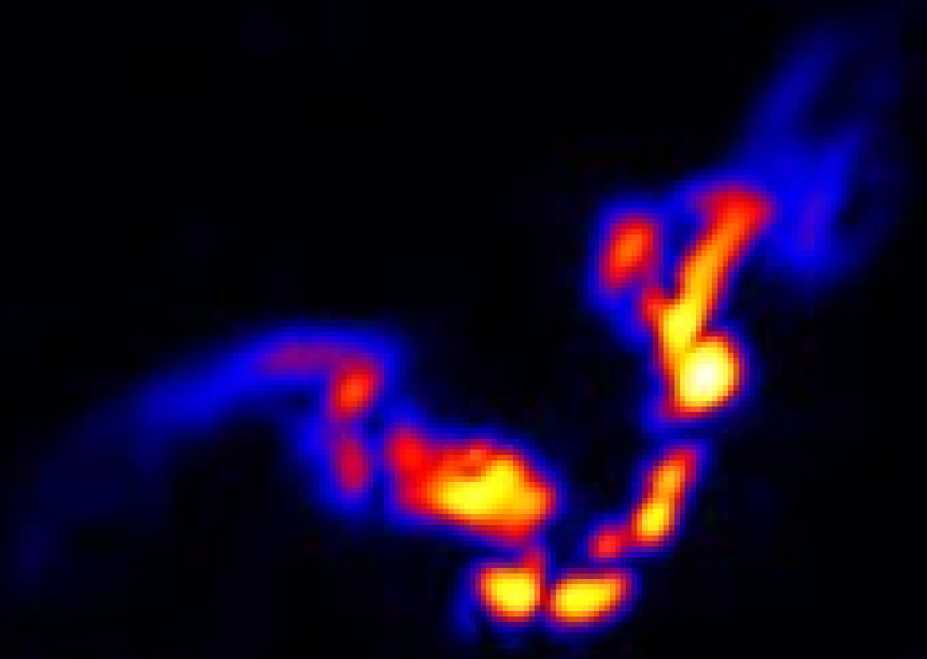


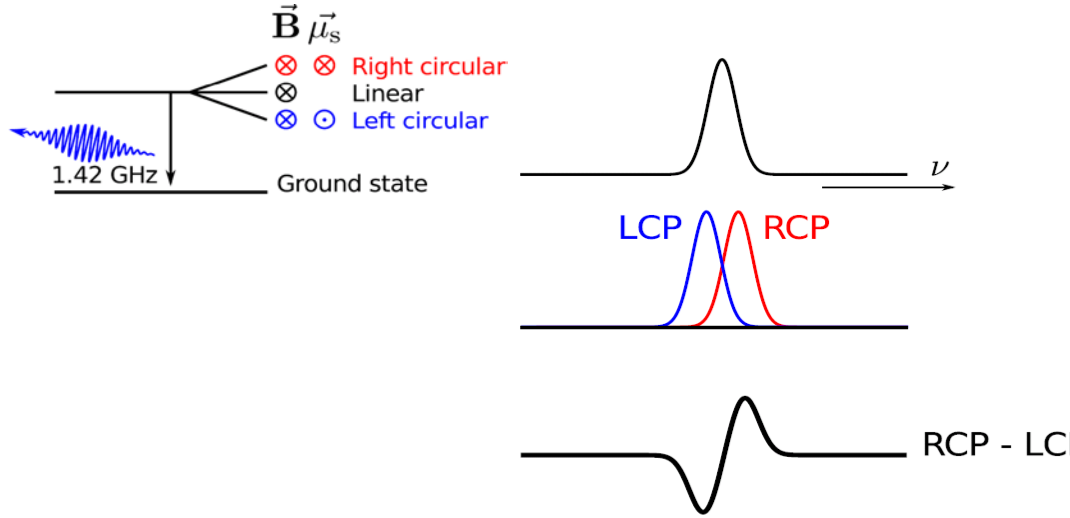
Polarization Calibration

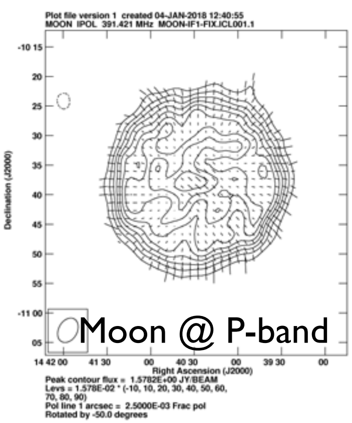
Frank Schinzel (NRAO)

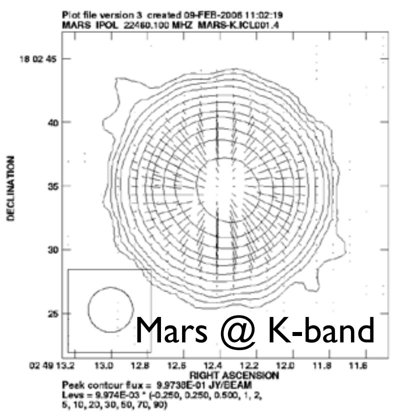
Polarized Radio Emission – Why do we care?

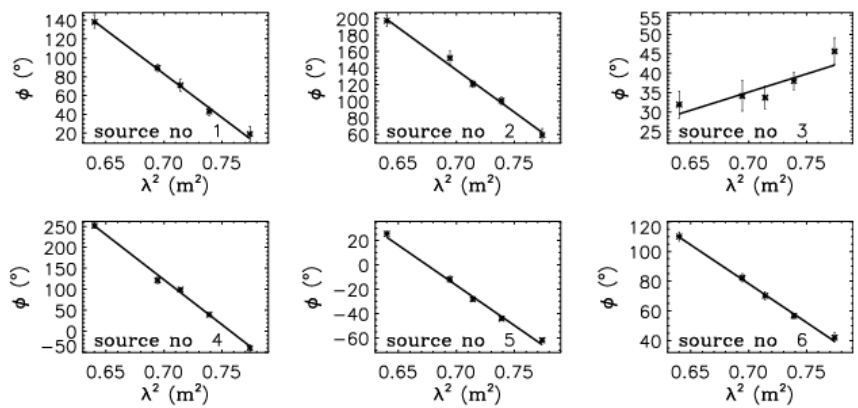
Synchrotron Emission

Zeeman Splitting







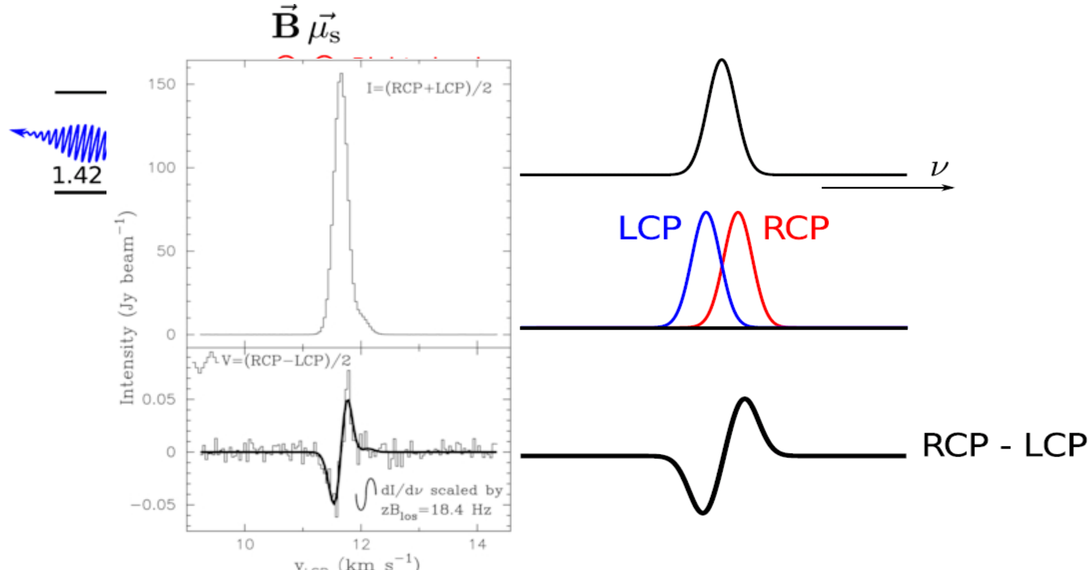


Haverkorn, Katgert, & de Bruyn 2003

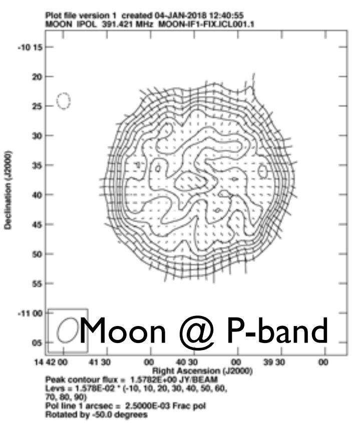
Polarized Radio Emission – Why do we care?

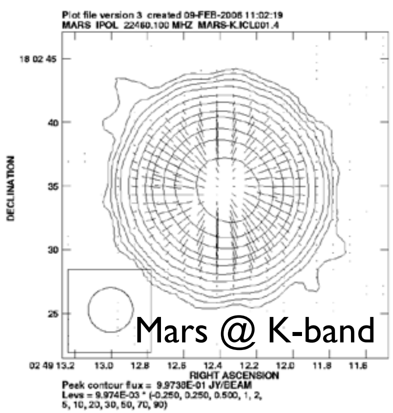
Synchrotron Emission

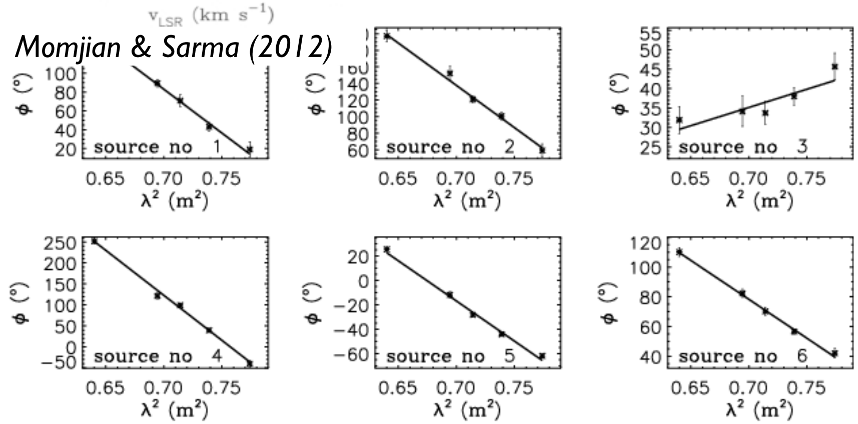
Zeeman Splitting



Momjian & Sarma (2012)







Haverkorn, Katgert, & de Bruyn 2003

Polarization Basics

on-axis linear polarization (VLA 1 – 50 GHz)

- VLA full polarization provides R*R, L*L, R*L, L*R
- Stokes Parameter (circular basis; interferometer):
  - I = (RR + LL)/2; V = (RR – LL)/2
  - Q = (RL + LR)/2; U = (RL – LR)/2i
- Polarized intensity $P = \sqrt{Q^2 + U^2 + V^2}$
- Polarization angle: $\chi = 0.5 \cdot \mathrm{atan2}(U/Q)$

Linear Polarization Observation Preparation

general recipe for circular basis

Two additional calibrators are needed:

– *Leakage Calibrator (D-terms)*:
Determine frequency dependent polarization impurity between the R and L polarizations (per-channel S/N >10).

