Circular Polarization User's Guide

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1 Introduction

This document discusses the scheduling and data-processing of ATCA circular polarization observations.

The procedures presented should allow you to obtain circular polarization measurements with precisions of $\sigma_{V/I} \sim 0.01\%$ in favourable conditions; the methodology outlined in this document was derived from observations of strong, compact sources at 6 cm, and may not be ideal or even appropriate for other observations (see Appendix A).

These comments are based on the investigations described in Rayner (2000), which are summarised in Rayner *et al.* (2000). This document does not, however, discuss the circular polarization error-budget. The derivation of the circular polarization error budget will be published in a separate paper, and a MIRIAD task will hopefully appear to simplify the calculation.

2 Scheduling

2.1 The leakage calibrator

For circular polarization experiments, it is critical to accurately calibrate the instrumental polarization leakages and xy-phases. These must be determined from an observation of a calibrator source. There are two options here, so *before* the experiment, you should consider your calibration requirements.

If you are *absolutely sure* that your target source is not linearly polarized, then a weakly-polarized calibrator source (eg. PKS 1934–638, or any source from ATCAT) will be fine. If, however, the target source is likely to have a few percent linear polarization, it is important to observe a specially selected *leakage calibrator*, which should be unresolved and *must* have a few percent linear polarization.

The issue here is that there are three *degrees of freedom* in leakage solution obtained from a weakly-polarized calibrator (Hamaker *et al.*, 1996; Sault *et al.*, 1996), and two of them cause leakage of linear polarization into circular at about the $\Delta V/I \sim 0.1 - 0.2\%$ level. Given that AGN typically have only $V/I \sim 0.1 - 0.2\%$ circular polarization anyway (Weiler and

De Pater, 1983; Rayner *et al.*, 2000), an error of that magnitude can be very serious. These degrees of freedom can be constrained from an observation of a strongly-polarized calibrator, as discussed below.

So in general, for circular polarization calibration, you should observe a leakage calibrator, as was done for the calibration example below. The best leakage calibrators I know (for 6 cm observations!) are PKS 0426–380, PKS 0451–282, PKS 0823–500, PKS 1514–241, B1908–202 and PKS 2005–489. Many of the ATCAT sources must be suitable leakage calibrators, but the lack of high-quality polarization data for southern sources means you will probably have to do some research to confirm a source's suitability. The ATCA SAX blazar monitoring programme (Hayley Bignall and Tasso Tzioumis) should provide high-quality, interferometer-resolution, linear polarization data for a large sample of potential leakage calibrators. If you're desperate, looking up calibrators in the ATCA positions database[1] and e-mailing the relevant principal investigator normally yields a result.

Note that the leakages only need to be determined once, for each frequency; you do not need to solve for the leakages individually for each source as you might do, for example, for phase calibration. The results of Rayner (2000, Chapter 6) suggest this is not even necessary to solve for the leakages every day. Realistically, higher-quality results will be obtained if the leakage calibrator is near the target source, and observed concurrently. Quite often the phase-calibrator will be suitable to use as a leakage calibrator. Also, if the target source is a non-IDV, highly-polarized point source, you can just run GPCAL on the target to solve for the leakages and target circular polarization all in one go!!

On a more practical note, because circular polarization observations are (justifiably) viewed with great scepticism, your resulting publication will be received much more favourably if you have observed several calibrators and can show that, regardless of which was used to obtain the leakages, the circular polarization of the target source was the same. Also, working out why the results are not the same is an excellent way of finding out what is really going on.

