BIMA Memo # 100: Polarimetry with the BIMA Interferometer: Observations to Data Reduction

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09 August 2003

Abstract

This memo covers the basics of BIMA polarimetry observing, including writing polarimetry proposals, templates of observing scripts (to include both continuum and line polarimetry together), and then data reduction using MIRIAD. Some knowledge of interferometry and MIRIAD is assumed.

1 The Basics

The BIMA array antennas have 115 and 230 GHz (on 10 and 9 antennas, respectively) receivers and are capable of polarization measurements using both receivers in continuum or spectral line modes. Incident radiation on the linear feeds can be paired with a variety of polarization plates. For example, use of quarterwave plates changes incident linearly polarized radiation (e.g. from interstellar dust) to circular, enabling measurement of linear polarization through cross-correlation of the circular terms.

There is only one plate optimized for short wavelength observations, so the 230 GHz quarterwave plates are always installed in front of the 230 GHz receivers. At 3mm, the choice of plates is quarterwave 86 GHz, quarterwave 115 GHz or halfwave 115 GHz. Only one of the 3mm choices can be installed in front of the 3mm receiver at any given time. Each of the antennas has only one receiver at each wavelength; hence the array cannot do “dual polarization” measurements, i.e., we cannot detect both R and L (or X and Y in the case of the 115 GHz halfwave plate) polarizations simultaneously on a given antenna. Therefore, measurement of Stokes parameters requires switching polarization plate orientation in front of the feeds. Time averaging then results in a quasi-simultaneous measurement of the four relevant circular polarization components on each baseline (RR, LL, RL and LR).

Since the quarterwave plates are the typical mode of polarimetry observing at BIMA, we will discuss the polarimetry observing in terms of the circular components, right (R) and left (L), measured through those plates. We can solve for all four Stokes vectors if all four R and L combinations have been sampled quasi-simultaneously. The solutions basically take the form:

$$I = c(RR + LL)$$
$$Q = c(LR + RL)$$
$$U = ic(LR - RL)$$
$$V = c(RR - LL)$$

where c is a constant related to the gains and effective apertures of the antennas and will be different for each baseline.

To achieve quasi-simulateous measurements of Stokes parameters, all four combinations of R and L circular polarization hands must be observed before phase gains can occur ($<$ 5 minutes in practice).

Faster changes between L and R may be required in long baseline arrays (B and A) rather than in short baseline arrays (D and C). The optimal switching patterns for each antenna can be generated using the program **walgen** based on the Walsh sampling function. This program, written by R. Rao, determines the optimal sequence for R/L switches for all antennas, based on their locations a given array. It is available at Hat Creek in the directory /obs/obs/polarization_calibration.

The output of walgen is a "polarization grid" of 10 x 16 which executes a sequence of 16 configurations of L/R measurements on 10 antennas. Note that although antenna 3 does not have a 230 GHz receiver, there must be a column for antenna 3 in the grid even for 230 GHz projects or the observations will not be carried out successfully. A grid looks like this:

```
llrlllllll,
llrlrllrrr,
rlrrrrrrrl,
rlrrlrrllr,
rrrlrrllll,
rrrllrlrrr,
lrrrllrrrl,
lrrrrlrllr,
rlrrllllrl,
rlrrrllrlr,
llrlrrrrll,
llrllrrlrr,
lrrrrrllrl,
lrrrlrlrlr,
rrrlllrrll,
rrrlrlrlrr,
```

If you are doing a "standard" polarization observation (i.e., measuring all four Stokes' parameters at either 3mm or 1.3mm) then a grid may already be in place in the "$UGRID" directory at Hat Creek. You may create your own grid for custom polarization observations, but in either case, the grid should be placed in the $UGRID directory as designated in the observing script (see § 3.2).

2 Planning Polarization Proposals

There is nothing inherently more complicated about polarization proposals than non-polarization proposals. However, it can be very difficult to estimate the flux expected in polarization maps for two reasons. The expected degree of polarization may be unknown, and many sources typically observed in polarization (i.e., Galactic) may be substantially resolved by the interferometer, leading to a further decrease in the expected polarized flux. In this regard, it can be worthwhile to identify existing interferometric maps or even map sources first with the interferometer; this is much more effective than attempting to extrapolate a flux from a single dish map. Choosing a reasonable expected degree of polarization is usually necessary. Ideally, one would like to obtain *at minimum* 3σ on the polarized flux.

The BIMA tool "Jrms" (accessible from the BIMA web page) can then be used to determine the rms expected in a single track for a source at a given declination, frequency, array configuration and channel width. This tool will also give the synthesized beam expected. Note that if spectral line data are to be obtained simultaneously with the continuum data, then the bandwidth available for continuum will generally be 700, not 800, MHz. For Galactic protostellar sources, one corf is generally sufficient to measure a spectral line (even CO). For extragalactic sources, the entire USB may have to be employed to obtain the CO line (for instance). The rms obtained for a single track is for intensity data. With overheads (sampling both L and R) and calibration for polarimetry, the effective observing time is only about 1/5 – 1/4 of the on-source time. Therefore, 4 – 5 tracks are required to reach this same rms in a polarized emission map.