– *Absolute Polarization Angle Calibrator*:
Determine the R-L phase/delay offsets.

Your flux density/bandpass calibrator and complex gain calibrator can double as polarization calibrators. Requiring no additional overheads in this case.

Linear Polarization Observation Preparation

general recipe for circular basis

Different observing strategies for leakages:

1. *Unpolarized Leakage Calibrator: Df*
   (one scan sufficient)
2. *Polarized/or Unknown polarization Leakage Calibrator: Df+QU*
   (at least 3 scans; >60 deg. parallactic angle coverage)
3. *Known polarization Leakage Calibrator: Df+X*
   (at least 2 scans; >30 deg. parallactic angle coverage; known polarized model)

Note: In case of strategy 2: If the leakage calibrator has significant frequency dependent polarization properties, i.e. large rotation measure, the derived D-terms will be less accurate. *CASA currently does not support Df+QUf.*

For Polarization Angle Calibrator, a single scan on a bright source with known polarization is sufficient (Typically 3C48, 3C138, or 3C286).

Polarization Calibration

on-axis linear polarization (VLA 1 – 50 GHz)

- Parallel Hand Calibration for Stokes I discussed by Amy Kimball
- For Cross-hand calibration we need three fundamental steps and one step to prepare:

0. Preparation
1. Correct for any signal delay offset between the R and L circular pol.
2. Correct for leakage of signal between the R & L circular pol. signals; i.e. instrumental leakage
3. Align the phases of the RL visibilities to obtain information on the orientation of the measured linear polarization angle.
4. Apply calibration tables & inspect results

Some words about the VLA pipeline

- VLA calibration pipeline currently does not support polarimetry (except for VLASS)
- Can use parallel hand calibration of pipeline in two ways to follow the steps discussed in this presentation:

  1. Carry all calibration tables generated and used in the final applycal step to continue polarization calibration.

  2. Revert application of parallactic angle correction, then apply calibration from pipeline and split out the corrected column.

- VLA pipeline discussed later today, here we focus on the polarization calibration steps that are universal.

Step 0: Preparation

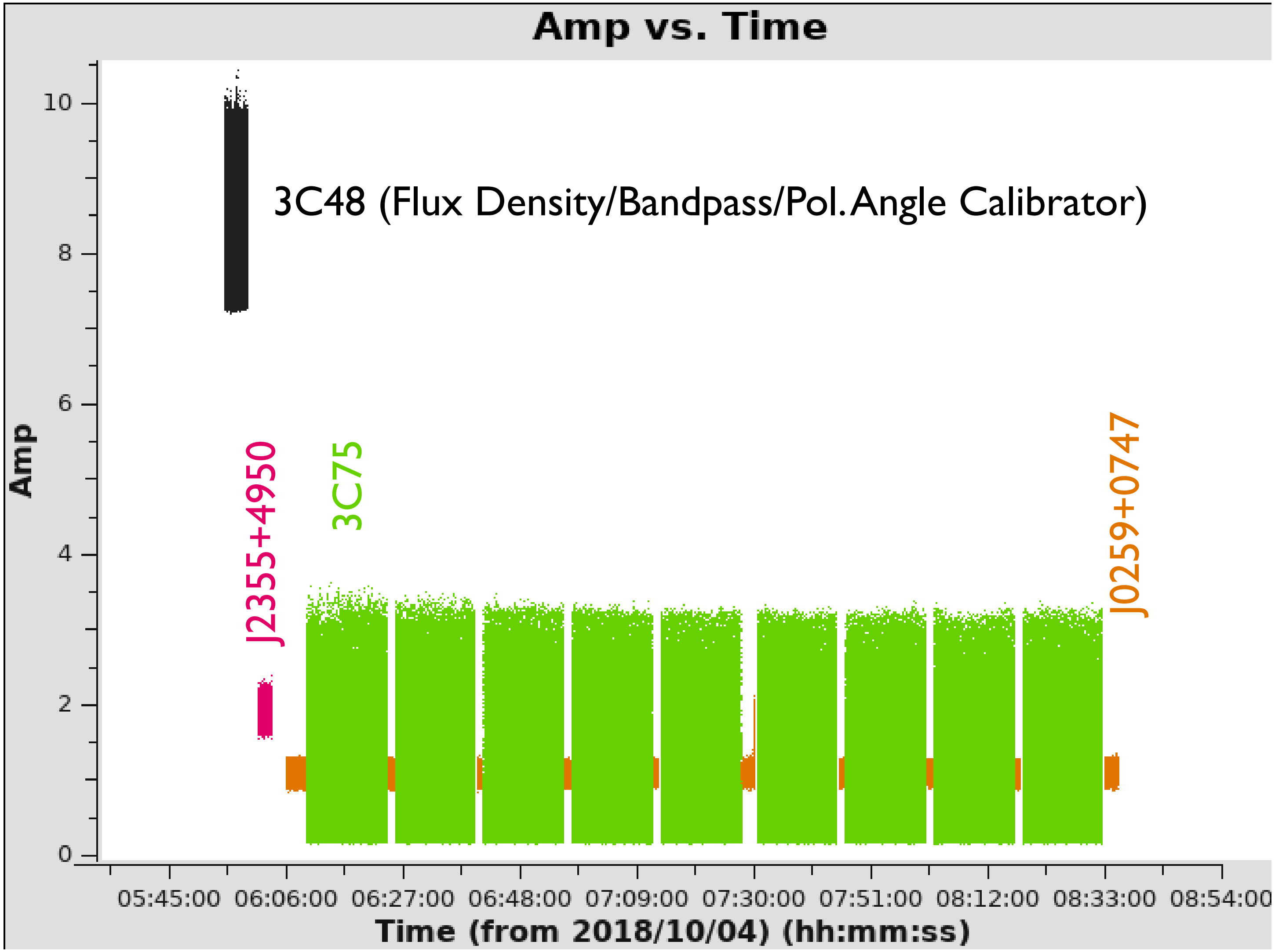
Example dataset: 3C 75

```
File  Edit  View
Search Message:                                   Filter: Time
Message
  ObservationID = 0         ArrayID = 0
 Date        Timerange (UTC)          Scan  FldId FieldName             nRows     SpwIds            Average Interval(s)          ScanIntent
 04-Oct-2018/05:47:35.0 - 05:48:30.0     3      0 0137+331=3C48          30888  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [SYSTEM_CONFIGURATION#UNSPECIFIED]
             05:48:35.0 - 05:49:00.0     4      0 0137+331=3C48          14040  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [SYSTEM_CONFIGURATION#UNSPECIFIED]
             05:49:05.0 - 05:53:25.0     5      0 0137+331=3C48         146016  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_BANDPASS#UNSPECIFIED,CALIBRATE_FLUX#UNSPECIFIED,CALIBRATE_POL_ANGLE#UNSPECIFIED]
             05:53:30.0 - 05:57:55.0     6      1 J2355+4950            148824  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED]
             05:58:00.0 - 06:03:55.0     7      2 J0259+0747            199368  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED,CALIBRATE_POL_LEAKAGE#UNSPECIFIED]
             06:04:00.0 - 06:18:55.0     8      3 3C75                  502632  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [OBSERVE_TARGET#UNSPECIFIED]
             06:19:00.0 - 06:20:10.0     9      2 J0259+0747             39312  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED,CALIBRATE_POL_LEAKAGE#UNSPECIFIED]
             06:20:15.0 - 06:35:05.0    10      3 3C75                  499824  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [OBSERVE_TARGET#UNSPECIFIED]
             06:35:10.0 - 06:36:20.0    11      2 J0259+0747             39312  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED,CALIBRATE_POL_LEAKAGE#UNSPECIFIED]
             06:36:25.0 - 06:51:20.0    12      3 3C75                  502632  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [OBSERVE_TARGET#UNSPECIFIED]
             06:51:25.0 - 06:52:30.0    13      2 J0259+0747             36504  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED,CALIBRATE_POL_LEAKAGE#UNSPECIFIED]
             06:52:35.0 - 07:07:30.0    14      3 3C75                  502632  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [OBSERVE_TARGET#UNSPECIFIED]
             07:07:35.0 - 07:08:45.0    15      2 J0259+0747             39312  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED,CALIBRATE_POL_LEAKAGE#UNSPECIFIED]
             07:08:50.0 - 07:23:40.0    16      3 3C75                  499824  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [OBSERVE_TARGET#UNSPECIFIED]
             07:23:45.0 - 07:26:25.0    17      2 J0259+0747             89856  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED,CALIBRATE_POL_LEAKAGE#UNSPECIFIED]
             07:26:30.0 - 07:41:25.0    18      3 3C75                  502632  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [OBSERVE_TARGET#UNSPECIFIED]
             07:41:30.0 - 07:42:40.0    19      2 J0259+0747             39312  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED,CALIBRATE_POL_LEAKAGE#UNSPECIFIED]
             07:42:45.0 - 07:57:35.0    20      3 3C75                  499824  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [OBSERVE_TARGET#UNSPECIFIED]
             07:57:40.0 - 07:58:50.0    21      2 J0259+0747             39312  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED,CALIBRATE_POL_LEAKAGE#UNSPECIFIED]
             07:58:55.0 - 08:13:50.0    22      3 3C75                  502632  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [OBSERVE_TARGET#UNSPECIFIED]
             08:13:55.0 - 08:15:05.0    23      2 J0259+0747             39312  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED,CALIBRATE_POL_LEAKAGE#UNSPECIFIED]
             08:15:10.0 - 08:30:00.0    24      3 3C75                  499824  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [OBSERVE_TARGET#UNSPECIFIED]
             08:30:05.0 - 08:32:45.0    25      2 J0259+0747             89856  [0,1,2,3,4,5,6,7]  [5, 5, 5, 5, 5, 5, 5, 5] [CALIBRATE_AMPLI#UNSPECIFIED,CALIBRATE_PHASE#UNSPECIFIED,CALIBRATE_POL_LEAKAGE#UNSPECIFIED]
           (nRows = Total number of rows per scan)
Fields: 4
Insert Message:                                   Lock scroll
```