2.2 Parallactic angle

For circular polarization work, the observations of the leakage calibrator must cover a wide range of parallactic angle χ. If they do not, the MIRIAD task GPCAL cannot unambiguously disentangle the leakages from the source linear polarization (Conway and Kronberg, 1969). This is especially true when solving the "strongly polarized" equations with a leakage calibrator (Sault *et al.*, 1996). Actually, the requirement is really that the observations have good coverage of $cos(2\chi)$ and $sin(2\chi)$, because the XY and YX correlations are functions of $cos(2\chi)$ and $sin(2\chi)$ (eg. Sault *et al.*, 1991). The easiest way to see what this means is to use the MIRIAD task PARAPLOT. For example, for PKS 1519–273, use:

```
Task:   paraplot
lat     = -30.313445
elev    =
dec     = -27.3
device  = /xs
```

---

[1] http://www.atnf.csiro.au/observers/dbases.html

the output from which is shown in Figure 1. Most of the variations in $cos(2\chi)$ and $sin(2\chi)$ occur in the 1 hour spanning transit. For sources with declination further north or south of $-30°$, the functions cover a much wider range of hour-angle.

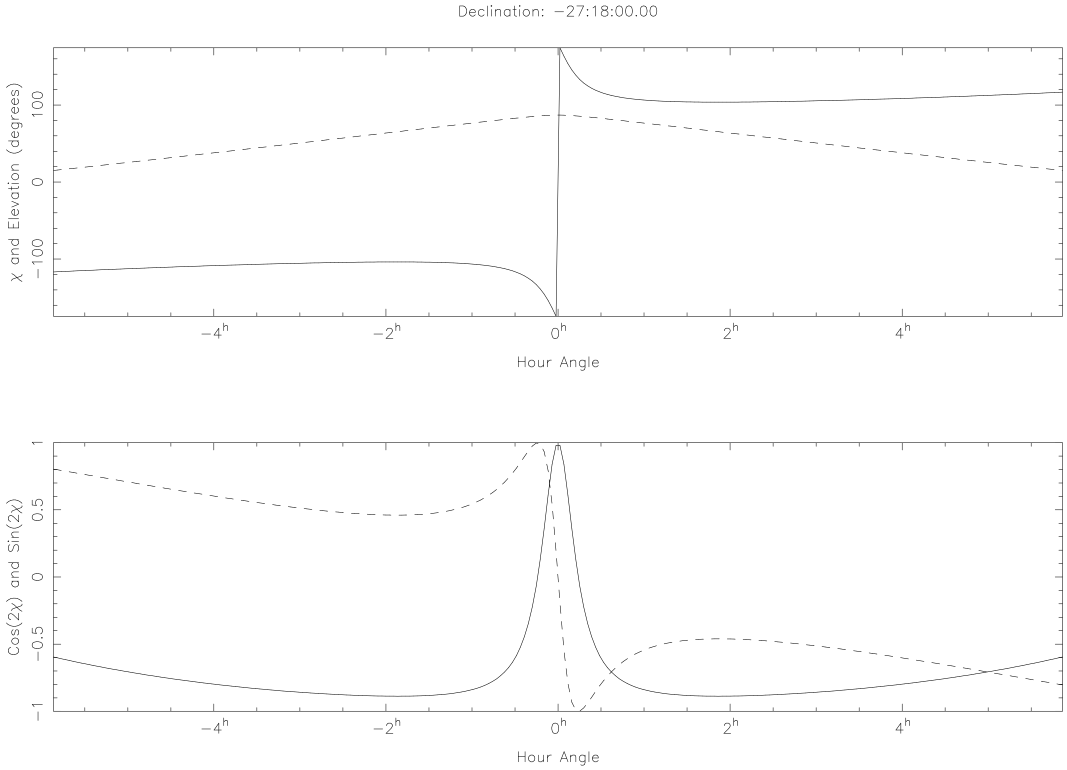

Figure 1: The parallactic angle χ, elevation, and the functions $cos(2\chi)$ and $sin(2\chi)$ as a function of hour angle for the source PKS 1519–273, as plotted by PARAPLOT. Most of the variation in $cos(2\chi)$ and $sin(2\chi)$ occurs in the hour across transit.

