Amplitude Calibration of ALMA Using Polarized Calibrators

W. D. Cotton September 14, 2011

Abstract—**An amplitude calibration technique to reduce the problems of linear polarization of the phase reference calibrator using linearly polarized feeds is presented. This technique makes use of the low intrinsic linear polarization of the thermal sources used for flux density calibration. The technique is applied to a sample ALMA dataset at 340 GHz.**

Index Terms—**ALMA amplitude calibration**

I. INTRODUCTION

CALIBRATION of interferometers with linearly polarized feeds using linearly polarized calibrators present special problems as the parallel hand correlations are sensitive to a combination of Stokes I, Q and U.

A technique for using the thermal flux density calibrator to avoid the some of the potential problems is presented and applied to sample ALMA 340 GHz observations. The techniques discussed are implemented in the Obit package ([1], http://www.cv.nrao.edu/~bcotton/Obit.html).

II. RESPONSES OF LINEARLY POLARIZED FEEDS

First order approximations to the response of aligned, linearly polarized feeds to an unresolved polarized source are the following [2] :

$$V_{XX}/(g_{X1}g_{X2}^*) \;=\; I \;+\; Qcos(2\chi) \;+\; Usin(2\chi)$$

$$V_{YY}/(g_{Y1}g_{Y2}^*) \;=\; I \;-\; Qcos(2\chi) \;+\; Usin(2\chi)$$

$$V_{XY}/(g_{X1}g_{Y2}^*) = I(D_{X1}+D_{Y2}^*)-Qcos(2\chi)+Usin(2\chi)+jV$$

$$V_{YX}/(g_{Y1}g_{X2}^*) = I(D_{Y1}+D_{X2}^*)-Qcos(2\chi)+Usin(2\chi)-jV$$

where X and Y indicate the orthogonal linear feeds, g is the gain required to calibrate the data, the D terms are the feed "leakages", χ is the parallactic angle, $j = \sqrt{-1}$ and $I, Q, U,$ and V are the Stokes parameters of the source. If the feeds are misaligned all products contain sines or cosine times Stokes I.

In order to determine the gains (g) needed to calibrate the data from observations of a celestial source from the parallel hand data, the Stokes I, Q and U are all required. Once the data are calibrated, Stokes I can be recovered from the average of the parallel hand correlations.

National Radio Astronomy Observatory, 520 Edgemont Rd., Charlottesville, VA, 22903 USA email: bcotton@nrao.edu

Manuscript received ; revised

III. CALIBRATING X/Y GAINS USING A THERMAL CALIBRATOR

Calibration at millimeter and sub-millimeter wavelengths frequently involves an unresolved quasar or blazar as a phase reference/astrometric calibrator and a thermal source of predictable flux density for the photometric calibration. Quasars are generally polarized at these wavelengths, sometimes highly so, whereas thermal sources are generally weakly polarized. This can be exploited to simplify the gain calibration using only the parallel hand correlations.

If we can assume that the gains can be factorized into two terms, one representing the time variable atmospheric opacity and antenna gain, and the other a constant value representing the effects of the electronics, then an initial calibration based on the thermal calibrator can be used to track opacity and antenna gain variations using any calibrator.

In the equations above we can replace the g_{pi} for antenna i polarization p by:

$$g_{pi} = \frac{1.0}{f_{pi}h_i^t}$$

where f_{pi} is a constant polarization specific factor and h_i^t the time variable factor not depending on polarization. f_{pi} includes most of the effects of the electronics and h_i^t the atmospheric delay and opacity and antenna gains. The parallel hand equations above then become:

$$V_{XX}f_{X1}f_{X2}^*h_1^th_2^{*t} \;=\; I \;+\; Qcos(2\chi) \;+\; Usin(2\chi)$$

$$V_{YY}f_{Y1}f_{Y2}^*h_1^th_2^{*t} \;=\; I \;-\; Qcos(2\chi) \;+\; Usin(2\chi)$$

For a time segment of data on a thermal (or other weakly polarized) source, we can set the $h_i^t = 1 + j0$, absorbing the atmospheric and antenna contributions at that time into f_{pi}, and solving these equations for f_{pi} with $Q = U = 0$.

At other times, only the polarization independent h_i^t terms are fitted from the Stokes I given by:

$$I/(h_1^th_2^{*t}) \;=\; 0.5(f_{X1}f_{X2}^*V_{XX} + f_{Y1}f_{Y2}^*V_{YY})$$

Note, the source polarization specific terms cancel in the above equation.