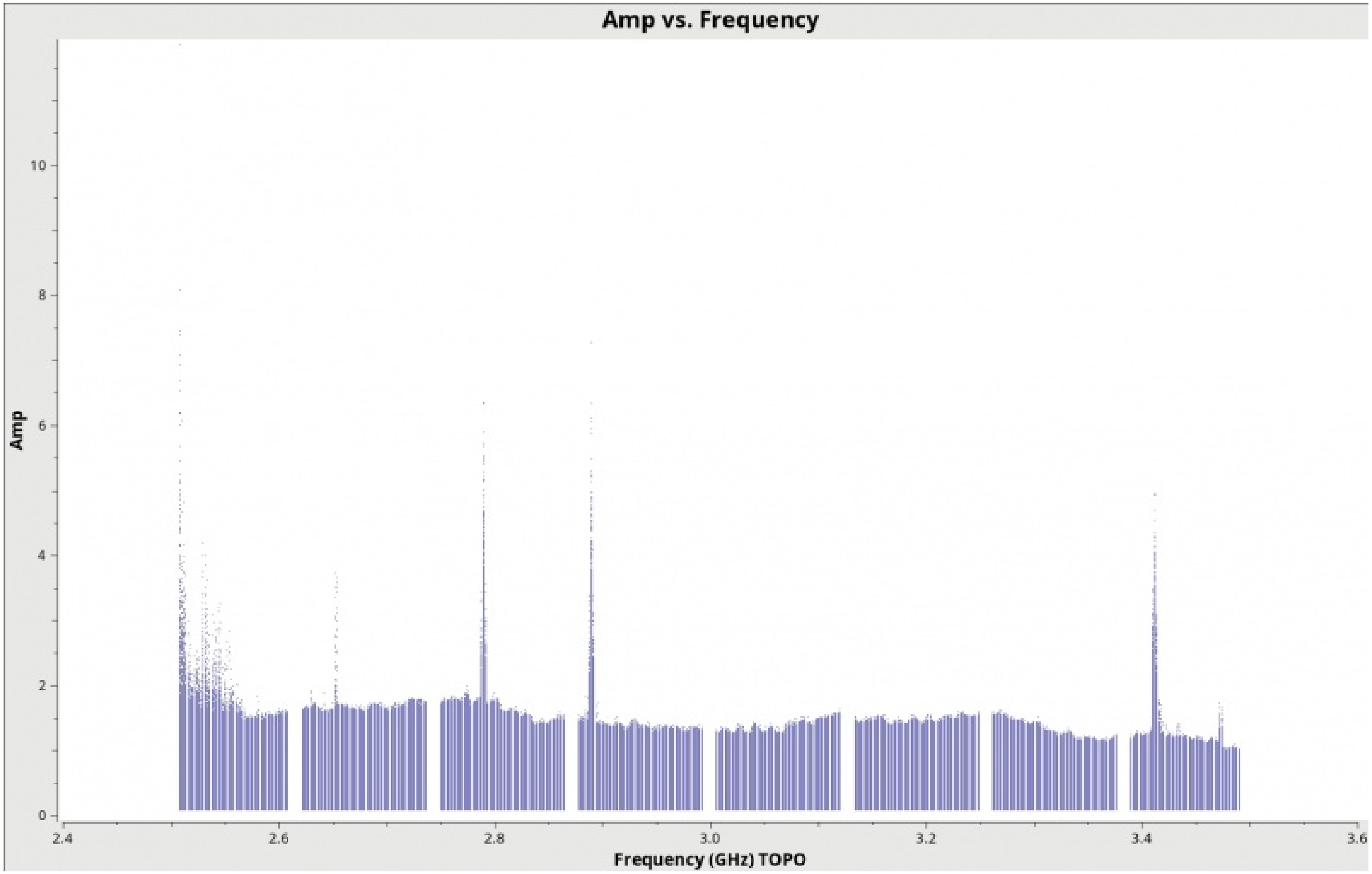
- Frequency setup: 8x128 MHz spectral windows, 2.488 – 3.512 GHz
- Target: 3C 75 (intent = OBSERVE_TARGET)
- Bandpass/Flux Density Calibrator: 3C 48 (1 scan)
- Instrumental polarization calibrator (D-term): J0259+0747
- Guess why we also observed J2355+4950?

  (marked as phase calibrator)

Inspect dataset



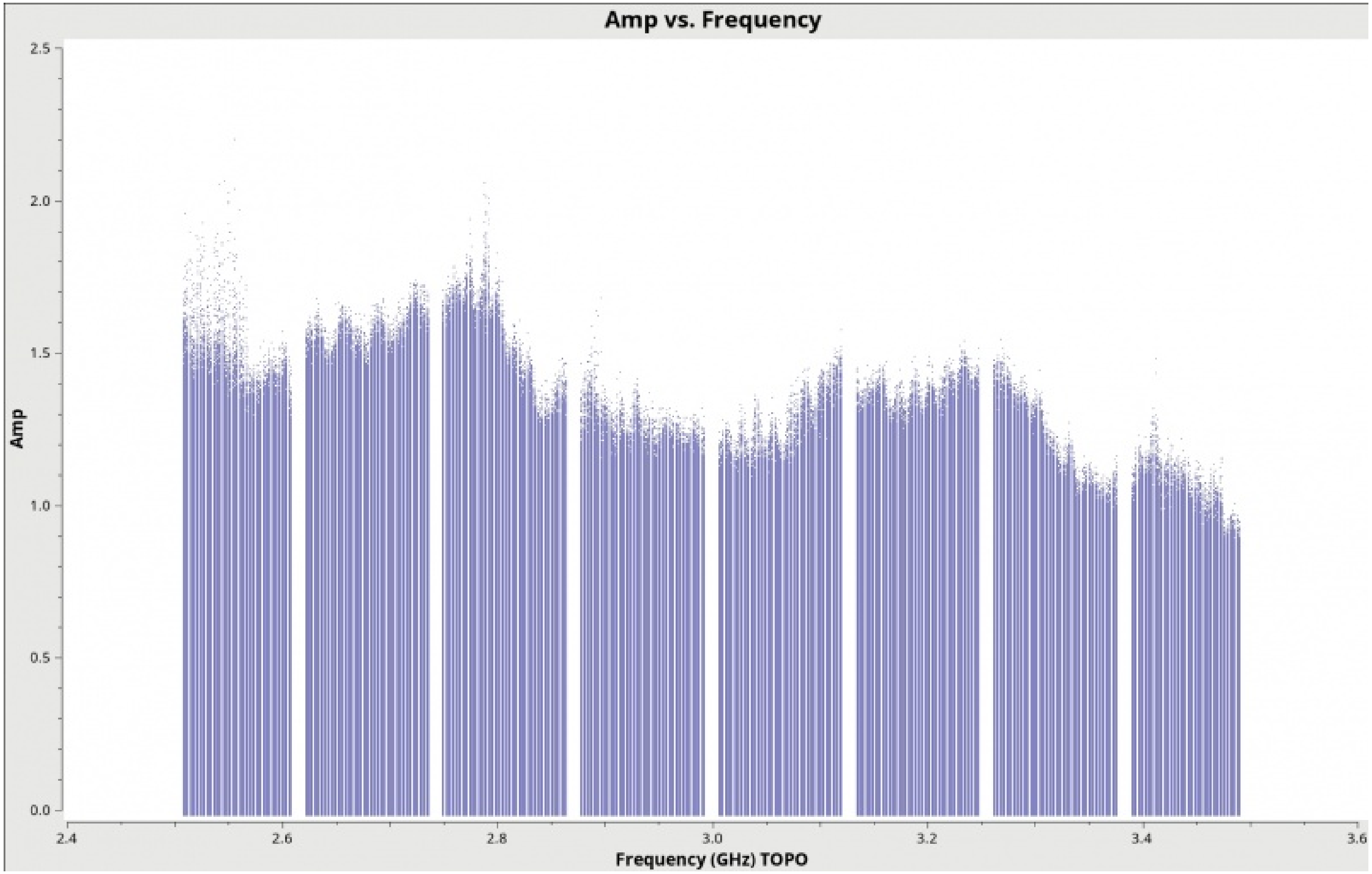
RL/LR Amplitudes – residual RFI



Additional flagging of RL/LR

```
# for all correlations
flagdata(vis='TDRW0001_calibrated.ms',
        mode='tfcrop',
        field='0~2',
        correlation='',
        freqfit = 'line',
        extendflags = False,
        flagbackup = False)

# for the cross-hands
flagdata(vis='TDRW0001_calibrated.ms',
        mode = 'rflag',
        datacolumn='data',
        field = '0~2',
        correlation='RL,LR',
        extendflags = True,
        flagbackup = False)
```

RL/LR Amplitudes – after flagging



Linear polarization angle calibrator models

- You can find broad-band polarimetric information on 3C48, 3C138, 3C147, and 3C286 in Perley & Butler (2013)
- Note, 3C48, 3C138, and 3C147 are variable. Updated values from 2019 available on VLA webpages:
  - https://science.nrao.edu/facilities/vla/docs/manuals/oss/performance/fdscale
  - https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/pol
  - http://www.aoc.nrao.edu/~fschinze/DRW21/ (for 3C48)
- Additional calibrators monitored through projects TPOL0003 & TCAL0009, currently you have to reduce this data yourself if needed.
- We are working on providing time and frequency dependent models in the near future.

CASA task setjy (https://casa.nrao.edu/casadocs/casa-6.1.0/global-task-list/task_setjy/about)

Note: setjy in manual w/o model assumes all emission is from a point source at the phase center! No spatial models are provided within CASA or by NRAO for polarimetry.

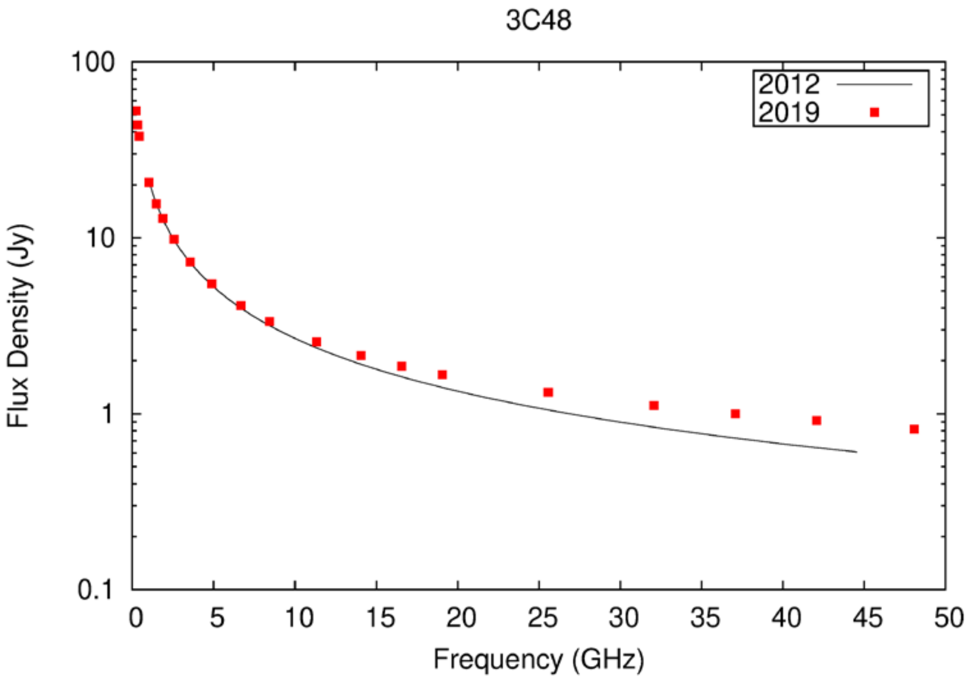
```
standard     =  'manual'      #  Flux density standard
fluxdensity  =  [1, 0, 0, 0]  #  Specified flux density in Jy [I,Q,U,V]
spix         =  []            #  Spectral index (including higher terms) of I fluxdensity
reffreq      =  ''            #  Reference frequency for spix
polindex     =  []   #  Coeff. of an expansion of freq.-dependent linear pol. fraction
polangle     =  []   #  Coeff. of an expansion of freq.-dependent  pol. angle (in radians)
rotmeas      =  0.0           #  Rotation measure (in rad/m^2)
```