In practice, 230 GHz observing conditions are relatively rare at Hat Creek, so if the rms obtained from Jrms is $<< 1\sigma$ rms required for a 3σ detection of polarized flux, the source is too faint to be observed by BIMA at 230 GHz from its current location (since achieving that rms already requires 4 or 5 tracks). 115 or 86 GHz projects are not severely constrained by the weather, but can be prohibitive due to the number of tracks required if the source emission follows the Rayleigh-Jeans Law.

The future CARMA site will, by all accounts, be much more favorable for 230 GHz observations. This means more tracks can be requested in individual proposals. Additionally, the increase in correlator bandwidth by a factor of 5 will greatly enhance our sensitivity to polarized emission in continuum at both wavelengths.

Estimation of the sensitivity to CO line emission is less critical, since it is technically obtained for free with the continuum data. If your proposal science is driven by CO (or another spectral line) data, however, more stringent estimates of the SNR expected would be practical. The process is the same, except the bandwidth is replaced by the *individual* channel width in Jrms.

3 Polarization Observations

3.1 Calibration

The primary requirement for calibration of polarimetry data from the BIMA array is the determination of the "true instrumental feed response", commonly referred to as "leakage". Leakage is a measure of how much contamination of the orthogonal polarization hand is detected in either the right or left orientations of the quarterwave plates. These values are derived for each antenna by observations of a bright continuum source of known polarization properties. At BIMA, these observations are typically done using either 3c273 or 3c279. The leakage data are stored in tables which are then copied into the relevant source directories for application to the science observations.

The measurment of leakage is obtained by an observation over a good range of parallactic angle. This allows "leakage" versus "time" to be determined. Appendix B contains a sample reduction script for a calibration observation (see § 4 for more information on data reduction). The generation of leakage terms should be done separately for the lower and upper sidebands.

Bower, Wright & Forster recently examined a range of 230 GHz polarization calibration data and determined that the leakage terms are constant with time (see BIMA Memo #89). Therefore, it is unnecessary to include calibration tracks with your calibration project. The only changes to the leakage terms are produced when the receivers themselves are removed (which was an annual practice in the case of the 3mm receivers when BIMA used to switch to 1cm receivers in the summertime) and then reinstalled, since their alignment with respect to the feeds may have changed. The polarization plates themselves are rigidly mounted and maintain their orientation to the feeds very well. Annual calibration tracks are recommended to monitor the leakage terms.

3.2 Polarization Observing Scripts

Observations are carried out at the telescope with observing scripts. Details of composing scripts can be found on the BIMA website. However, no templates of polarization scripts are available elsewhere. Hence, we provide two here which are heavily annotated to explain what the script is doing at each step, as well as highlighting some of the key points which are crucial to executing your observations successfully. There is a MIRIAD observing script called "polcal" which is now somewhat out of date and should be used with caution.

Some general things to keep in mind for all scripts:

- select the brightest, closest phase calibrator you can (obtained best using "xplore" if available or "calfind" on the BIMA web site)
- test your script for all possible LSTs in which it could run (using the on-site program "checker")
- for 230 GHz observations, pointing must be checked during the daytime for both polarization and non-polarization projects (the sample scripts all contain daytime pointing).

Several sample scripts are provided in Appendix A. The script can also be downloaded from http://astron.berkeley.edu/∼brenda/BIMA for easy editing. Included in Appendix A is the script t835c230.20126 which is setup for a 230 GHz polarization observation of a protostellar core in continuum, with CO *J=2–1* observed in a 50 MHz corf in the USB, with the rest of the USB used for continuum. For sources with very wide CO lines, the entire USB may be required to measure the CO polarization. An example is the recent observation of M82 with the polarimeter. In the interests of space, it is not included here, but can be downloaded from the website given above. If you are only interested in continuum, and want to avoid the CO lines (at 115 or 230 GHz) entirely, you can look at t846c230.m82.cont, which is also in Appendix A. This M82 script is set up for mosaicking over 3 fields, which is not typical for polarimetry due to sensitivity constraints.

4 Data Reduction

Reduction of BIMA data is typically done using the MIRIAD (Multi-channel Image Reconstruction, Image Analysis and Display) software package. The recipes provided here assume access to MIRIAD. The best way to reduce BIMA data is to write a script which allows you to re-reduce data quickly. You may have to reduce the data in several different ways (with different weighting for instance) to get the optimal result.

Appendix B contains two c-shell scripts: one to reduce a leakage calibration observation and one to reduce a set of science data. There are many similarities between these. Before presenting the scripts, the key programs utilized are listed and their basic uses summarized.

4.1 MIRIAD programs used in Polarization Data Reduction

The programs used in the scripts of Appendix C are listed in alphabetical order. A complete list of MIRIAD programs is available on the BIMA web page. Note that in MIRIAD, help can be obtained on any program by typing "mirhelp <program name>".