Observationally, the implication is that, if your schedule includes sources which pass within a few degrees of the zenith, you shouldn't use a simple, cycling schedule. You need to write a schedule to observe these sources more often as they transit. "Local knowledge" suggests that six well-spaced (in parallactic angle) cuts is adequate to obtain a good leakage solution, but observe more if time permits. Do not skimp on parallactic angle when scheduling or requesting time! Experience suggests that something is going to break at sometime during the observation[2]; you might as well be prepared for it.

As an aside, none of this would probably be mentioned if it weren't that three of the most variable and interesting AGN in the southern sky — PKS 1519–273, PKS 1921–293 and PKS 1034–293 — all transit at the ATCA very close to zenith.

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[2] Or your supervisor might beg some time to look for aliens. Don't laugh; it happened!

2.3 Setting the zero-point with a PKS 1934–638 observation

For circular polarization observations of strong sources, a long observation of PKS 1934–638 may be required. The source PKS 0823–500 is fine for the initial array calibration (CACAL), but you *must* observe PKS 1934–638 to set the circular polarization zero-point.

The error in a circular polarization image is estimated using Equation 1 of Rayner *et al.* (2000), where it was claimed that:

$$\sigma_{V/I}^2 = \sigma_t^2 + \sigma_c^2 + \ldots \tag{1}$$

where the terms σ_t and σ_c represent the precision of the target and primary calibrator observations, respectively. Formally:

- σ_t is given by

  $$\sigma_t = \frac{rms}{I}\bigg|_{\text{target}} \tag{2}$$

  where *rms* is the *rms* of the Stokes V clean-residual image in a small region about the target source, and I is the peak flux-density of the target source. The term incorporates contributions from both system-noise and any residual non-physical artifacts.

- σ_c is given by

  $$\sigma_c = \frac{rms}{I}\bigg|_{\text{primary}} \tag{3}$$

  where *rms* is the *rms* of the Stokes V image of the ATCA primary calibrator PKS 1934–638, and I is the flux-density of PKS 1934–638. This term represents the precision with which the zero-point has been measured for a particular observation. The measured σ_c is usually close to what would be expected from system noise alone.

The relevant point is that the precision of a circular polarization observation may be limited by the precision of the PKS 1934–638 observation, rather than the precision of the target observation. For observations of IDV sources, this is never a problem, as the maximum integration time on target is only a few minutes. But for a full synthesis it may be important, especially if you are re-processing old data to get the circular polarization and have only observed PKS 1934–638 for a minute.

As a rough guide, for observations of sources with peak flux density $S_{6cm} \sim 1$ Jy, observe PKS 1934–638 for ~ 5 minutes three times per synthesis.

2.4 Offset the phase centre from the source

All sources should be offset from the array phase centre, so that any artifacts due to DC terms in the correlator output will not corrupt the image of the source. Correlator DC terms are extremely rare for ATCA data — if some equipment failure introduces a DC error you can usually see it in the visibilities if you've done even a half-decent calibration — but it seems to be pretty well entrenched into the collective subconscious, and the path of least resistance is to offset all your sources from the phase centre. Unfortunately, there isn't (as of last time I complained about it) a simple way to offset the phase centre for ATCA observations. Instead, the usual practice is to add an offset to the source co-ordinates in the schedule, which has the effect of offsetting both the phase and the pointing centre. An offset of 20 arcsec is typical for 6 cm observations.

This is fine for total-intensity experiments, but for circular polarization experiments it is important to observe sources at the pointing centre so that the experiment is not corrupted by the primary beam polarization response. This is especially important for observations at 13 cm and 3 cm. So for circular polarization experiments, if you add an offset — say -20 arcsec — to the declination of all the sources, use:

```
PntCntrOffset=0,20
```

in SCHED to move the primary beam centre away from the phase centre and back onto the source. Silly, but it works.