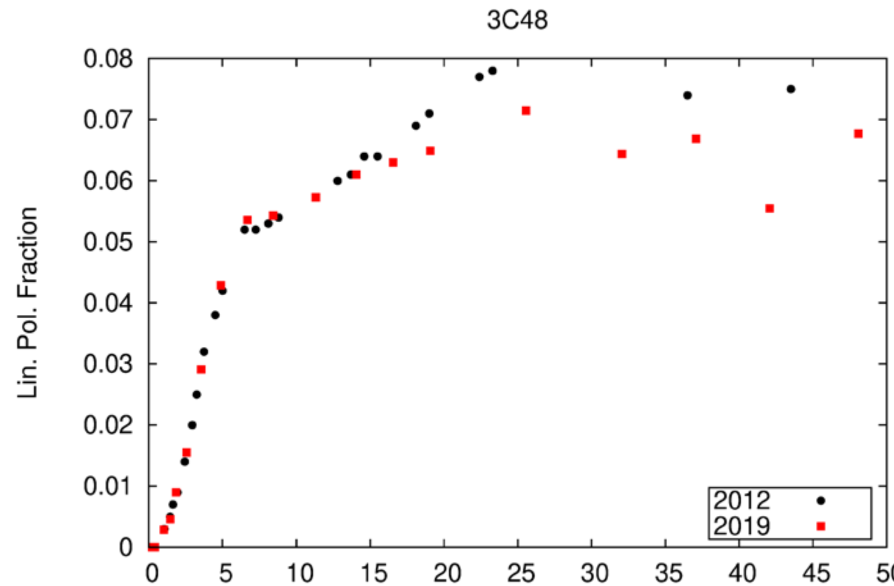
$$S(\nu) = fluxdensity[0] * \frac{\nu}{reffreq}^{spix[0]+spix[1]*log(\nu/reffreq)+..}$$

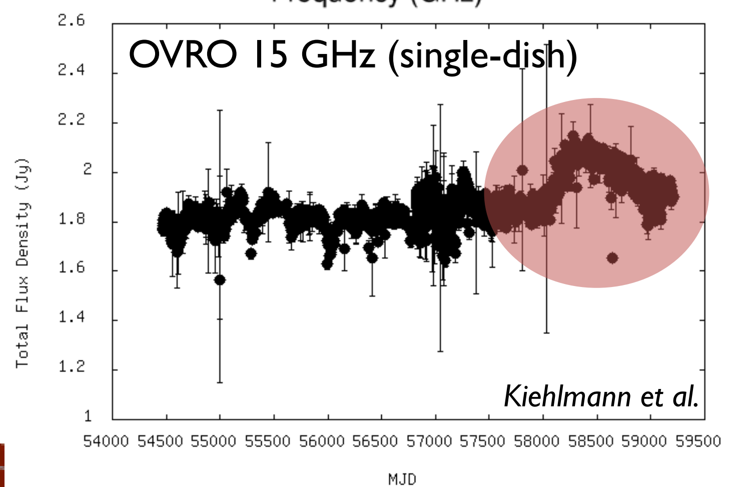
$$PI = \frac{\sqrt{Q^2+U^2}}{I} = p0 + p1 * \frac{\nu - reffreq}{reffreq} + p2 * (\frac{\nu - reffreq}{reffreq})^2 + \ldots$$

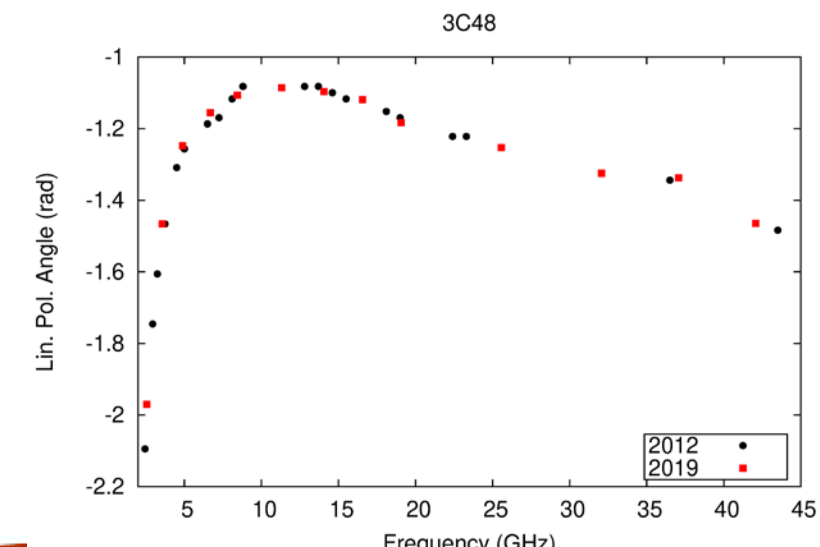
$$\chi = 0.5 arctan \frac{U}{Q} = a0 + a1 * \frac{\nu - reffreq}{reffreq} + a2 * (\frac{\nu - reffreq}{reffreq})^2 + ..$$

3C48: Lin. Pol. Angle Calibrator





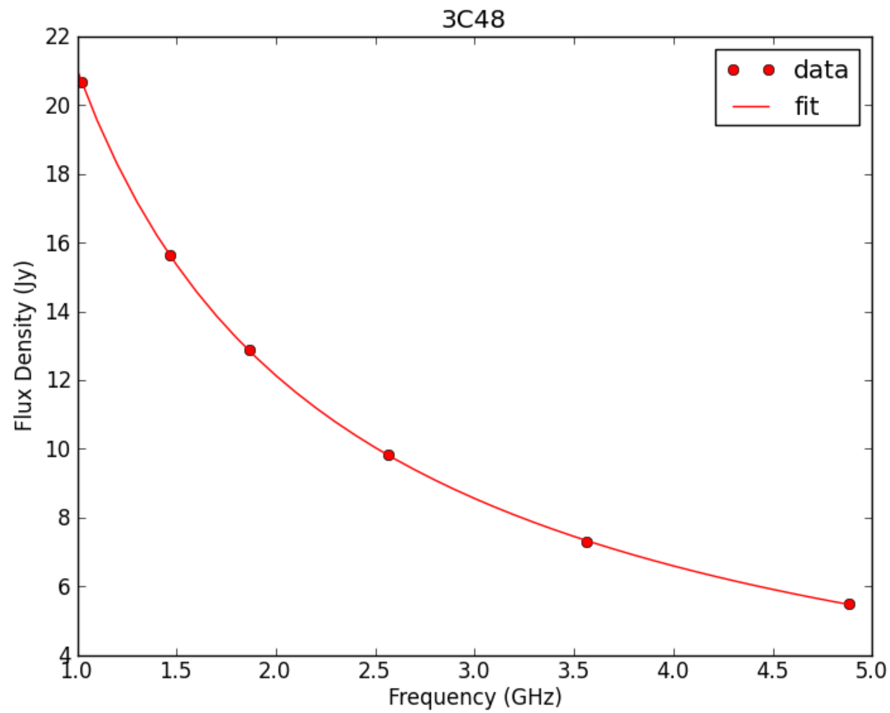




CASA task setjy (https://casa.nrao.edu/casadocs/casa-6.1.0/global-task-list/task_setjy/about)

Common question: determining the coefficients for 3C48 at S-band – Spix
http://www.aoc.nrao.edu/~fschinze/DRW21/fit_I.py

We use known values of 3C48 to fit Stokes I and spectral index & curvature.



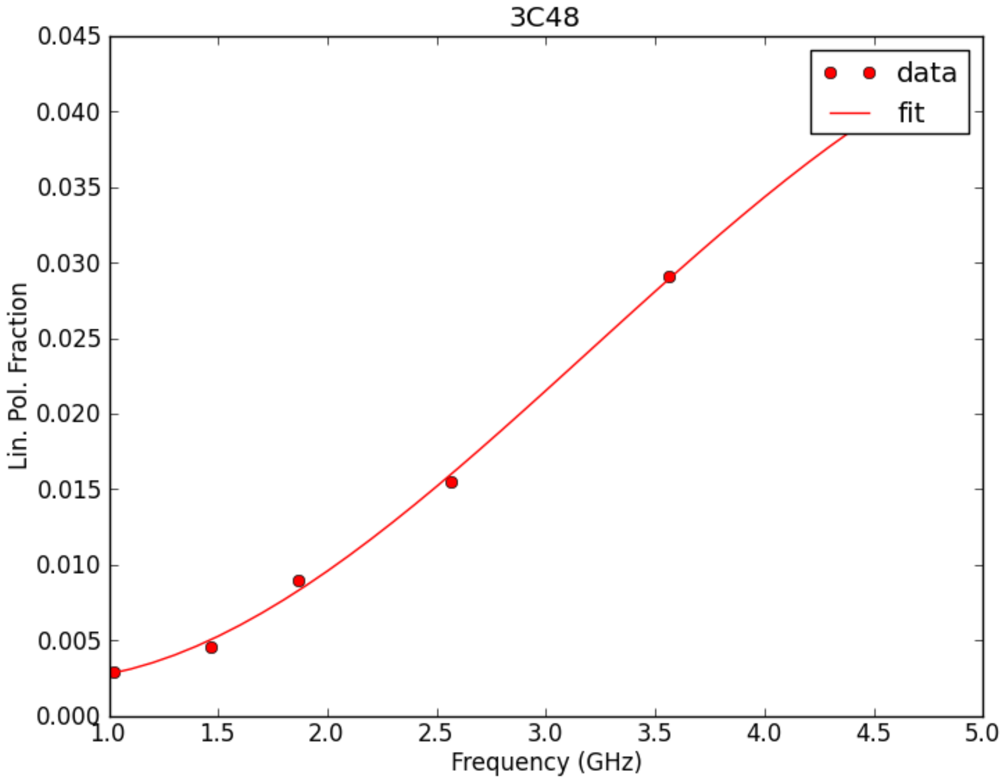
I@3GHz = 8.5555 Jy
spix = [-0.88640,
-0.14323]

CASA task setjy (https://casa.nrao.edu/casadocs/casa-6.1.0/global-task-list/task_setjy/about)

Common question: determining the coefficients for 3C48 at S-band – polindex

http://www.aoc.nrao.edu/~fschinze/DRW21/fit_PF.py

We use known values of 3C48 to fit linear polarization fraction.