- cgdisp: MIRIAD display tool. ok for examination on screen, but not great for hardcopies of polarization data.
- clean: clean the dirty map (various options are available). Note that "mossdi" should be used instead of clean for mosaicked data.
- gpcal: generate leakage tables from calibration tracks.
- gpcopy: transfer the gains for one source (cal) to another; also used for transfering leakage terms (gains) to source data.
- gpplt: show antenna gains (amplitude gains will be flat unless amplitude selfcal is performed).
- imlist: summarize information about a data set with options=stat.
- impol: produce polarization percentage, position angle, polarized intensity maps from the Stokes maps produced from invert.
- imtab: tabulates selected regions of an image. To make decent maps of polarization data, extraction of the data into a tabular format for use in a routine like WIP will usually be necessary.
- invert: make a dirty map from unflagged visibilities (see § 4.2 for important details about how variable in selfcal can affect the visibilities available for invert).
- linecal: deduce the line lengths corrections (gains) to correct for changes (should not be done if there are apparent problems with the linelengths).
- mselfcal: perform self-calibration (see § 4.2 for important details about selfcal). mselfcal is like selfcal, but with a more reasonable determination of intervals.
- restor: make a map with the clean components and the clean beam.
- selfcal: perform self-calibration (see § 4.2 for important details about selfcal; also see mselfcal entry).
- uvaver: average visibility data over some time interval (essential in polarization to get both L and R data into the same time bins).
- uvcat: make a new map and apply gains as default.

- uvflag: flag undesirable data (typically high amplitude visibilities or visibilities between phase or amplitude jumps in calibrator observations, where data are unreliable).
- uvplt: examine visibility data.

4.2 Potential Pitfalls

4.2.1 Self-Calibration Intervals

One of the potential pitfalls in reducing data with MIRIAD arises in use of the "selfcal" program, which has a default "interval" of 5 minutes. The duration of "interval" sets the range of time over which gains from the calibrator will be applied to the source data. Hence, it is crucial that this interval be set to *at least* 1/2 - 2/3 the elapsed time between phase calibration measurements. If the interval is set to the duration of the phase calibration observation (typically about 5 minutes), then the data taken on source around that calibration ($\pm$5 minutes) will be gain calibrated (and hence used). Data without gain calibration (i.e., 10 minutes out of a 20 minute source observation for instance) will be <u>discarded</u>. The "invert" program, which converts visibilities to maps will warn you if substantial amounts of visibilities are not being used; this can be a clue that the selfcal interval has been chosen poorly.

Ideally, what one would actually like to do is selfcal over as short an interval as possible (i.e., length of the calibration observation) but be able to then apply the gains over very long intervals (i.e., perhaps $> 2\times$ the length of a source observation. This would prevent interpolation of calibration observations that have been taken back to back (for instance if a script is stopped and then restarted at the telescope), and the utilization of more source data in the event that a phase calibration were skipped (for instance, if the phase calibrator briefly exceeded the elevation limit for observing during transit). To execute this, one can use a short interval in selfcal or mselfcal, and then use

```
puthd in=<dataset>/interval value=1
```

to set the interval in the science data header to 1 day.

4.2.2 The "line" Parameter

Failure to specify the line parameter (e.g. line=wide,1,2 for the USB average) can cause all kinds of problems when reducing data with MIRIAD. It is best to select it explicitly. .