It is important to offset *all* the sources in your schedule, *including* the target, phase calibrators, leakage calibrators and even the primary calibrator PKS 1934–638. If you don't offset the calibrators, DC terms in the calibrator observations can propagate through to the target sources during calibration. However, you shouldn't use an offset PKS 1934–638 or PKS 0823–500 observation for initial array calibration with CACAL, and so you will probably want a separate setup schedule. When observing PKS 1934–638 with an offset, it pays to give the source name a "o" suffix or similar, which prevents UVSPLIT from lumping your setup data in with the primary-calibration data:[3]

```
Source Name=1934-638o
```

A final side-effect is that SCHED will probably assign

```
CalCode=C
```

(ie. calibration source flag) to any source loaded from `AT.CAT` or `VLA.CAT` and, if you then offset the source coordinates, ASSISTANCE will spend the rest of the night complaining about the phases. For peace-of-mind, turn it off:

```
CalCode=
```

2.5 Reference pointing

The multi-frequency circular polarization observations described in Rayner (2000, Chapter 9) showed significant calibration errors for the 3 cm and 13 cm bands. Other high-precision, multi-band experiments, however, have showed no such errors.

Recent investigations strongly suggest that these errors are due to systematic pointing errors. This means that a significant improvement in the precision of 3 cm circular polarization observations can be obtained by using "reference pointing" mode. A comprehensive description of reference pointing is located at http://wwwnar.atnf.csiro.au/operations/ref_pointing.html.

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[3] A better trick is to close the correlator file immediately after setup, but I always forget

Note that the use of reference pointing will require sources which have not been offset from the phase-centre. Is that schedule file starting to look pretty crowded?

Reference pointing is unlikely to assist 13 cm observations, because of the larger beam size. This both reduces the magnitude of off-axis effects, and limits the precision which reference-pointing can attain. The circular polarization response of the ATCA at 13 cm has not been thoroughly investigated.

2.6 Turret rotations

As was discussed in Rayner (2000, Section 5.3), errors in the antenna feed-turret positioning can cause errors in circular polarization observations. What appears to happen is that, if the turret is rotated to change from the 3/6 cm horn to the 13/20 cm horn, it does not lock precisely into position. In the worst case observed, the error was bad enough to prevent the MIRIAD calibration routines from converging. Thus, if possible try and schedule 3/6 cm and 13/20 cm observations separately, rather than interleaved.

In some cases, however, it is impossible to observe 3/6 cm and 13/20 cm on different days eg. circular polarization observations of intraday variable sources. Certainly, multi-frequency, turret-rotating experiments have been successfully conducted (eg. Macquart *et al.*, 2000; Fender *et al.*, 2000) but if you decided to do this, you're on your own. To minimise the effect of turret rotations, make sure that the turrets are not rotated while the antennas are at high elevation ($\gtrsim 70°$?).

3 Data processing

This section describes the steps required to calibrate circular polarization data in MIRIAD (Sault *et al.*, 1995). This section assumes you are familiar with data processing in MIRIAD[4], and doesn't address such tasks as flagging bad data, examining gains and visibilities etc.

3.1 Initial processing

3.1.1 atlod

The data are loaded into MIRIAD using fairly standard options:

```
Task:   atlod
in      = /data/RPFITS/*.c745
options = birdie,xycorr,reweight
out     = c745.uv
```

The "rewieght" and "xycorr" options are essential.

3.1.2 transfix

Next, the visibilities have to be corrected for the effect of field rotation due to antenna pointing errors (Kesteven, 1997). The pointing model parameters are redetermined after each array reconfiguration, but are stored on the machine Leon at Narrabri in the file `at$log:pparams.log`. Wade through `pparams.log`, until you come to the last "New global solution" table before the date of your observation. In this example, the observations were made on 30 September – 01 October, 1999, so the appropriate table is:

`pparams.log`:

```
.
.
5  -12.0,   14.0,  -12.0,   52.0,  -73.0,    0.0,  -43.0,    0.0,    0.0,  105.0,    0.0,
6   -5.0,   48.0,    0.0,  121.0,  -89.0,   43.0,  -35.0,   -5.0,   12.0,   51.0,    0.0,
!a    ax      ay      ey      fx      fz      ea      ee      ca      sa   ce_dz      se
! Stations:  14 15 16 17 20 37
!  5-OCT-99 17:33:11 AEST ; Pointing zeroed


1  -20.0,   24.0,    0.0,  406.0,  -11.0,  -73.0,  -44.0,    0.0,    0.0,  105.0,    0.0,
2    7.0,   28.0,    0.0,  -10.0,   12.0,  -72.0,  -44.0,    0.0,    0.0,  105.0,    0.0,
3   -2.0,   21.0,    0.0,   22.0,    0.0,  -81.0,  -39.0,    0.0,    0.0,  105.0,    0.0,
4  179.0,   10.0,    0.0,   92.0,  -72.0, -305.0,  -44.0,    0.0,    0.0,  105.0,    0.0,
5  -14.0,   -3.0,  -12.0,   52.0,  -73.0, -132.0,  -43.0,    0.0,    0.0,  105.0,    0.0,
6   -5.0,   48.0,    0.0,  121.0,  -89.0,   43.0,  -35.0,   -5.0,   12.0,   51.0,    0.0,
!a    ax      ay      ey      fx      fz      ea      ee      ca      sa   ce_dz      se
! Stations:   3 11 16 30 34 37
!  9-SEP-99 20:26:03 AEST ; New global solution
```

---

[4] If not, first consult the *Miriad User's Manual (Sault and Killeen, 1999)*

```
1  -20.0,    19.0,    0.0,  404.0,  -11.0,  -68.2,  -44.0,     0.0,     0.0,  105.0,    0.0,
2    6.0,    28.0,    0.0,  -15.0,   12.0,  -77.8,  -44.0,     0.0,     0.0,  105.0,    0.0,
3   -2.0,    20.0,    0.0,   16.0,    0.0,  -77.4,  -39.0,     0.0,     0.0,  105.0,    0.0,
.
.
```

Copy the table to a local file (here `pparams_990909`) – omit the trailing commas:
`pparams_990909`:

```
1  -20.0,    24.0,    0.0,  406.0,  -11.0,  -73.0,  -44.0,     0.0,     0.0,  105.0,    0.0
2    7.0,    28.0,    0.0,  -10.0,   12.0,  -72.0,  -44.0,     0.0,     0.0,  105.0,    0.0
3   -2.0,    21.0,    0.0,   22.0,    0.0,  -81.0,  -39.0,     0.0,     0.0,  105.0,    0.0
4  179.0,    10.0,    0.0,   92.0,  -72.0, -305.0,  -44.0,     0.0,     0.0,  105.0,    0.0
5  -14.0,    -3.0,  -12.0,   52.0,  -73.0, -132.0,  -43.0,     0.0,     0.0,  105.0,    0.0
6   -5.0,    48.0,    0.0,  121.0,  -89.0,   43.0,  -35.0,    -5.0,    12.0,   51.0,    0.0
```

and then apply the corrections using TRANSFIX:

```
Task:   transfix
vis     = c745.uv
pparams = @pparams_990909
out     = c745_t.uv
```

3.1.3 uvedit

If you offset the source coordinates from their actual positions, as described above, the sources will still appear at their correct co-ordinates in the images. The source will not, however, be at the centre of the image, because the image centre is by default the array phase centre. This might not be a problem for the target source, but it *is* a problem for the calibrator sources because GPCAL will assume the source is at the phase centre. If you offset the coordinates of all sources equally, then you can artificially move them all to the phase centre with:

```
Task:   uvedit
vis     = c745_t.uv
dec     = 20
out     = c745_c.uv
```

This, of course, moves any DC artifact 20 arcsec too.

3.1.4 uvsplit

That's all that can be done for the data-set as a whole; easiest thing now is to follow standard procedure and split the data into separate source/frequency datasets:

```
Task:   uvsplit
vis     = c745_c.uv
```

3.2 Primary calibration

Typically, `uvsplit` produces a large number of files, of which we'll deal with only three:

- `1934-638o.4800`, the primary calibrator.
- `j1911-2007.4800`, the leakage calibrator, and
- `1320-446o.4800`, the target source.