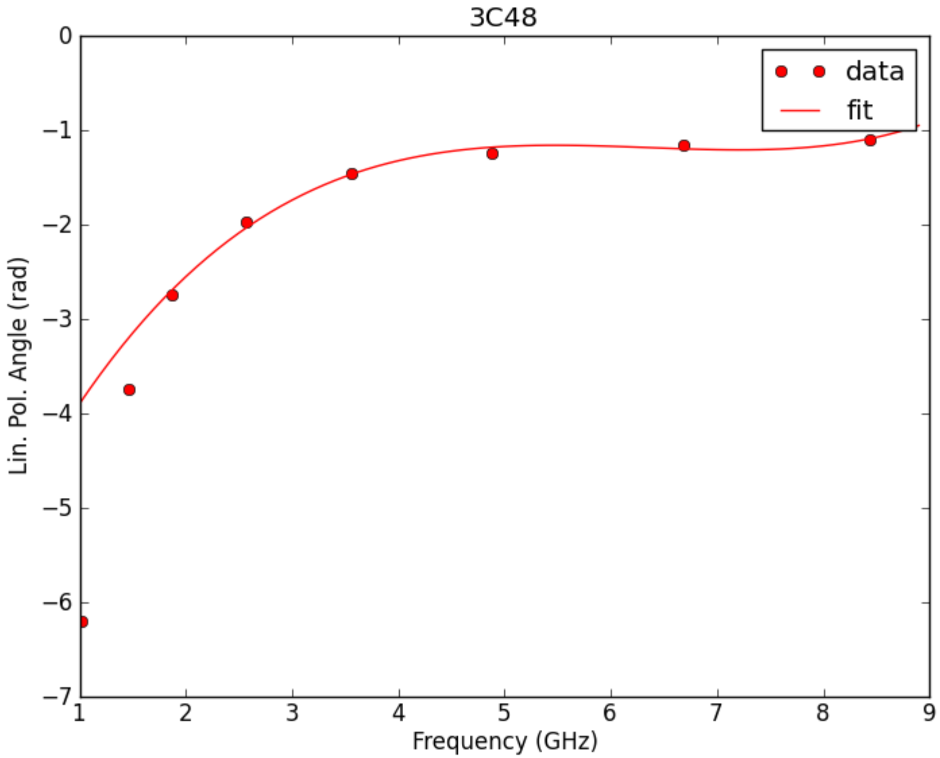


polindex = [0.02152579,
0.03924469,
0.00382036,
-0.0192665]

CASA task setjy (https://casa.nrao.edu/casadocs/casa-6.1.0/global-task-list/task_setjy/about)

Common question: determining the coefficients for 3C48 at S-band – polangle
http://www.aoc.nrao.edu/~fschinze/DRW21/fit_PA.py

We use known values of 3C48 to fit linear polarization angle in radians.



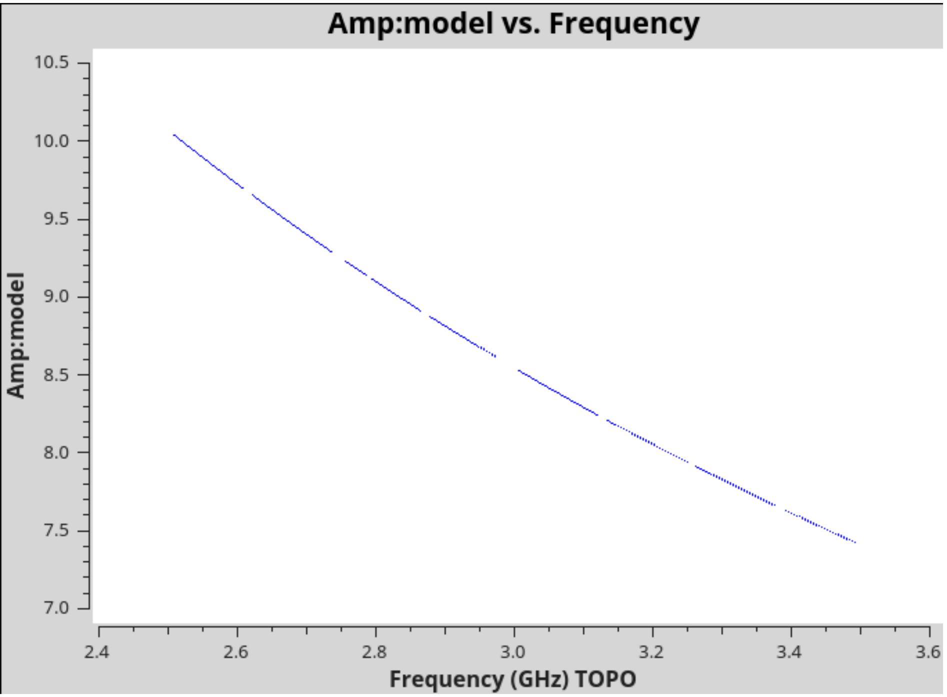
polangle = [-2.74383385,
1.77521589,
-1.76969593,
0.60267279,
0.96191507]

Putting it all together in a setjy() call

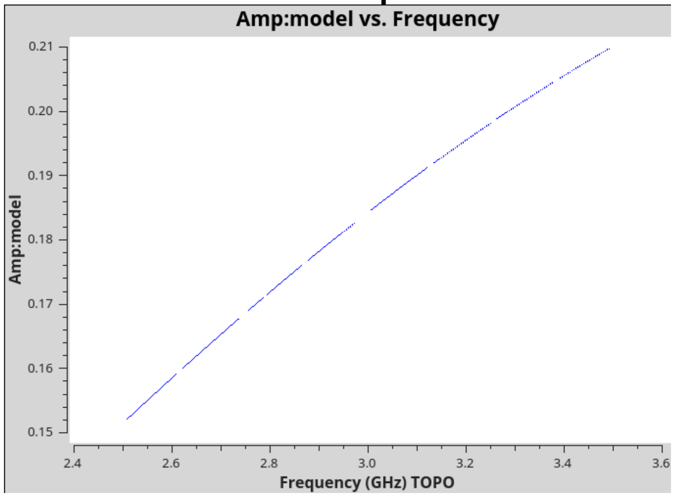
```
%cpaste
reffreq    = '3.0 GHz'          # reference frequency for fit values
I          = 8.5555       # Stokes I flux density @ reference frequency
alpha      = [-0.8864, -0.14323] # spectral index and curvature
polindex   = [0.02152579, 0.03924469, 0.00382036, -0.0192665] # polarization fraction
polangle   = [-2.74383385, 1.77521589, -1.76969593, 0.60267279, 0.96191507] # pol. angle

mysetjy = setjy(vis = 'TDRW0001_calibrated.ms',
          field='0137+331=3C48',
          scalebychan=True,
          standard='manual',
          fluxdensity=[I,0,0,0],
          spix=alpha,
          reffreq=reffreq,
          polindex=polindex,
          polangle=polangle,
          rotmeas=0,
          usescratch=True)
```

Check the model was set correctly

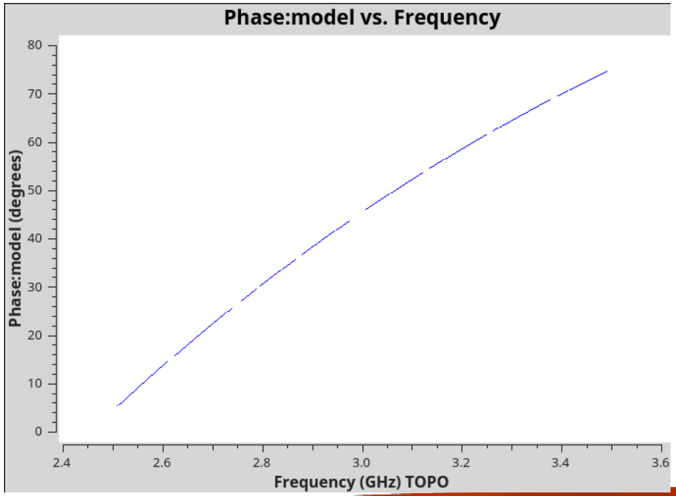
RR amplitude



RL amplitude



RL phase



Step 1: Determine R-L delay

Solving for the cross-hand delays

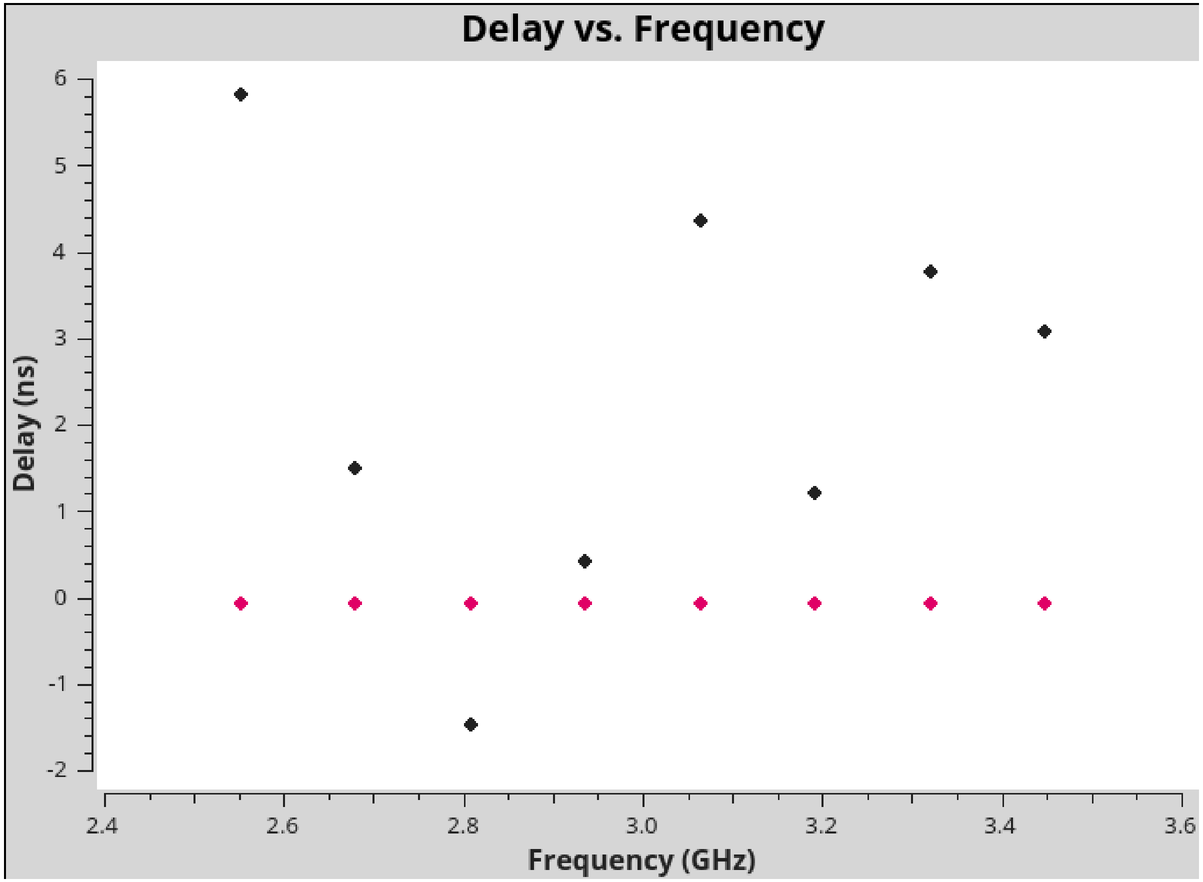
```
# solve using Single Band Delay
kcross_sbd = 'TDRW0001_calibrated.Kcross_sbd'
gaincal(vis='TDRW0001_calibrated.ms',
    caltable=kcross_sbd,
    field='0137+331=3C48',
    spw='0~7:5~58',              # ignore edge channels
    refant='ea10',               # same reference antenna used from parallel hand calibration
    gaintype='KCROSS',
    solint='inf',
    combine='scan',
    calmode='ap',
    append=False,
    gaintable=[''],
    gainfield=[''],
    interp=[''],
    spwmap=[[]],
    parang=True)
```