5 Appendix A: Observing Scripts

5.1 Continuum and Line Polarimetry

For sources with very wide CO lines, the entire USB may be required to measure the CO polarization. An example is the recent observation of M82. In the interests of space, it is not included here, but can be downloaded from the same website as the following scripts (http://astron.berkeley.edu/∼brenda/BIMA). The script below is appropriate for sources with relatively narrow CO lines (e.g. protostars). One corf of the USB is used for CO 2-1 measurement, while the rest of the USB measures continuum. More information about BIMA scripts and their format on the BIMA website at http://bima.astro.umd.edu/user/setups/hcobsman.

```
#! /bin/csh -f
#
#   Project: t835c230.20126 -  polarization observations
#
# include information needed by observer here
# This can include a brief summary of the project.
#
#   Note that the script will end on the source. This is a compromise
#   to avoid loops, which double the amount of time spent on the calibrator
#   during the track due to the necessity of daytime pointing at 1mm.
#
#   Investigators: list them here!
#
#   Contact information:
#       I.M. Peye
#       email address here
#       (O) contact phone
#       (H) numbers!
#
#       possible LST range for script: 1340 to 0230
#
#       Source       = IRAS 20126+4104
#       Obs. Freq.   = Continuum, 230 GHz, CO 2-1 line
#       RA(2000)     = 20:01:43.49
#       DEC(2000)    = 41:08:24.235
#       vlsr     = -3.9 km/s
#
#       Sources (20 deg)
#       I20126+4104:     1330 to 0235 20d elevlim (1935-2020 above 86d)
#       2015+372         1355 to 0235 20d elevlim 3.6 Jy at 86 GHz (< 5d away)
#                                        (2005-2024 above 86d - never to 87)
#       Uranus          1925 to 0050 25 d elevlim
#
# Setups follow     ==========================================
#
```

```
# setup to allow xscribe, the scheduling tool, to inform the observer that
# this is a 1mm polarization script
# note: the ‘‘plates’’ command should be used for polarization scripts only;
# setting plates=none for non-polarization scripts is really obnoxious at the
# telescope!

setup name=xscribe plates=1mmquarterwave

# tell the script which antennas to use
# Antenna 3 is left out because it has no 1mm receiver.
# ‘‘a’’ is the designation for Antenna 10.
set ants=12456789a

set itime=23                # integration time in seconds
set so = i20126             # source name
set cal = 2015+372          # phase calibrator
set p = 2015+372            # pointing calibrator
set f=uranus                # flux calibrator

# Tune receivers (one for 1mm observing; one for 3mm pointing)
# One wants to do this as infrequently as possible
# 3mm setup is only used for daytime pointing
setup name=tune_1mm freq=230.538 iffreq=530 dopsrc=$so dopcat=$UCAT/bcm.cat
setup name=tune_3mm freq=86.243  iffreq=-150 ants=$ants

# Set up correlator

# For most Galactic sources, mode 8 (wideband) is fine.
# There is one spectral line, for which 65 km/s is adequate coverage
# and 1 km/s is adequate spectral resolution.
# The restfrqs settings in the USB reflect the CO 2-1 rest frequency.
# In practice, only the restfqs in the corfs where CO will be
# detected need to be set (and even if they aren’t, they can be set
# later during data reduction).

setup name=mode8 cormode=8 coptions=hanning \
      restfqs=0,0,0,0,0,0,0,0,230.538,0,0,0,0,0,0,0 \
      corf=555,214,410,755 corbw=50,100,100,100

# Set up the switching patterns for the polarization plates

# different grids since do not need all four combinations for calibrator
# just RR and LL are needed to track its phase
# most phase calibrators will not exhibit linear polarization, so measuring
# RL and LR is not necessary

setup name=pol  polar=$UGRID/wal.c03
```

```
setup name=polcal  polar=$UGRID/wal.c03.calib

# Set up source and calibrator information

# nchan=1 means all spectral line data will be retained
# nchan=0 means only save wideband averages

setup name=so source=$so vis=$so catalog=$UCAT/bcm.cat elevlim=20,85 \
        nchan=1 itime=$itime stop=+35 setup=pol trakopt=+chk

setup name=cal source=$cal vis=$cal elevlim=15,85 \
        nchan=0 itime=$itime stop=+5 setup=polcal trakopt=+chk

# typically, maxobs=1 for flux calibrators, we use 2 here so that
# this observation will last the duration of the source transit
# (when the source el is too high to track)
setup name=uranus source=$f vis=$f elevlim=25,85 \
        nchan=0 itime=$itime stop=+20 setup=polcal maxobs=+2 trakopt=+chk

# setup for daytime pointing
setup name=point task=xpnt source=$p elevlim=15,85 niter=1 ants=$ants

# Set up quality information
# this is needed so that the quality routine at Hat Creek can
# run once the observing is complete
setup name=quality s=$so c=$cal f=$f sendplots=n email=<address here>

#
# Observing follows ==========================================
#
set pjstop = ‘value name=pstart | cut -d= -f2‘   # Get project stop time

scan setup=tune_1mm          # Tune receivers
scan setup=mode8             # Set up correlator

# - FOR DAY OBSERVING ---
#  Note: Pointing correction is needed for day time observing at 1mm,
#        which is included in this script.

daytime:
if (‘cksrc source=sun elevlim=5‘ == n) then
  goto nighttime
  else goto continue
endif
continue:
zerolas                       # set pointing offsets to zero
scan setup=tune_3mm           # tune receivers
scan setup=point               # point on the phase calibrator
```

```
scan setup=tune_1mm              # tune receivers
scan setup=cal                   # observe the phase calibrator
scan setup=so                    # observe the source
if (‘cksrc source=sun elevlim=5‘ == y) then
  goto daytime
  else goto nighttime
endif

# - FOR NIGHT OBSERVING ---

if (‘cksrc source=sun elevlim=5‘ == n) then
  goto nighttime
  else goto daytime
endif

nighttime:
if (‘cksrc source=sun elevlim=5‘ == y) then
  goto daytime
  else goto continuen
endif
continuen:
zerolas                           # set pointing offsets to zero
scan setup=cal                    # observe the calibrator
scan setup=so                     # observe the source
if (‘cksrc source=2015+372 elevlim=84‘ == y) then
  scan setup=uranus               # observe the flux calibrator when phase cal transits
  else goto resume
endif
resume:
if ( "‘timesup start=$pjstop‘" != quit) then
  goto nighttime
  else goto end
endif

#
# End of observing ===========================================
#

end:
exit 0
```