If you changed the source name for the offset 1934–638 observations, there's a slight hitch; the MIRIAD bandpass-calibration routine MFCAL has a table of calibration sources with known spectra, but 1934–638o won't be in included. To change the source name to something MFCAL can recognise:

```
Task:   puthd
in      = 1934-638o.4800/source
value   = 1934-638
```

Then the real calibration process begins. Solve for the bandpass and the initial gain and leakage solutions in the standard way, using:

```
Task:   mfcal
vis     = 1934-638o.4800
refant  = 3
minants = 3
interval= 1
```

followed by:

```
Task:   gpcal
vis     = 1934-638o.4800
refant  = 3
minants = 3
tol     = 0.0001
interval= 0.1
options =
```

With no options, GPCAL solves using the "weakly polarized" equations – this is the best that can be done with an unpolarized source. Note that it is this step sets the circular polarization zero-point, which GPCAL assumes is $V = 0$ for PKS 1934–638.

The option "xyvary" is commonly used with GPCAL, but (provided you used `options= xycorr` in `atlod`) there seems no justification for this (see Rayner, 2000, Section 6.2.1). It won't hurt, though, if you're religiously committed to it.

3.3 Solving the "strongly polarized" equations

Now it's time to use that leakage calibrator to accurately determine the instrumental leakages, by solving the "strongly polarized" equations (Sault *et al.*, 1996). First, copy the initial gain and leakage solutions from the primary to the leakage calibrator:

```
Task:   gpcopy
vis     = 1934-638o.4800
out     = j1911-2007.4800
```

The following is then used to solve the "strongly polarized" equations:

```
Task:   gpcal
vis     = j1911-2007.4800
refant  = 3
minants = 3
tol     = 0.0001
interval= 0.1
options = qusolve,vsolve,xyref,polref
```

If the source is not sufficiently linearly polarized to solve the strongly polarized equations, GPCAL will report a:

```
### Warning:  Turning off XYREF/POLREF for this iteration
```

message during every iteration[5]. If this occurs, you'll have to try another leakage calibrator – you did observe more than one, didn't you?

Using GPCAL on a leakage calibrator to solve the strongly polarized equations can corrupt the zero-point, which was set by running GPCAL on PKS 1934–638 (see Rayner, 2000, Section 5.5 for the gory details). The resultant error is typically $\Delta V/I \lesssim 0.1\%$. If this level of precision is required, then you must copy the newly determined "absolute" gains and leakages from the leakage calibrator back to the primary calibrator, and then go through the process again:

```
Task:   gpcopy
vis     = j1911-2007.4800
out     = 1934-638o.4800

Task:   gpcal
vis     = 1934-638o.4800
refant  = 3
minants = 3
tol     = 0.0001
interval= 0.1
options = noxy
```

---

[5] Do not worry if this message is reported for just the first iteration

The `options=noxy` is used to preserve the xy-phase determined from the solution to the strongly polarized equations, although even if `options=noxy` is omitted, GPCAL is sufficiently clever that it recognises the presence of an xy-phase term it cannot solve for, and leaves the xy-phases alone.

```
Task:   gpcopy
vis     = 1934-638o.4800
out     = j1911-2007.4800
```

```
Task:   gpcal
vis     = j1911-2007.4800
refant  = 3
minants = 3
tol     = 0.0001
interval= 0.1
options = qusolve,vsolve,xyref,polref
```

And the polarization calibration is complete!

Finally, apply the primary calibrator gain correction. This is almost certainly unimportant for circular polarization observations, and a simple-minded bootstrap, independent of elevation, is probably good enough:

```
Task:   gpboot
cal     = 1934-638o.4800
vis     = j1911-2007.4800
```

You should now have a set of optimally-calibrated leakage and xy-phase corrections, and be ready to take on the world.