Solving for the cross-hand delays
Output printed in the logger

For single band delay there are 8 solutions:

- Spw=0 Global cross-hand delay=5.71477 nsec
- Spw=1 Global cross-hand delay=1.51269 nsec
- Spw=2 Global cross-hand delay=-1.36895 nsec
- Spw=3 Global cross-hand delay=0.468607 nsec
- Spw=4 Global cross-hand delay=4.29537 nsec
- Spw=5 Global cross-hand delay=1.23363 nsec
- Spw=6 Global cross-hand delay=3.72454 nsec
- Spw=7 Global cross-hand delay=3.04475 nsec

Solving for the cross-hand delays
visualize resulting delays



Solving for the cross-hand delays

```
# solve using Multi-Band Delay
%cpaste
kcross_mbd = 'TDRW0001_calibrated.Kcross_mbd'
gaincal(vis='TDRW0001_calibrated.ms',
    caltable=kcross_mbd,
    field='0137+331=3C48',
    spw='0~7:5~58',              # ignore edge channels; spw of a single baseband 1 GHz
    refant='ea10',               # same reference antenna used from parallel hand calibration
    gaintype='KCROSS',
    solint='inf',
    combine='scan,spw',          # combine spectral windows
    calmode='ap',
    append=False,
    gaintable=[''],
    gainfield=[''],
    interp=[''],
    spwmap=[[]],
    parang=True)
```

Solving for the cross-hand delays
Output printed in the logger

For single band delay there are 8 solutions:

Spw=0 Global cross-hand delay=5.71477 nsec
Spw=1 Global cross-hand delay=1.51269 nsec
Spw=2 Global cross-hand delay=-1.36895 nsec
Spw=3 Global cross-hand delay=0.468607 nsec
Spw=4 Global cross-hand delay=4.29537 nsec
Spw=5 Global cross-hand delay=1.23363 nsec
Spw=6 Global cross-hand delay=3.72454 nsec
Spw=7 Global cross-hand delay=3.04475 nsec

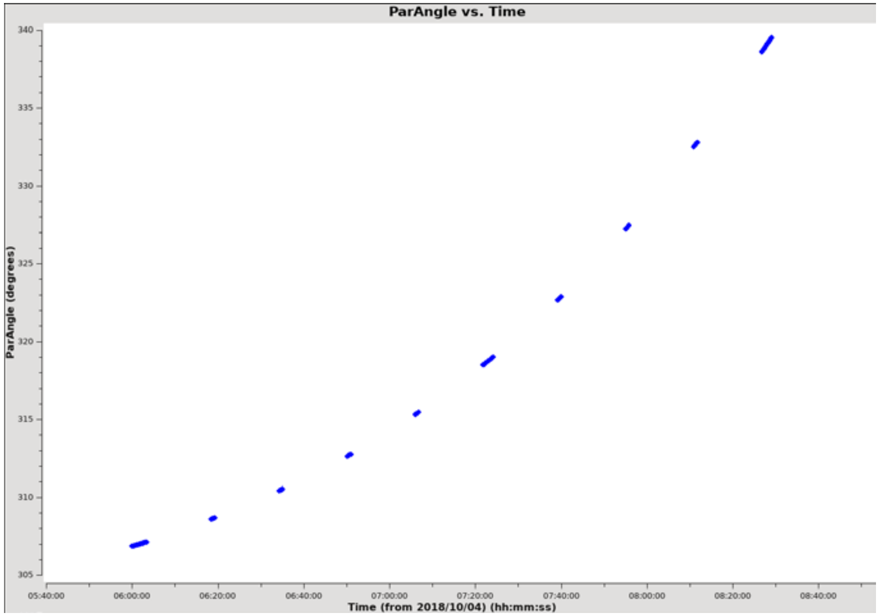
mean: 2.33 nsec; median: 2.28 nsec

For multiband delay there is one solution:

Multi-band cross-hand delay=3.68198 nsec

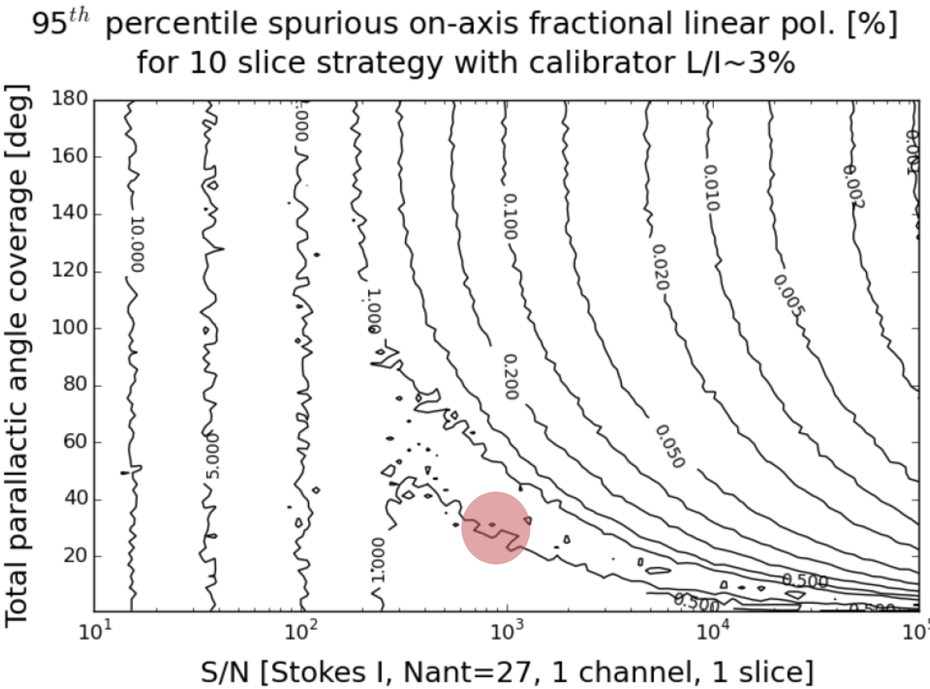
Step 2: Determine Polarization Leakage b/w R & L

Solving for instrumental polarization J0259+0747



~33 degrees parallactic angle coverage

10 scans/slices; Flux density ~0.9 Jy



Hales (2017)

1 min scan ~ 900 S/N ~ 1% on-axis spurious will check using J2355+7828

Solving for instrumental polarization J0259+0747 / Df+QU – polarized

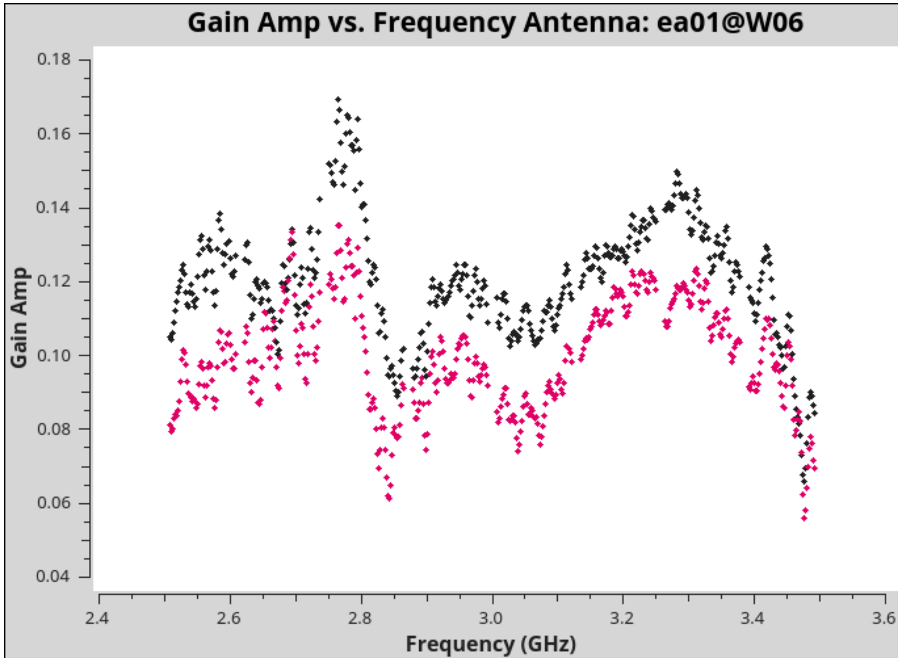
```
%cpaste
dtab_J0259 = 'TDRW0001_calibrated.DfQU'
polcal(vis='TDRW0001_calibrated.ms',
       caltable=dtab_J0259,
       intent='CALIBRATE_POL_LEAKAGE#UNSPECIFIED',
       spw='0~7',
       refant='ea10',
       poltype='Df+QU',
       solint='inf,2MHz',
       combine='scan',
       gaintable=[kcross_mbd],    # Note, we are using the multi-band Kcross delay solutions.
       gainfield=[''],
       spwmap=[[0,0,0,0,0,0,0,0]],
       append=False)
```

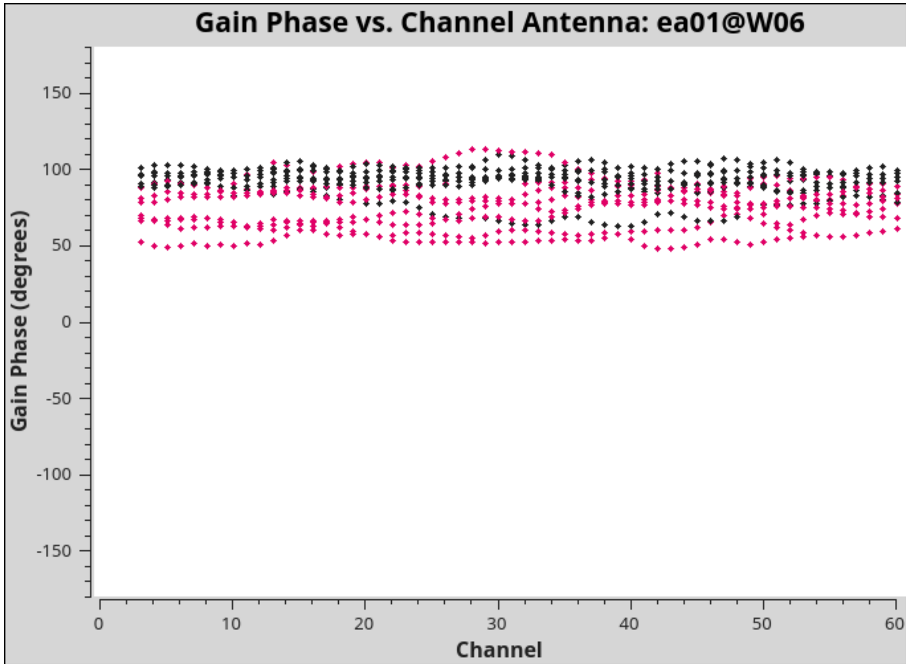
Solving for instrumental polarization J0259+0747 / Df+QU – polarized