5.2 Continuum Polarimetry Only

The script below measures continuum only in both lower and upper sidebands. Again, since it is a 1mm script, daytime 3mm pointing is included.

```
#! /bin/csh -f
#
#   Project: t846c230.m82 -  polarization observations
# amended script to do continuum only - usb does not do CO
#
#   PI’s : list them here
#
#   Note that the script will end on the source. This is a compromise
#   to avoid loops, which double the amount of time spent on the calibrator
#   during the track due to the necessity of daytime pointing at 1mm.
#
#   Contact information:
#       P. Eye
#       email address
#       (O) contact phone
#       (H)  numbers
#
#       possible LST range for script: 05:00 to 15:00
#
#       Source       = M82
#       Obs. Freq.   = Continuum, 230 GHz
#       RA(2000)     = 09 55 52.19
#       DEC(2000)    = +69 40 48.8
#       vlsr         = 203 km/s
#
#       Source and calibrator are circumpolar.
#       Polarization observations should be centered on TRANSIT for
#       sensitivity
#
#       Best LST times for this script:
#       M82:          0500-1500
#       0841+708:     0500-1500
#
#
# Setups follow     ==========================================
#

# setup to allow xscribe, the scheduling tool, to inform the observer that
# this is a 1mm polarization script
# note: the ‘‘plates’’ command should be used for polarization scripts only;
# setting plates=none for non-polarization scripts is really obnoxious at the
# telescope!
```

```
setup name=xscribe plates=1mmquarterwave

# tell the script which antennas to use
# Antenna 3 is left out because it has no 1mm receiver.
# ‘‘a’’ is the designation for Antenna 10.
set ants=12456789a

set s=m82               # source name
set p=0841+708          # phase calibrator

# Tune receivers (one for 1mm observing; one for 3mm pointing)
# One wants to do this as infrequently as possible
# 3mm setup is only used for daytime pointing
setup name=tune_1mm freq=227 iffreq=550 dopsrc=$s dopcat=$UCAT/bolatto.cat
setup name=tune_3mm freq=86.243 iffreq=-150 ants=$ants

# Set up correlator

# use the wideband mode (mode8) with all default settings for corf and corbw.
setup name=mode8 cormode=8 coptions=hanning \
      restfqs=0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
      corf=200,400,600,800 corbw=100,100,100,100

# Set up the switching patterns for the polarization plates
setup name=pol  polar=$UGRID/wal.c03
setup name=polcal  polar=$UGRID/wal.c03.calib

# Set up source and calibrator information

# grid defines the three pointings to observe in M82
# nreps=16,2 means to execute each of the 16 polarization grid sequences at each
# of the positions given in ‘‘grid’’ 2x.  The observation will be executed at the
# first spatial position with the whole polarization grid of 16 plate sequences,
# then the second and third spatial positions. The whole set of 48 will then be
# repeated again before the cal is done. This sequencing can supercede stop times
# if this so-called ‘‘grand cycle’’ of 48 takes less time.
setup name=so setup=pol source=$s catalog=$UCAT/bolatto.cat \
      grid="dra(-0.41,0,0.41),ddec(0,0,0)" nreps=16,2 vis=$s elevlim=20 \
      nchan=1 itime=23 stop=+30 trakopt=+chk

setup name=cal setup=polcal source=$p vis=$p elevlim=15,85 nchan=0 \
      itime=23 stop=+5 trakopt=+chk

# set up pointing task which will be needed for daytime observing
setup name=point task=xpnt source=$p elevlim=20,85 niter=1 ants=$ants

# Set up quality information (so data can be assessed at the telescope)
```

```
setup name=quality s=$s c=$p sendplots=n email=<address>

#
# Observing follows =========================================
#
set pjstop = ‘value name=pstart | cut -d= -f2‘ #get project stop time

# - FOR NIGHT OBSERVING -
# Note: pointing correction is needed for daytime observing at 1mm
# which is included in this script

scan setup=tune_1mm     # tune receivers
scan setup=mode8        # Set up correlator

if (‘cksrc source=sun elevlim=5‘ == n) goto nighttime
else goto daytime
endif

nighttime:
zerolas                 # set pointing offsets to zero
scan setup=cal          # observe the phase calibrator
scan setup=so           # observe the source
if (‘cksrc source=sun elevlim=5‘ == n) goto nighttime
else goto daytime
endif

# - FOR DAYTIME OBSERVING -
daytime:
if (‘cksrc source=sun elevlim=5‘ == n) goto nighttime
else goto continue:
endif
continue:
zerolas                 # set pointing offsets to zero
scan setup=tune_3mm     # tune receivers
scan setup=point        # point on phase calibrator
scan setup=tune_1mm     # tune receivers
scan setup=cal          # observe the phase calibrator
scan setup=so           # observe the source
if ("‘timesup start=$pjstop‘" != quit) goto daytime

#
# End of observing ==========================================
#

end:
exit 0
```

