	RR
8	R	R	R	RR	RR	RR	RR	RR	RR

Examining Table 1, we see that the 27 baselines in the groups AB, AC and BC sample all 4 polarization pairs for an equal amount of time, and the other 9 baselines within the groups A, B, and C sample LL and RR for equal times. Any antenna can be chosen as a reference antenna for calibration since cycle 1 and 8 respond to the total intensity (Stokes I) simultaneously for all baselines.

We can trade off polarization observations for more integration time in total intensity, or vice-versa. For example, using only cycles 3 - 6 provides 18 baselines in groups AB and AC with full polarization, 9 baselines in group BC sample only LR and RL, and 9 baselines within the groups A, B and C sample only LL and RR. In this case the reference antenna for calibration must be chosen from group A, and the calibration of all antennas cannot be made simultaneously. Adding cycle 1 or 8 to 3 - 6 provides simultaneous calibration of all antennas; alternatively using cycles 2 - 7 gives more integration time to RL and LR. The choice of antennas within each group should be made with consideration to which baselines are required with full polarization, and which with only total intensity. Multiple tracks would allow permutations of antennas within each group. Other permutations are possible.

The calibration problem was investigated using the Miriad task UVGEN to generate polarization switched uv-data for the Walsh cycle of length 16, and for the cycle of length 8 in table 1. We used the BIMA a-array and a 20% polarized point source model with 30 degrees of phase noise. The model uv-data were imaged and combined to produce I, Q, U, and V images. Note that both real and imaginary parts of the LR and RL data must be imaged. The task WALPOL was used to generate Walsh patterns. The shortest calibration interval which could be used with the Walsh cycle was 1.6 times the integration interval if both LL and RR were used to calibrate the data. With this calibration interval, the amplitude of both unpolarized and polarized components was about 88% of the model amplitude, corresponding to 28 degrees of residual phase noise after the calibration. The resulting images were almost identical for both switching patterns using a point source model. For the cycle of length 8, we can use a calibration interval equal to the integration interval. In this case the LL and RR images are recovered almost perfectly, and the LR and RL images are improved to 95% of the model amplitude. For more complex models, different results will be obtained, depending on the sample interval and the source structure. A model with 5 compact components with 20% polarization and 30 degrees phase noise also worked well with either switching pattern. Models with more complex source structures, or higher phase noise which requires self-calibration, work better with a short polarization cycle giving better uv-sampling of RR and/or LL. If the polarization structure is also complex, then good uv-sampling of LR and RL is also required, and multiple uv-tracks are required with either switching pattern. The choice of switching pattern will probably be dictated by practical constraints of switching time, a-priori knowledge of source structure, and available observing time. This memo is respectfully submitted for consideration by those who may be mathematically inclined.

References

Fomalont,E.B, & Wright,M.C.H, 1974, in Galactic and Extragalactic Radio Astronomy, Springer-Verlag, New York, eds. G.L.Verschuur & K.I.Kellermann.

BIMA memo 48.

Calibrating and Imaging Polarization Switched Data

Melvyn Wright, 01-AUG-96

This memo defines the algebra and outlines the steps used for calibrating polarization switched data, and making polarization images. A tutorial csh script is available in $MIRBIN/polcal.

Definitions

I	Stokes I, total intensity.
Ip	linear polarized intensity.
psi	polarization position angle
Q	Stokes Q = Ip * cos(2*psi)
U	Stokes U = Ip * sin(2*psi)
V	Stokes V, circular polarized intensity.
chi	Parallactic angle
m,n	baseline from antenna, m, to antenna, n
p,q	polarizations, either L,R circular, or X,Y linear.
D(p,m)	Leakage into polarization, p, on antenna, m

At Hat Creek we measure

RR = I + V
LL = I - V
LR = Ip * expi(2*psi) * expi(-2*chi) + I * (D(L,m) + conjg(D(R,n))
RL = Ip * expi(-2*psi) * expi(2*chi) + I * (D(R,m) + conjg(D(L,n))

Assuming that Stokes V is small, we calibrate using both LL and RR with a long enough calibration interval to include LR and RL data.
For Alt-Az antennas, the phase of a linearly polarized source rotates with the parallactic angle, whereas the leakage terms are constant. Plotting the LR and RL uv-data imaginary versus real over a wide range of parallactic angle shows the linear polarization as circles offset by the polarization leakage.