Check output in logger:

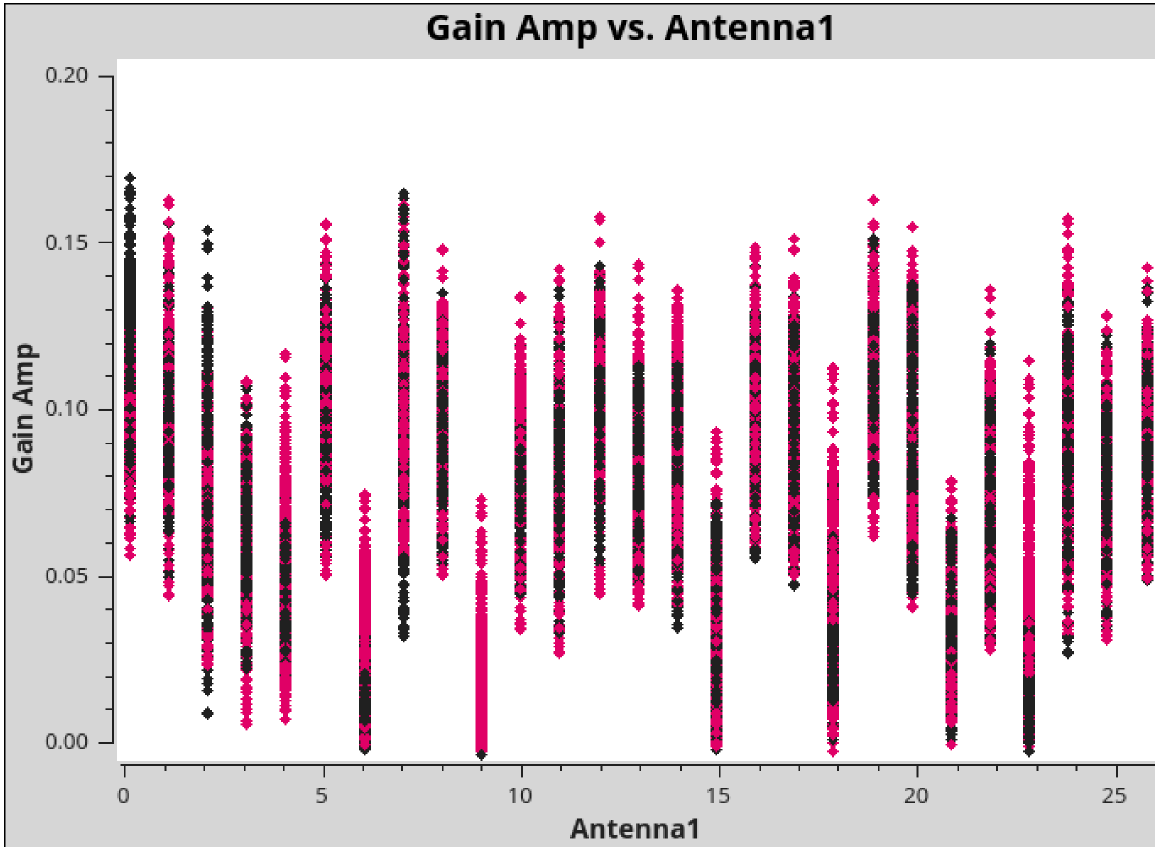
Fractional polarization solution for J0259+0747 (spw = 0): : Q = 0.0261594, U = 0.0334233 (P = 0.0424432, X = 25.9754 deg)
Fractional polarization solution for J0259+0747 (spw = 1): : Q = 0.0145776, U = 0.038399 (P = 0.041073, X = 34.6057 deg)
Fractional polarization solution for J0259+0747 (spw = 2): : Q = 0.016288, U = 0.0391953 (P = 0.042445, X = 33.7171 deg)
Fractional polarization solution for J0259+0747 (spw = 3): : Q = 0.0111993, U = 0.041723 (P = 0.0432, X = 37.4874 deg)
Fractional polarization solution for J0259+0747 (spw = 4): : Q = 0.00822594, U = 0.040461 (P = 0.0412887, X = 39.254 deg)
Fractional polarization solution for J0259+0747 (spw = 5): : Q = 0.00605818, U = 0.0410209 (P = 0.0414658, X = 40.7995 deg)
Fractional polarization solution for J0259+0747 (spw = 6): : Q = -0.00189636, U = 0.0432816 (P = 0.0433232, X = 46.2544 deg)
Fractional polarization solution for J0259+0747 (spw = 7): : Q = -0.00785128, U = 0.0475776 (P = 0.048221, X = 49.6853 deg)

Solving for instrumental polarization
J0259+0747 / Df+QU – polarized – inspect results





Solving for instrumental polarization
J0259+0747 / Df+QU – polarized – inspect results

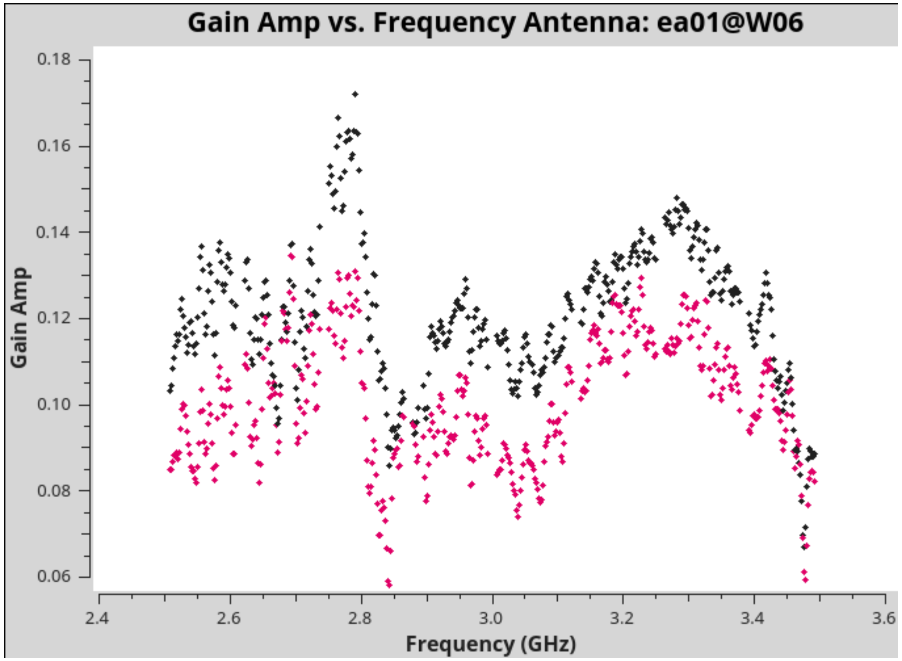


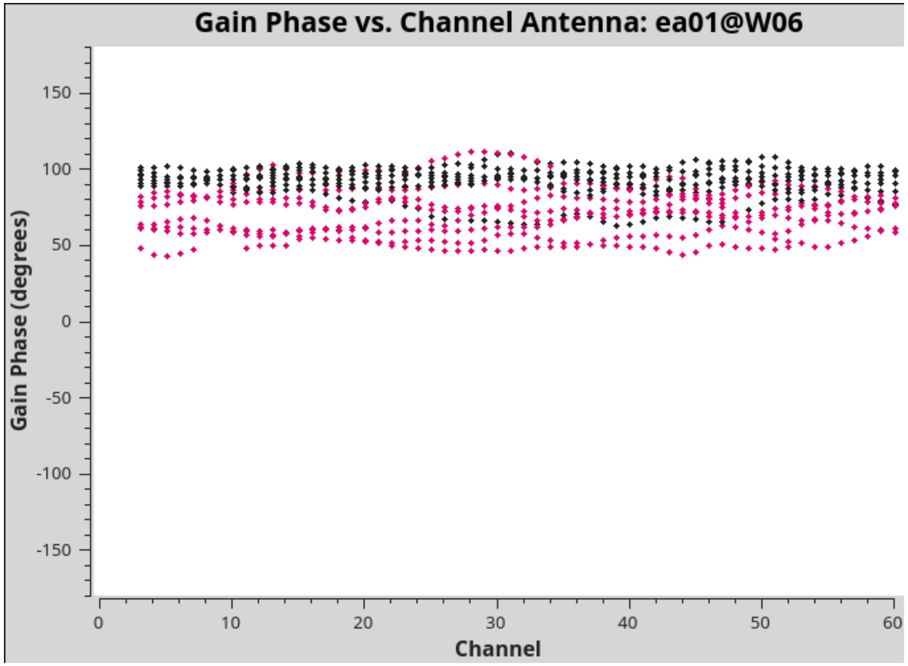
Solving for instrumental polarization J2355+4950 / Df - unpolarized

```
dtab_J2355 = 'TDRW0001_calibrated.Df'
polcal(vis='TDRW0001_calibrated.ms',
       caltable=dtab_J2355,
       field='J2355+4950',
       spw='0~7',
       refant='ea10',
       poltype='Df',
       solint='inf,2MHz',
       combine='scan',
       gaintable=[kcross_mbd],
       gainfield=[''],
       spwmap=[[0,0,0,0,0,0,0,0]],
       append=False)
```

Solving for instrumental polarization

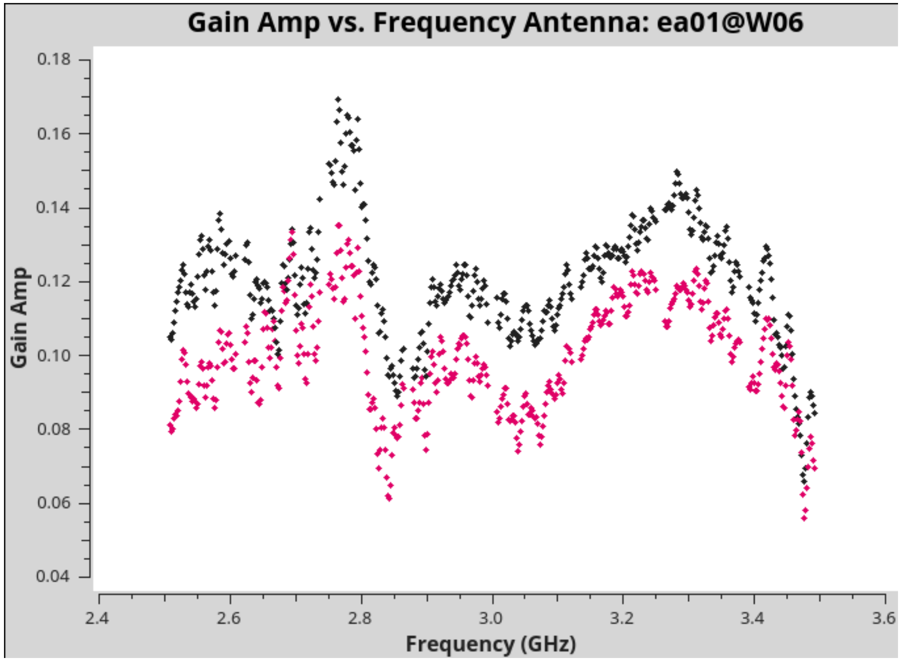
- J2355+4950 / Df – unpolarized – inspect results