A. Misaligned Feeds

Preproduction ALMA 340 GHz feeds are rotated by 37.5° wrt the production feeds; several of the preproduction feeds were in use in the array at the time of the observations discussed here. The ASDM does not give the orientation of the feeds so it was necessary to determine which antennas had aligned feeds from examining the visibility spectra. A visibility
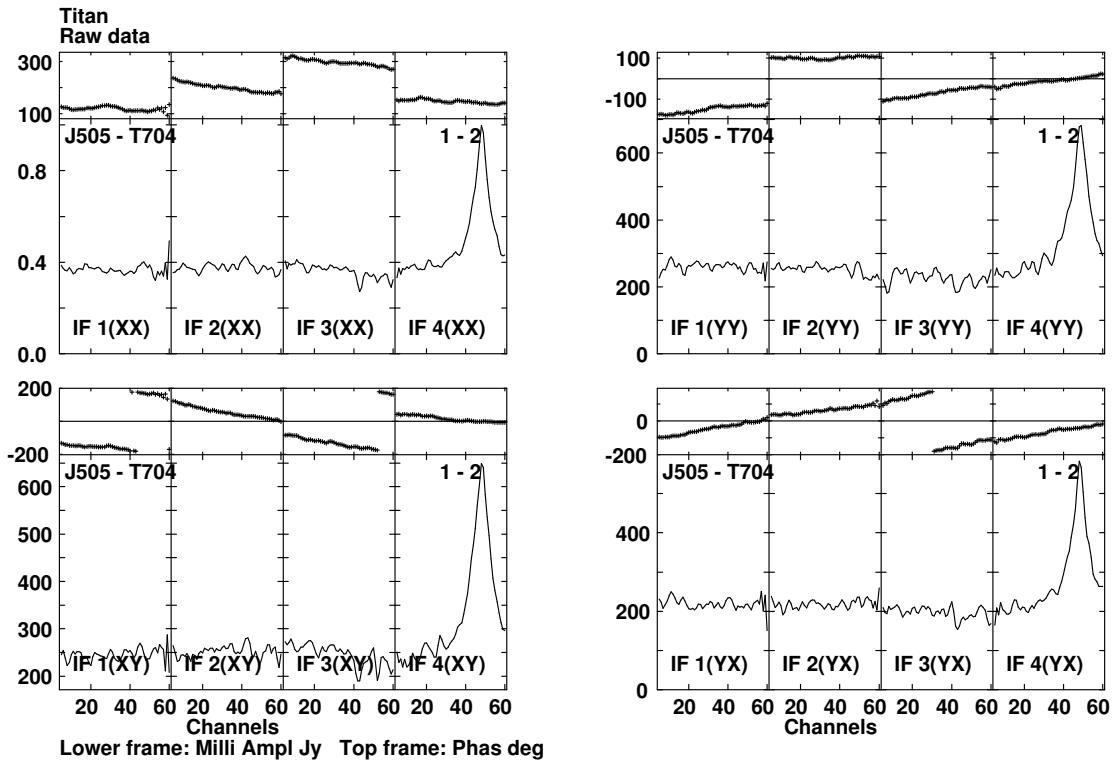
Fig. 1.   Visibility spectrum of baseline J505-T704 observing Titan with strong fringes in all correlation products indicating misaligned feeds. A strong, broad emission line is seen in the 4th sub-band.

spectrum plot of the baseline J505–T704 is given in Figure 1 showing strong fringes in all correlations whereas Figure 2 shows a similar plot for baseline T704–J510 which has only weak cross polarized fringes. This shows that antenna 1 (J505) is misaligned with the others. Antenna J505 was excluded from all subsequent analysis.

B. Calibration

The data were then calibrated into units of the apparent brightness of Titan (flux density at the top of the atmosphere as modified by atmospheric opacity. As the calibrators are potentially resolved, they were self calibrated and imaged and CC tables scaled such that the total flux density on Titan was 1.00. The processing used the following steps, the python script fragment used is given in the Appendix.

1) **Edit ASDM to give approximate position for Titan.** The position given is (0,0) which is about as far as possible from the actual position.
2) **Read data using BDFin.** Convert data into AIPS format.
3) **Edit data.** Write flagging entries in FG table 1 using UV.PFlag to remove, antenna 1, the first and last 5 channels from each sub-band and the channels in the Titan spectra with the bright emission line.
4) **Create initial CL table.** Initial CL table with all terms 1s and 0s using UV.PTableCLGetDummy.
5) **Delay calibration.** Use Obit task Calib to determine the group delays and phases using a 20 second solution interval to write SN table 1.