Average to get source polarization.

We can remove the parallactic angle variation using UVCAL options=parang
LR = LR * expi(2*chi)
RL = RL * expi(-2*chi)
and average the output to reduce the effect of the polarization leakage.
LR = Ip * expi(2*psi) + I * (D(L,m) + conjg(D(R,n)) * expi(2*chi)
RL = Ip * expi(-2*psi) + I * (D(R,m) + conjg(D(L,n)) * expi(-2*chi)
For an unresolved source, averaged over a range of parallactic angle,
<LR> = Ip * expi(2*psi)
<RL> = Ip * expi(-2*psi)

Determine the polarization leakage.

To estimate the polarization leakage, we subtract the source polarization from the calibrated data using UVCAL polcal=Ip * expi(2*psi) and average in time to get the polarization leakage for each baseline.

Finding the polarization leakage for each antenna.

The task ANTPOL lists RL/(0.5*(RR+LL)) and RL/(0.5*(RR+LL)) for each baseline. The average polarization leakage is about 6% for each baseline, or 3% for each antenna at 86 GHz. We can fit the leakage for each antenna using the task GPCAL. Although GPCAL was designed for simultaneous measurements of YX,XY,YY,XX, we can average our polarization switched data so that each averaged interval contains LR,RL,LL,RR data. We then change the polarization codes from LR,RL,LL,RR to YX,XY,YY,XX using UVCAL polcode=-4 and fit antenna-based instrumental polarization. GPCAL also fits the antenna gains and XY phases, which in our case are the phase differences between L and R polarizations. These gains can be applied to the data, if needed.
The fitted antenna-based leakage terms are relative to the leakage into the reference antenna.

Subtracting the instrumental polarization using a source model.

In order to subtract the polarization leakage we must have an estimate of the total intensity, I, for each time interval and baseline.
With polarization switching we do not have simultaneous measurements of LR, RL, LL and RR on each baseline, but can estimate I from a source model, and subtract the polarization leakage using UVMODEL options=polcal.
The polarization leakage is given as a table of four values for each antenna, being the real and imaginary parts for leakage into L and R polarizations respectively. The table can be extracted from the history of the GPCAL fit.
Iterate if needed to get better estimates for source and instrumental polarization.

Making polarization images.

After calibrating the uv-data and correcting for the polarization leakage, images can be made and deconvolved using the usual Miriad tasks. We can make images of the Stokes I, Q, U, and V from the uv-data using the relations:

$$RR = I + V$$
$$LL = I - V$$
$$LR = Q + jU$$
$$RL = Q - jU$$

If Stokes V is small, then both LL and RR data can be used together to make an I image. Alternatively LL and RR data can be imaged separately and the sum and difference used to make I and V images. With polarization switching the sampling is different for LL and RR data. Better sampling and deconvolution may be obtained using LL and RR data together. The deconvolved I image can be used as the source model for subtracting the instrumental polarization from LR and RL data.

The LR and RL data are not Hermitian, as assumed by the INVERT task. The Q image is obtained in the usual way by imaging LR or RL data. We must use both the select and stokes keywords to select either LR or RL data. The U image is obtained using INVERT options=imaginary to image the conjugate of the uv-data. Thus we obtain an estimate of Q and U from the LR data, and an estimate of Q and U from the RL data. The sampling is different for LR and RL data. The synthesised beam is obtained with the Q image, and can be used to deconvolve both Q and U images. A better deconvolution may be obtained by averaging the Q and U images and beams from the LR and RL data. An estimate of the errors can be obtained by examining the differences.

The Q, U, and I images can be combined into Ip and psi images using either MATHS or IMPOL tasks, and plotted using CGDISP or IMPLOT.