6 Appendix B: Data Reduction Scripts

6.1 Generation of Leakage Tables

Execution of this c-shell script assumes that one has a calibration observation of a bright, polarized source of known polarization properties. The known polarization data can then be used to fit the data and ascertain the extraneous polarizations, which are known as leakage terms.

```
#! /bin/csh -f
#
# leakagecal - modified version of autocal (M. Wright)  for polarimetry
# for calculation of leakage terms
#& bcm
#

# set some parameters:
set refant=7            # reference antenna (use: mselfcal)
set imsize=129          # image size in pixels (use: invert)
set minants=5           # minimum \# antennas for solution
set avinterval=10       # averaging interval for pol'n data

echo "**************************************************************"
echo "    Generation of leakage tables using mselfcal
echo "**************************************************************"

if($#argv<5) then
  echo " "
  echo "Usage: leakagecal source device source_line select (-ant(3)) self-cal interval
  echo " "
# usually both source and phase calibration data are reduced.
# sources appropriate for leakage table generation are bright enough
# to be self-calibrated without the need of an external phase calibrator
  echo "  source        uv-data file for source."
  echo "  device        PGPLOT device. e.g. /xw"
  echo "  source_line   MIRIAD line type for source. e.g. wide,1,1"
  echo "  select        MIRIAD data select. e.g. 'amp(0,30),-ant(3)'"
  echo "  interval      Self-cal interval (used by mselfcal)
  exit 1
endif

echo Check if uvdata files exist
if (!(-e $1)) then
  echo "  Can't find uv-data file for source."
  goto end
endif

#   move the ''start:'' line as appropriate when re-running the script
```

```
goto start
start:

echo LINELENGTH CALIBRATION
if (-e $1.lc) \rm -r $1.lc
# linecal generates a table of gains appropriate for line length correction
linecal vis=$1
# uvcat applies the gains and creates a new file with the gains applied
uvcat vis=$1 out=$1.lc

echo PLOT THE OBSERVED CALIBRATOR AMPLITUDE AND PHASE
echo Edit the data to remove amplitudes which are too high or too low.
echo Phase jumps may corrupt adjacent data.

# plot amp vs. time to look for jumps or high amps
uvplt vis=$1.lc device=$2 line=$3 axis=time,amp select=$4,’pol(RR,LL,RL,LR)’ \
          nxy=4,3 options=nocal,nopol size=2

# plot phase vs. time to look for phase jummps
uvplt vis=$1.lc device=$2 line=$3 axis=time,phase yrange=-180,180 \
          options=nocal,nopol nxy=4,3 size=2 select=$4,’pol(RR,LL,RL,LR)’

# use these commands as needed to remove high amp data
# negative on select command means to flag all except specified values
echo EDIT OUT HIGH AMPLITUDES
#uvflag vis=$1.lc line=$4 flagval=flag select=’-amp(0,2.5)’

# run a self-cal on the data for each combination of R and L
mselfcal vis=$1.lc refant=$refant line=$3 interval=$5 \
        select=$4,’pol(RR,LL)’ minants=$minants

# average the data over the interval specified above to obtain
# quasi-simultaneous measures of each combination of R and L
if (-e $1.aver) \rm -r $1.aver
uvaver vis=$1.lc interval=$avinterval line=$3 out=$1.aver \
        select=$4,’pol(RR,LL,RL,LR)’

# gpcal is the program which creates the leakage tables.
# circular must be specified, or linear input is assumed
# qusolve lets it solve for Q and U fluxes
gpcal vis=$1.aver options=circular,qusolve refant=$refant

echo "Gain table completed"
goto end
err:
echo "Some error occured; premature termination"
end:
```

6.2 Reduction of a Science Polarization Dataset

Below, we present a sample reduction script modeled after “autocal”. It handles the preliminary reduction (which is very similar to autocal), and then the averaging and leakage corrections needed for polarization data. If line data has been collected, but is limited to only a portion of a sideband, then the average of that sideband (wide,1,1 for LSB or wide,1,2 for USB) will contain line emission. In order to measure continuum in the remaining wide channels, one should make a new average of those channels.

For example, CO emission is always measured in the USB. Therefore, line=wide,1,1 gives a measure of continuum over 800 MHz in the LSB, but wide,1,2 (the USB average) contains CO emission. In the t835b230.20126 script in Appendix A, the CO is measured in the first corf of the USB. This is wide channel 11 of 18. Hence, a new USB continuum average can be made of channels 12-18 using uvaver:

uvaver vis=<source> line=wide,1,12,7 out=<source>_usb

which makes a new file called <source>_usb with one channel. It uses 7 of the original channels, starting with the 12th.