6) **Apply group delay calibration.** Use Obit task CLCal to apply SN table 1 to CL table 1 writing CL table 2.
7) **Bandpass calibration.** Use Obit task BPass and 3C273 to determine the bandpass corrections which are written to BP table 1. Initial calibration used CL table 2. This table was applied in all following steps.
8) **Self calibrate 3C273 and Titan.**
   a) **Calibration with point model using 3C273.** Use Calib and a point model with 1 Jy flux density for a test calibration of the data.
   b) **Apply test amplitude calibration.** Apply SN table 2 to CL table 2 writing CL table 3.
   c) **Self calibrate calibrators.** Use Obit task SCMap to determine self calibrated images of 3C273 and Titan using the test calibration. Multiple iterations of delay/phase only calibration with 20 sec. intervals were followed by a single amplitude and phase calibration with 2 min. solution interval.
   d) **Scale images.** Scale the images and CC tables for Titan and 3C273 by the inverse of the sum of the CLEAN components in the Titan image.
9) **Amplitude calibration using Titan image model.** Calib uses 2 min. amplitude and phase solutions for each polarization separately. Prior calibration used CL table 2; SN table 3 written
10) **Apply Titan calibration.** Apply SN table 3 to CL table 2 writing CL table 4.
11) **Opacity and antenna gain using 3C273.** Calib uses 2 min. amplitude and phase solutions averaging polarization. Prior calibration used CL table 4; SN table 4
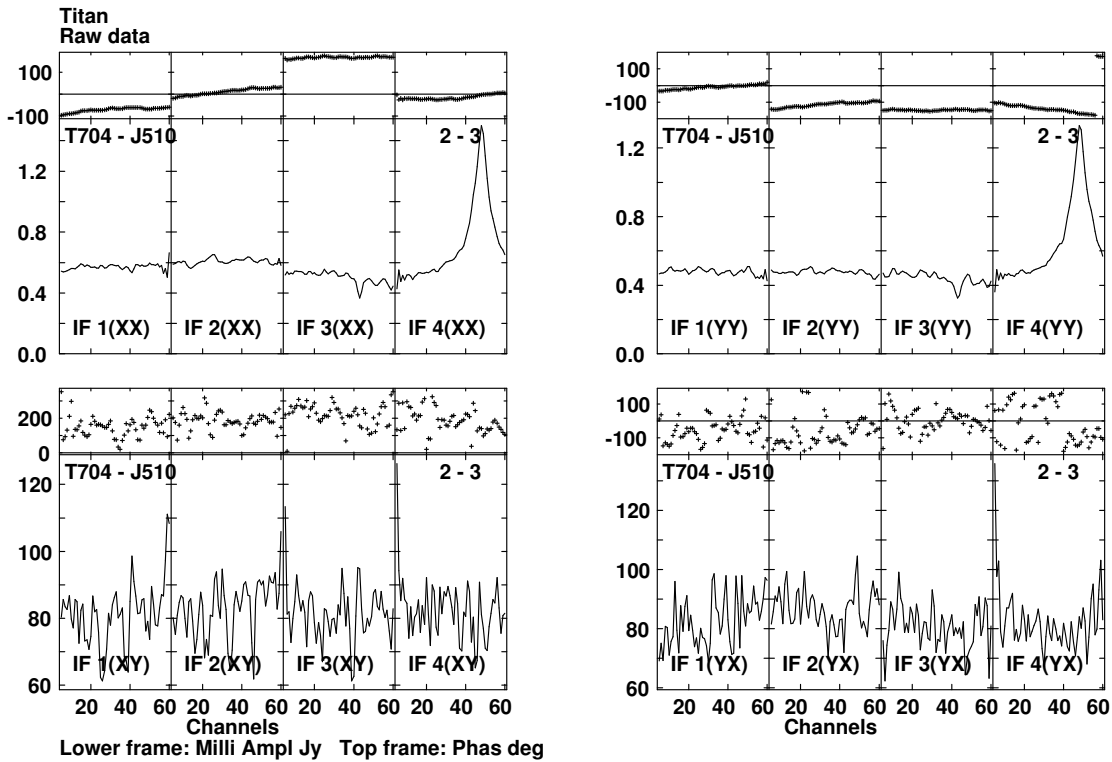
Fig. 2. Visibility spectrum of baseline T704-J510 observing Titan. Weak fringes in cross–hand correlation products indicate aligned feeds. A strong, broad emission line is seen in the 4th sub-band.

written

12) **Apply opacity/gain calibration.** Apply SN table 4 to CL table 4 writing CL table 5. Calibrated sample visibility spectra for Titan and 3C273 are shown in Figures 3 and 4.