3.4 Target calibration

What you do with the target depends on whether the target is significantly resolved, whether it is strong enough to self-calibrate etc. But the essential point is; copy the bandpass, leakages and xy-phases from the leakage calibrator to the target, and then do not mess with them. Probably the safest way to do this is to copy them over with:

```
Task:   gpcopy
vis     = j1911-2007.4800
out     = 1320-446o.4800
```

and then apply them with:

```
Task:   uvaver
vis     = 1320-446o.4800
out     = 1320-446o_aver.4800
```

From here on you can image, clean and self-calibrate the total-flux and linear-polarization, and provided you do not re-solve for the bandpass, xy-phases or leakages, the circular polarization will be unaffected. For the current example, the target PKS 1320–446 is an ATCA calibrator source, so I immediately performed amplitude and phase self-calibration:

```
Task:   gpcal
vis     = 1320-446o_aver.4800
refant  = 3
minants = 3
tol     = 0.0001
interval= 0.1
options = qusolve,nopol,noxy
```

The `options=nopol,noxy` prevents GPCAL from changing the leakages or xy-phase, which preserves the polarimetric calibration. Similarly, GPSCAL should be used with `options=noxy`. Note that there is no guarantee that this procedure will give the best *linear polarization* results; that's a project for another day.

When the gain amplitudes and phases are solved to your satisfaction (very accurate gain amplitude and phase calibration isn't required for circular polarization work), you'll probably want to make a Stokes V image. For high dynamic-range observations, best circular polarization results are obtained if `options=mfs` is omitted in INVERT (see Rayner, 2000, Section 5.8). This is because GPCAL solves for the leakages and xy-phases of the bandpass as a whole, rather than for each channel. You may want to run INVERT separately for Stokes I and Stokes V.

```
Task:   invert
vis     = 1320-446o_aver.4800
map     = vmap
beam    = vbeam
line    = chan,1,1,13,1
sup     = 0
stokes  = v
```

For well-calibrated data, the highest sensitivity is obtained using "natural weighting", which corresponds to `sup=0` in INVERT. For sufficiently strong detections, the circular polarization image can be CLEANed and RESTORed.

Measure the circularly polarized flux from the Stokes V image using your favourite tool. For the current example, PKS 1320–446 is unresolved, so I simply recorded the flux-density of the brightest pixel:

```
Task:   imstat
in      = vmap
region  = arcsec,box(-2,2,2,-2)
```

Frequency (MHz)	V/I (%)	σ_z (%)
1384	+0.031	0.003
2496	+0.067	0.007
4800	+0.029	0.005
8640	-0.043	0.011

Table 1: The circular polarization zero-point for the ATCA. The listed V/I corrections must be *added* to the measured V/I for all circular polarization observations.

3.5 Zero-point correction

Finally, the circular polarization of the target source must be corrected for the circular polarization zero-point error (see Rayner, 2000, Section 5.6). GPCAL sets the zero-point by assuming $V = 0$ for PKS 1934–638, which is known to be incorrect.

This correction might be as simple as adding the appropriate correction from Table 1. For the current example, PKS 1320–446 was measured to have $V/I = -0.046\%$ at 6 cm. The appropriate correction from Table 1 is $V/I = +0.029\%$, yielding a corrected circular polarization of $V/I = -0.017\%$ for PKS 1320–446.

To obtain a zero-point corrected circular polarization image, use:

```
Task:   maths
in      = <vmap>+(0.00029*<imap>)
out     = vmap_corrected
```

And that, I think, is that. Happy observing!

References

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Appenix A: Caveats

The methodology outlined in this document was derived from observations of strong, compact sources at 6 cm, and may not be ideal or even appropriate for other observations. In particular, additional problems can be expected for deep observations of:

- highly extended sources, for which the primary beam polarization can not be ignored,
- strong, highly polarized ($m_l \gtrsim 10\%$) sources, for which calibration using a "leakage calibrator" is unlikely to determine the leakages to a precision comparable with the system noise, and
- sources with flux-densities comparable with or stronger than the primary calibrator PKS 1934–638.