One would then run the following script three times to reduce the data: once with line=wide,1,1 on both the calibrator and source; once with line=wide,1,2 on the calibrator and line=wide,1,1 using the <source>_usb data set; and once with line=wide,1,2 on the calibrator and line=channel,xx,yyy where xx is the number of channels in the corf containing the line emission and yyy is the starting channel number in that corf.

```
#! /bin/csh -f
#
# polreduce - modified version of autocal for polarimetry
#
#  POLREDUCE is a csh script to use AUTOCAL amended for polarization data.
#  30 minute time interval to derive calibrator gains

# set some parameters:
set refant=8            # select the reference antenna
set imsize=129          # size of output image in pixels
set minants=3           # minimum antennas for phase closure (4 for amp selfcal)
set interval=30         # self-cal interval
set avinterval=5        # averaging interval

echo "**************************************************************"
echo "    Polarization Reduction using mselfcal
echo "**************************************************************"

if($#argv<7) then
  echo " "
  echo "Usage: polcal calib source device cal_line source_line select leakage"
  echo " "
  echo "  calib         uv-data file for calibrator."
  echo "  source        uv-data file for source."
```

```
  echo "  device        PGPLOT device. e.g. /xw"
  echo "  cal_line      MIRIAD line type for calibrator. e.g. wide,1"
  echo "  source_line   MIRIAD line type for source. e.g. channel,4,30,3,1"
  echo "  select        MIRIAD data select. e.g. 'amp(0,30),-ant(1)(3)'"
  echo "  leakage       table of leakage terms."
  exit 1
endif

echo Check if uvdata files exist
if (!(-e $1)) then
  echo "  Can't find uv-data file for calibrator."
  goto end
endif
if (!(-e $2)) then
  echo "  Can't find uv-data file for source."
  goto end
endif

goto start #move the "start:" command as required
start:

echo LINELENGTH CALIBRATION
if (-e $1.lc) rm -r $1.lc
if (-e $2.lc) rm -r $2.lc
linecal vis=$1
linecal vis=$2
uvcat vis=$1 out=$1.lc
uvcat vis=$2 out=$2.lc

echo ""
echo PLOT THE OBSERVED CALIBRATOR AMPLITUDE AND PHASE
echo Edit the data to remove amplitudes which are too high or too low.
echo ""

uvplt vis=$1.lc device=$3 line=$4 axis=time,amp select=$6,'pol(RR,LL)' nxy=4,3 \
           options=nocal size=2

uvplt vis=$1.lc device=$3 line=$4 axis=time,phase yrange=-360,360 options=nocal \
           nxy=4,3 size=2 select=$6,'pol(RR,LL)'

echo TAKE A LOOK AT SOURCE AMPS AS A FUNCTION OF BASELINE
uvplt vis=$2.lc device=$3 line=$5 axis=time,amp options=nocal size=2 \
           select=$6,'pol(RR,LL,RL,LR)' nxy=4,3

echo EDIT OUT HIGH AMPLITUDES
#use commands as required
#uvflag vis=$1.lc line=$4 flagval=flag select='-amp(0,10)'
#uvflag vis=$2.lc line=$5 flagval=flag select='amp(2,100)'
```

```
echo DO A QUICK AMPLITUDE SELF-CAL JUST TO SEE THE RELATIVE GAINS
AND PHASES
#note that "apriori" calibration will not work unless flux is in the database.
# 1.3mm fluxes are not.
mselfcal vis=$1.lc refant=$refant line=$4 interval=$interval select=$6,'pol(RR,LL)' \
           minants=4 options=amp,apriori,noscale

gpplt vis=$1.lc device=$3 options=gains yaxis=amp yrange=0,10 nxy=4,3

gpplt vis=$1.lc device=$3 options=gains yaxis=phase yrange=-360,360 nxy=4,3

echo EDIT OUT AMPS and PHASE JUMPS
# use these as required to flag out bad antennas, baselines or time periods
#uvflag vis=$1.lc line=$4 flagval=flag select='time(00:00:00,00:00:00)','ant()'
#uvflag vis=$2.lc line=$5 flagval=flag select='time(00:00:00,00:00:00)','ant()'

echo ""
echo RUN SELFCAL ON THE CALIBRATOR
echo ""
echo Not using on-line amplitude calibration to Jy units -- 1mm:
mselfcal vis=$1.lc refant=$refant line=$4 interval=$interval \
           select=$6,'pol(RR,LL)' minants=$minants

echo ""
echo "PLOT THE ANTENNA GAINS (again)"
echo Edit the calibrator data to remove gains which are too high or too low.
echo ""

gpplt vis=$1.lc device=$3 yaxis=phase yrange=-360,360 nxy=4,3

#uvflux can be used to estimate the flux in the calibrator. This can then be input to
#an an amplitude, apriori selfcal

uvflux vis=$1.lc line=$4

echo ""
echo PLOT THE CORRECTED AMPLITUDE AND PHASE FOR THE SELFCAL CHANNEL
echo The calibrated amplitude should be the calibrator flux density.
echo The phase should be zero. Estimate the rms phase scatter.
echo Edit both calibrator and source data to remove bad time intervals.
echo ""
uvplt vis=$1.lc device=$3 line=$4 axis=time,amp select=$6,'pol(RR,LL)' average=10

uvplt vis=$1.lc device=$3 line=$4 axis=time,phase yrange=-180,180 \
          select=$6,'pol(RR,LL)' average=10

#rerun selfcal with amps if desired
```

```
#mselfcal vis=$1.lc refant=$refant line=$4 interval=$interval \
             select=$6,'pol(RR,LL)' minants=$minants options=amp flux=1.08

#echo REPLOT GAINS AGAIN
#gpplt vis=$1.lc device=$3 options=gains yaxis=amp yrange=0,10 nxy=4,3
#gpplt vis=$1.lc device=$3 options=gains yaxis=phase yrange=-360,360 nxy=4,3
#uvplt vis=$1.lc device=$3 line=$4 axis=time,amp select=$6,'pol(RR,LL)' average=10
#uvplt vis=$1.lc device=$3 line=$4 axis=time,phase yrange=-180,180
             select=$6,'pol(RR,LL)' average=10

echo ""
echo "MAP THE CALIBRATOR"
echo The peak is the calibrator flux density, multiplied by
echo " exp(-phase_rms**2/2)"
echo ""
if (-e $1.map)  rm -r $1.map
if (-e $1.beam) rm -r $1.beam
invert imsize=$imsize vis=$1.lc map=$1.map beam=$1.beam line=$4 select=$6 sup=0
cgdisp in=$1.map device=$3 region=quarter

echo ""
echo "CLEAN THE CALIBRATOR"
echo ""
if (-e $1.clean) rm -r $1.clean
if (-e $1.cm) rm -r $1.cm
clean map=$1.map beam=$1.beam niters=200 gain=.1 out=$1.clean

restor map=$1.map beam=$1.beam model=$1.clean out=$1.cm
if ($status != 0) goto err

cgdisp in=$1.cm device=$3 region=quarter

echo ""
echo TRANSFER THE GAINS TO THE SOURCE
echo ""
gpcopy vis=$1.lc out=$2.lc mode=copy options=nopol
if ($status != 0) goto err

echo ""
echo AVERAGE THE POL DATA TO SAMPLE L AND R
echo ""
if (-e $2.aver) \rm -r $2.aver
uvaver vis=$2.lc select=$6 line=$5 interval=$avinterval out=$2.aver
if ($status != 0) goto err

echo ""
echo ADD LEAKAGE TABLE CORRECTIONS
echo ""
```

```
gpcopy vis=$7 out=$2.aver mode=copy options=nocal,nopass
if ($status != 0) goto err

# for continuum data, after uvaver is run, only wide,1,1 in the $2.aver file
# wide,1,1 must be changed if line data
echo ""
echo PLOT THE CORRECTED AMPLITUDE AND PHASE FOR SOURCE
echo Edit the source data to remove bad time intervals.
echo ""
uvplt vis=$2.aver device=$3 line=wide,1,1 axis=time,amp select=$6 average=10

uvplt vis=$2.aver device=$3 line=wide,1,1 axis=time,phase yrange=-180,180 \
             select=$6 average=10
if ($status != 0) goto err

# use polcombine script to make a map of these data

goto end

err:
echo "Some error occured; premature termination"
end:
```