13) **Image Target.** Use Obit task Imager to image target applying flagging, BP table 1 and CL table 5.

IV. DISCUSSION

Figures 3 and 4 show cross hand visibilities at about the 3–4% level. These are a combination of the polarized components of the signal and the leakage terms. Since these are comparable in 3C273 (assumed) polarized and Titan (assumed unpolarized) a procedure using all 4 correlations to determine the gains must also include a solution for the leakage terms. The procedure outlined above is a simplified means to the same end although it does not allow imaging the polarized emission from the target.

A position for all targets in a data set should really be given at least approximately, even for moving sources. Since the BDFs do not contain u,v,w terms, they must be computed and using (0,0) as the position can give **VERY WRONG** values. Calibration quality would be improved if the observations avoided strong emission lines such as the one seen here for Titan.

REFERENCES

[1] W. D. Cotton, "Obit: A Development Environment for Astronomical Algorithms," *PASP*, vol. 120, pp. 439–448, 2008.
[2] R. J. Sault, N. E. B. Killeen, and M. J. Kesteven, "AT Polarization Calibration," *ATCA memo 39.015*, pp. 1–12, 1991.

APPENDIX

The following python fragments give the calibration and imaging details as used in ObitTalk.

```
# Process Target data user 106
aname  = "ALMAData"
aclass = "64Ch"
adisk  = 9
aseq   = 2
delaycals = ["3C273","Titan"]
bpcal     = "3C273"
ampcal    = "Titan"
ampflux   = 1.0 # Calibrator flux density
phzcal    = "3C273"
refant    = 2
target    = "Target"

uv = UV.newPAUV("Data", aname, aclass, \
    adisk, aseq, True, err)

# New default initial cal, 20 sec
zz = UV.PTableCLGetDummy(uv, uv, 1, err, \
    solInt=0.33333)

# Drop beginning, end, Ant 1
UV.PFlag(uv, err, Ants =[ 1,0 ], \
    Reason="Bad Feeds")
UV.PFlag(uv, err, Chans=[ 1, 5], \
    Reason="End Channels")
UV.PFlag(uv, err, Chans=[60,64], \
```
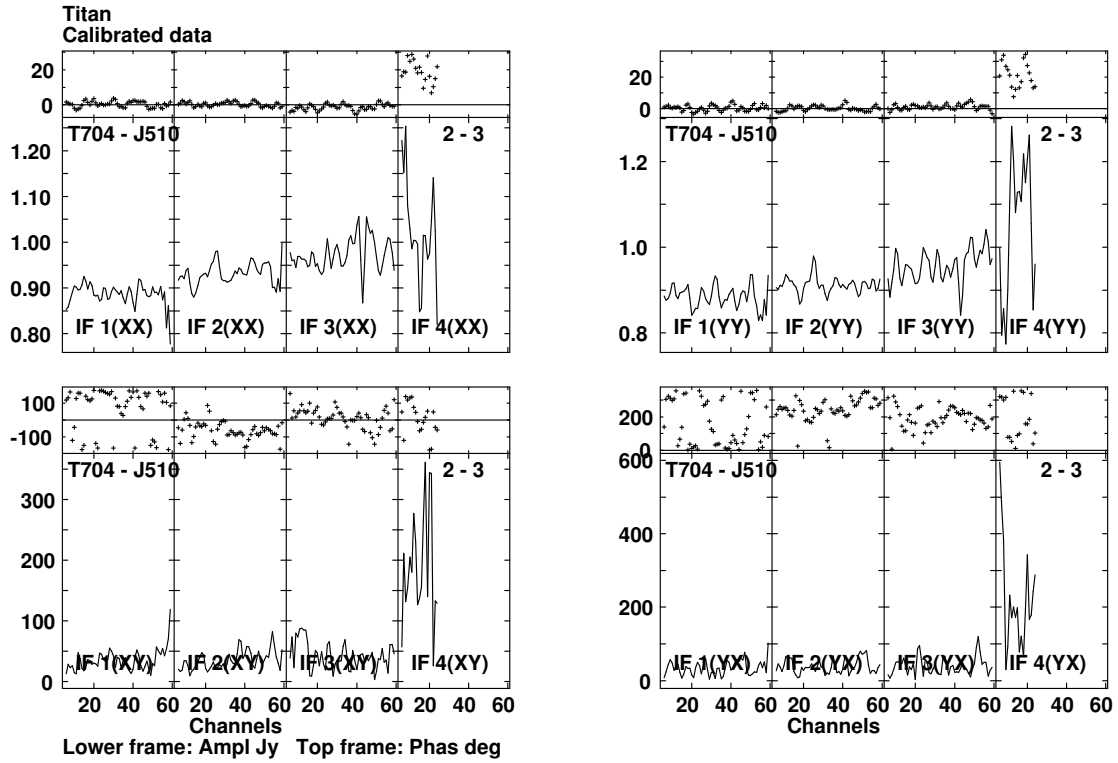
Fig. 3.   Calibrated, edited visibility spectrum of baseline T704-J510 observing Titan.
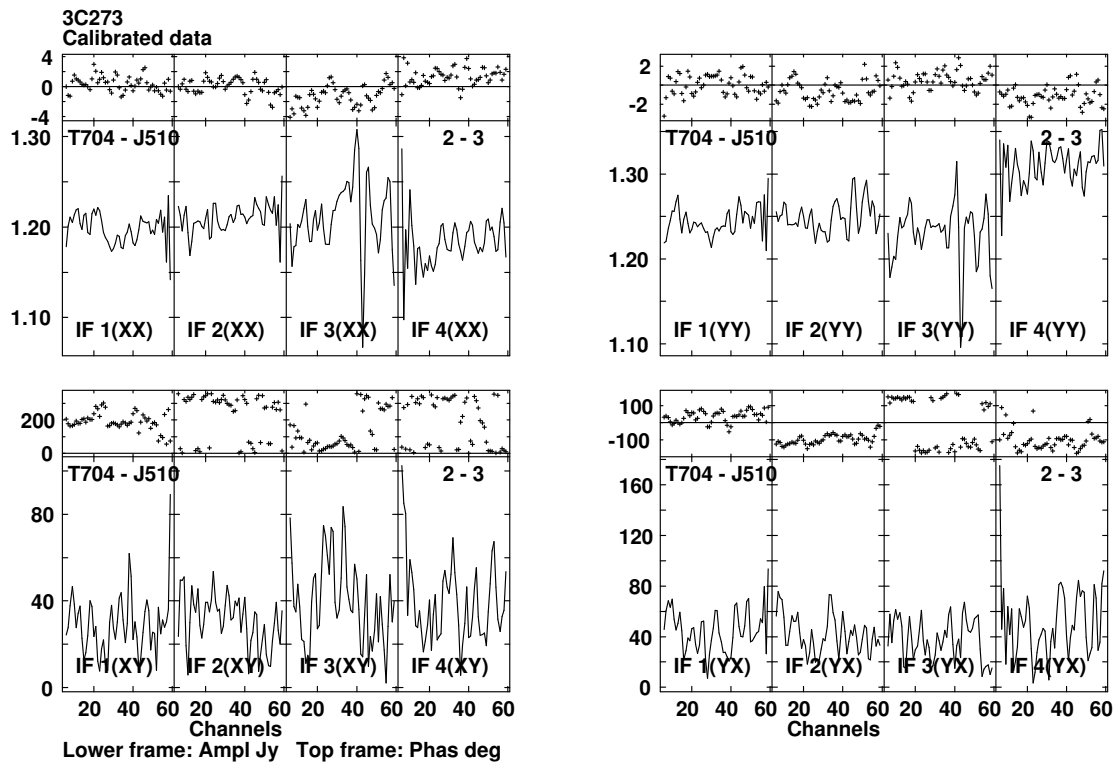