7 Appendix C: Combine Data for Stokes Vectors and Polarization Percentage/Position Angles

The next step is to make a polarization map of the source. This may be done for each individual data set, or many tracks may be combined to make a single map. Some iteration is required to use the “impol” routine, since it needs to know the rms of the I,Q, and U maps before generating the vectors. Generally, the rms in the Q and U maps can be estimated from the V map, which is devoid of signal for linearly polarized sources.

```
#! /bin/csh -f
#
#  polcombine - script to create polarization maps
#  & bcm

if($#argv<3) then
  echo " "
  echo "Usage: polcombine imsize source cell"
  echo " "
  echo "  imsize        #image size wanted
  echo "  source        #uv-data file for source."
  echo "  cell          #cell size (e.g. 1" for C array; 3" for D array)
  exit 1
endif

goto start
start:

# vis= all the files you want  included in the map
# for mosaicked continuum data, use ‘‘options=mfs,mosaic,double,systemp"
# for single pointing continuum data, use ‘‘options=mfs’’
# change the line option for spectral line data

echo ""
echo MAP THE SOURCE
echo ""
if (-e $2.Imap)  rm -r $2.Imap
if (-e $2.Qmap)  rm -r $2.Qmap
if (-e $2.Umap)  rm -r $2.Umap
if (-e $2.Vmap)  rm -r $2.Vmap
if (-e $2.beam) rm -r $2.beam
invert imsize=$1 vis=./LSB/$2.aver,./USB/$2.aver options=mfs,mosaic,double,systemp \
              stokes=i,q,u,v map=$2.Imap,$2.Qmap,$2.Umap,$2.Vmap beam=$2.beam \
              line=wide,1,1 select=’pol(rr,ll,rl,lr)’ sup=0 cell=$3

cgdisp in=$2.Imap device=/xs region=quarter
```

```
# measure the rms in the I map before cleaning
imlist in=$2.Imap options=stat

# clean the source down a cutoff of  1-2 sigma rms.
# for single beam data, use ‘‘clean" instead of ‘‘mossdi" which is for mosaics
echo ""
echo CLEAN THE SOURCE
echo ""
if (-e $2.clean)  rm -r $2.clean
if (-e $2.Icm) rm -r $2.Icm
mossdi map=$2.Imap beam=$2.beam niters=2000 gain=.1 out=$2.clean cutoff=0.03

echo ""
echo RECONSTRUCT THE MAP
echo ""
restor map=$2.Imap beam=$2.beam model=$2.clean out=$2.Icm
if ($status != 0) goto err

cgdisp in=$2.Icm device=/xs region=relpix,'box(-80,-60,80,60)'

# measure the rms in the cleaned map
imlist in=$2.Icm options=stat

# measure the rms in the Stokes V map (should be empty if source is linearly polarized)
imlist in=$2.Vmap options=stat

\rm -r $2.usb.polm
\rm -r $2.usb.polm_err
\rm -r $2.usb.pa
\rm -r $2.usb.pa_err
\rm -r $2.usb.poli
\rm -r $2.usb.poli_err
impol in=$2.usb.Qmap,$2.usb.Umap,$2.usb.Icm poli=$2.usb.poli,$2.usb.poli_err \
               polm=$2.usb.polm,$2.usb.polm_err pa=$2.usb.pa,$2.usb.pa_err \
               sigma=0.013,0.04 sncut=2,3 options=zero
#sigma=rms is Q(U), then I

# poli and poli_err - polarized intensity maps
# polm and polm_err - polarized percentage maps
# pa and pa_err  - polarization position angle maps

echo ""
echo DISPLAY THE MAP
echo ""
cgdisp in=$2.usb.poli,$2.usb.Icm,$2.usb.polm,$2.usb.pa type=p,c,amp,ang \
             region=quarter slev=a cols1=7 device=/xs \
             options=mirror,beambl labtyp=hms,dms  csize=0.85 lines=2,3,3 vecfac=5,1,1
```

```
goto end

err:
echo "Some error occured; premature termination"
end:
```

To extract the polarization data from MIRIAD map formats, use the “imtab” command on whichever maps you need: intensity, Stokes Q, Stokes U, Stokes V or polarized intensity, fractional polarization or position angle. These data files can then be combined with awk or paste.

Acknowledgements: Thanks to R. Forster, G. Bower, S.-P. Lai and M. Wright for helpful suggestions on this memo, and their various scripts which were invaluable for my polarization projects. R. Rao is acknowledged for contributing his walgen.f program and helpful discussions about BIMA polarimetry.