Fig. 4.   Calibrated visibility spectrum of baseline T704-J510 observing 3C273.

```
    Reason="End Channels")
UV.PFlag(uv,err,Chans=[25,64],IFs=[4,4],\
    Source="Titan",Reason="Emission line")

# Delay calibration 3C273 and Titan
calib = ObitTask("Calib");
setname(uv,calib)
calib.flagVer   = 1;
calib.modelFlux = 1.0
calib.solInt    = 0.3333;
calib.solMode   = "DELA"
calib.Sources   = delaycals
calib.refAnts   = [refant]
calib.avgPol    =  False
calib.g


# Apply
clcal = ObitTask("CLCal");
setname(uv, clcal);
clcal.refAnt  = 2
clcal.solnVer = 1;
clcal.calIn   = 1
clcal.calOut  = 2;
clcal.g



# Bandpass calibration of 3C273
bpass = ObitTask("BPass");
setname(uv, bpass)
bpass.Sources[0] = bpcal
bpass.doCalib   = 2
bpass.gainUse   = 2
bpass.BChan1    = 6
bpass.EChan1    = 60
bpass.BChan2    = 6
bpass.EChan2    = 60
bpass.ChWid2    = 5
bpass.refAnt    = refant
bpass.solInt1   = 0.3333  # phase solution
bpass.solInt2   = 5.0     # Bandpass soln
bpass.g


# Initial Amplitude cal, 3C273 = 1.000 -
# first pass
calib.flagVer   = 1
calib.doBand    = 1
calib.doCalib   = 2
calib.gainUse   = 2
calib.modelFlux = 1.0
calib.solInt    = 2.0
calib.solMode   = "A&P"
calib.Sources   = [phzcal,"","","","",""]
calib.refAnts   = [refant]
calib.avgPol    =  False  # Don't Fit ratio
calib.g


# Apply
clcal.refAnt  = refant
```

```
clcal.solnVer = 2;
clcal.calIn   = 2
clcal.calOut  = 3;
clcal.g

# Self cal Titan, 3C273,
# thereafter use images
# Only use IFs 1-3 to avoid line
sc=ObitTask("SCMap");
setname(uv,sc)
sc.Sources=[ampcal, phzcal]
sc.doCalib    = 2;
sc.doBand     = 1
sc.BIF        = 1
sc.EIF        = 3
sc.flagVer    = 1
sc.outDisk    = 9;  sc.outSeq  = 200
sc.out2Disk   = 9;  sc.out2Seq = 200
sc.FOV        = 10.0 / 3660. # 10" radius
sc.BLFact     = 1.01
sc.modelFlux  = 1.0
sc.Niter      = 100
sc.CLEANBox   = [-1,5]
sc.maxPSCLoop = 2
sc.minFluxPSC = 0.1
sc.solPInt    = 0.3333
sc.solPMode   = "DELA"
sc.maxASCLoop = 1
sc.minFluxASC = 0.5
sc.solAInt    = 5.0
sc.refAnt     = refant
sc.nThread    = 8
sc.prtLv      = 2
sc.g

# Scale image CCs
scale = 1.0/0.8764 # Scaling by sum of CCs
                   # for Titan to 1.0
inImage = Image.newPAImage("img", ampcal,\
    "IClean", 9, 200, True, err)
ImageUtil.PScaleImage(inImage, scale, err)

# Same scaling for 3C273
inImage = Image.newPAImage("img", phzcal,\
    "IClean", 9, 200, True, err)
ImageUtil.PScaleImage(inImage, scale, err)


# Redo Amplitude cal, Titan with model
calib.modelFlux = 0.0
calib.in2Name   = ampcal
calib.in2Class  = "IClean"
calib.in2Seq    = 200
calib.in2Disk   = 9
calib.nfield    = 1
calib.CCVer     = 1
calib.solInt    = 2.0
calib.solMode   = "A&P"
```

```
calib.avgPol     =  False  # Don't Fit ratio
calib.Sources    = [ampcal,"","","","","",""]
calib.refAnts    = [refant]
calib.doCalib    = 2
calib.gainUse    = 2
calib.g


# Apply - ignore last CL table
clcal.refAnt  = refant
clcal.solnVer = 3;
clcal.calIn   = 2
clcal.calOut  = 4;
clcal.g



# 3C273 with averaged poln for atmospheric
# variations
calib.in2Name    = phzcal
calib.solInt     = 2.0
calib.solMode    = "A&P"
calib.avgPol     =  True  # Force average
calib.Sources    = [phzcal,"","","","",""]
calib.refAnts    = [refant]
calib.doCalib    = 2
calib.gainUse    = 4
calib.g

# Apply
clcal.refAnt  = refant
clcal.solnVer = 4;
clcal.calIn   = 4
clcal.calOut  = 5;
clcal.g

# Image target
img=ObitTask("SCMap")
setname(uv,img)
img.Sources=[target]
img.doCalib    = 2;
img.gainUse    = 5
img.doBand     = 1
img.flagVer    = 1
img.outDisk    = 9;  img.outSeq  = 200
img.out2Disk   = 9;  img.out2Seq = 200
img.FOV        = 10.0 / 3660.  # 10" radius
img.BLFact     = 1.01
img.Niter      = 0
img.CLEANBox   = [-1,5]
img.nThread    = 8
img.prtLv      = 2
img.g
```