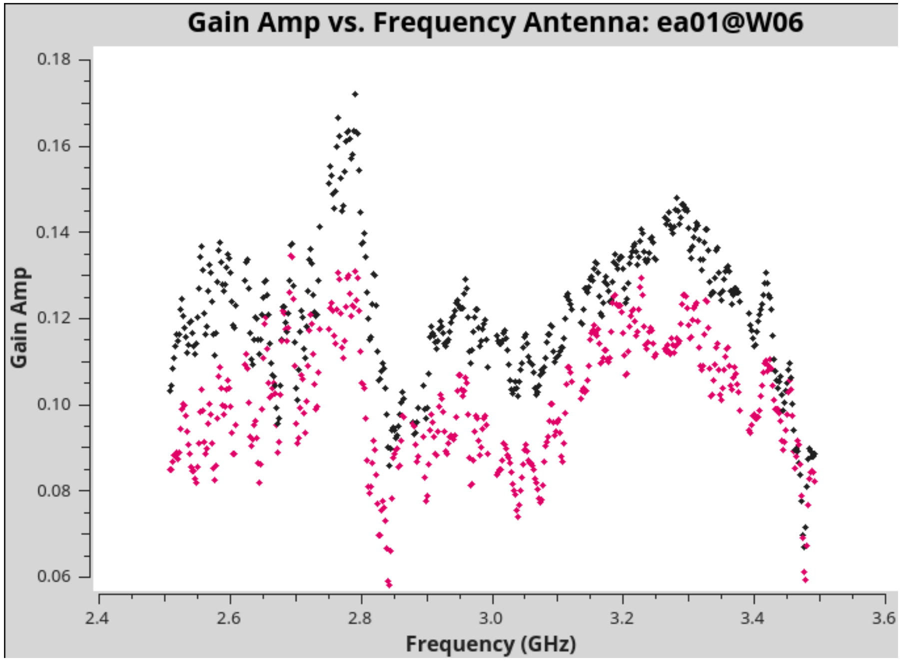


Solving for instrumental polarization
Comparison Df+QU / Df

Df+QU



Df



Flagging amplitude outliers in D-term solutions

In some cases there are outlier solutions above 0.25 that are most likely due to residual RFI. You can flag those using flagdata.

```
flagdata(vis=dtab_J2355,
        mode='clip',
        correlation='ABS_ALL',
        clipminmax=[0.0, 0.25],
        datacolumn='CPARAM',
        clipoutside=True,
        action='apply',
        flagbackup=False,
        savepars=False)

flagdata(vis=dtab_J0259, mode='clip', correlation='ABS_ALL', clipminmax=[0.0, 0.25],
        datacolumn='CPARAM', clipoutside=True, action='apply', flagbackup=False,
        savepars=False)
```

This clips everything above 25% instrumental polarization, which is unexpected.

Step 3: Determine/Set R-L phase

Setting R-L phase

To obtain accurate polarization position angle we need to rotate the R-L phase. We have set a model for 3C 48 before, which we will use now.

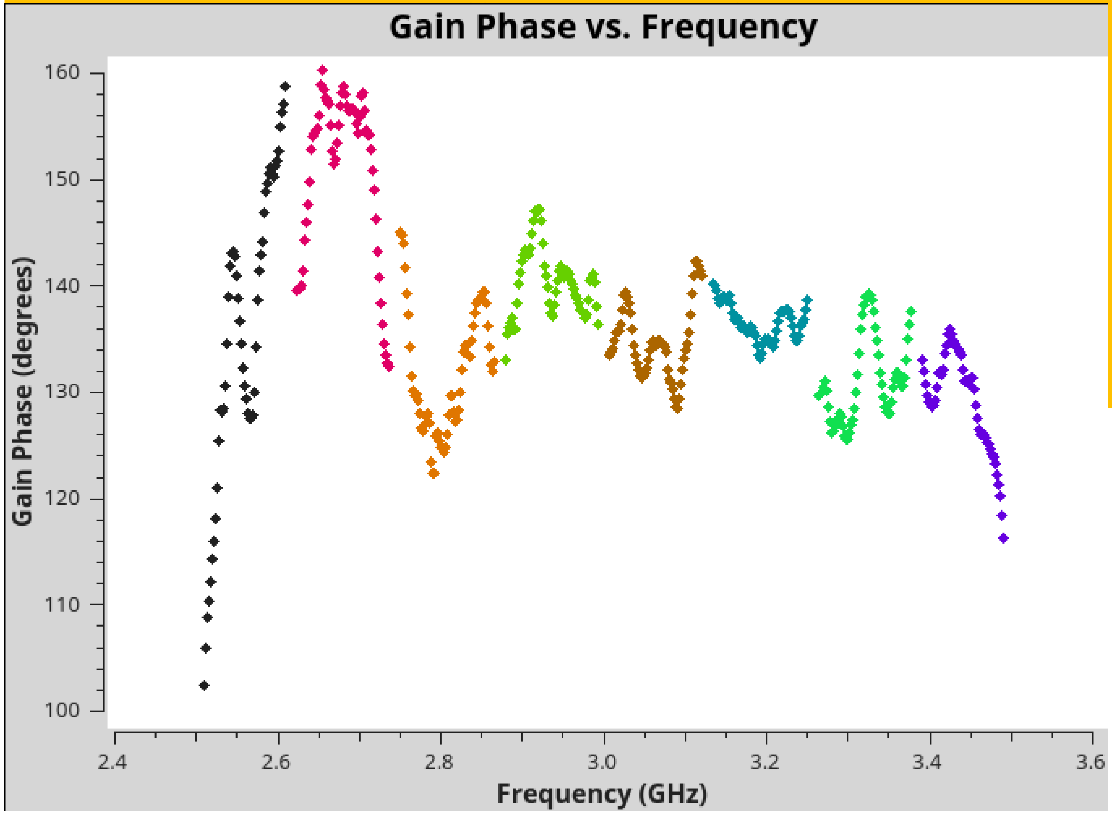
```
xtab = 'TDRW0001_calibrated.Xf'
polcal(vis='TDRW0001_calibrated.ms',
       caltable=xtab,
       spw='0~7',
       field='0137+331=3C48',
       solint='inf,2MHz',
       combine='scan',
       poltype='Xf',
       refant = 'ea10',
       gaintable=[kcross_mbd,dtab_J0259],
       gainfield=['',''],
       spwmap=[[0,0,0,0,0,0,0,0],[]],
       append=False)
```

Setting R-L phase

Inspect results

Check output in logger:

Mean position angle offset solution for 0137+331=3C48 (spw = 0) = 67.7459 deg.
(spw = 1) = 75.1599 deg.
(spw = 2) = 65.9715 deg.
(spw = 3) = 70.0648 deg.
(spw = 4) = 67.361 deg.
(spw = 5) = 68.2629 deg.
(spw = 6) = 65.6135 deg.
(spw = 7) = 64.6514 deg.

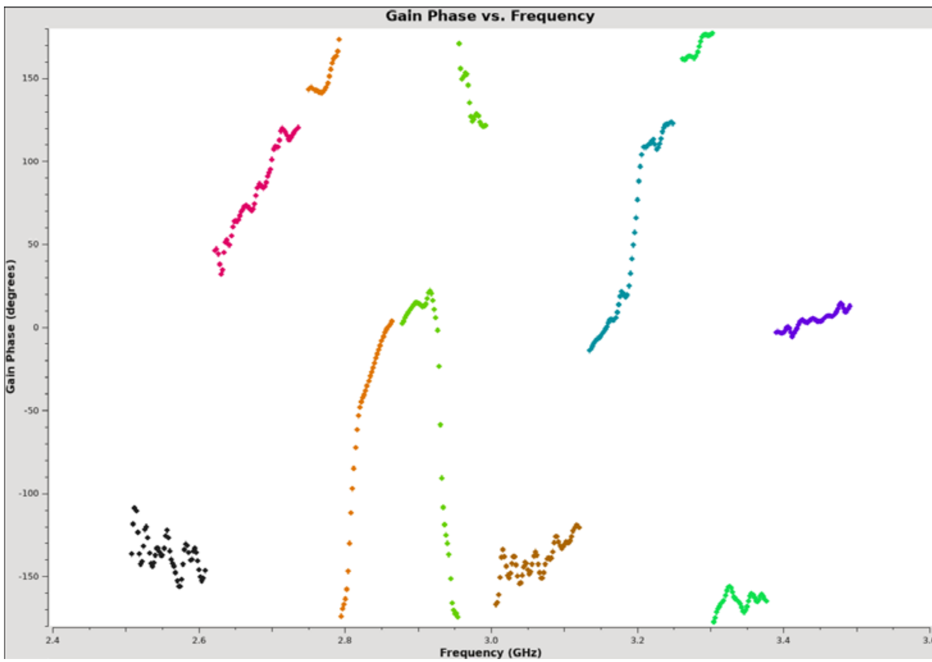



```
plotms(vis=xtab,
       xaxis='frequency',
       yaxis='phase',
       coloraxis='spw')
```

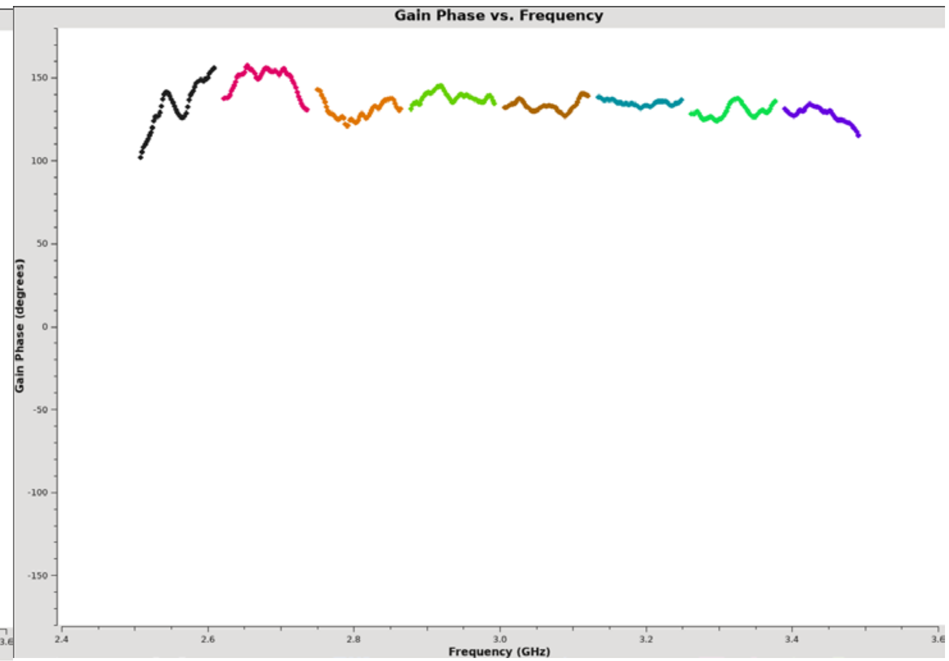
Setting R-L phase

If we had used single band delays, the R-L phase solutions are independent for each spectral window, but should be flat if the R-L delay offset was set correctly.

single-band delay

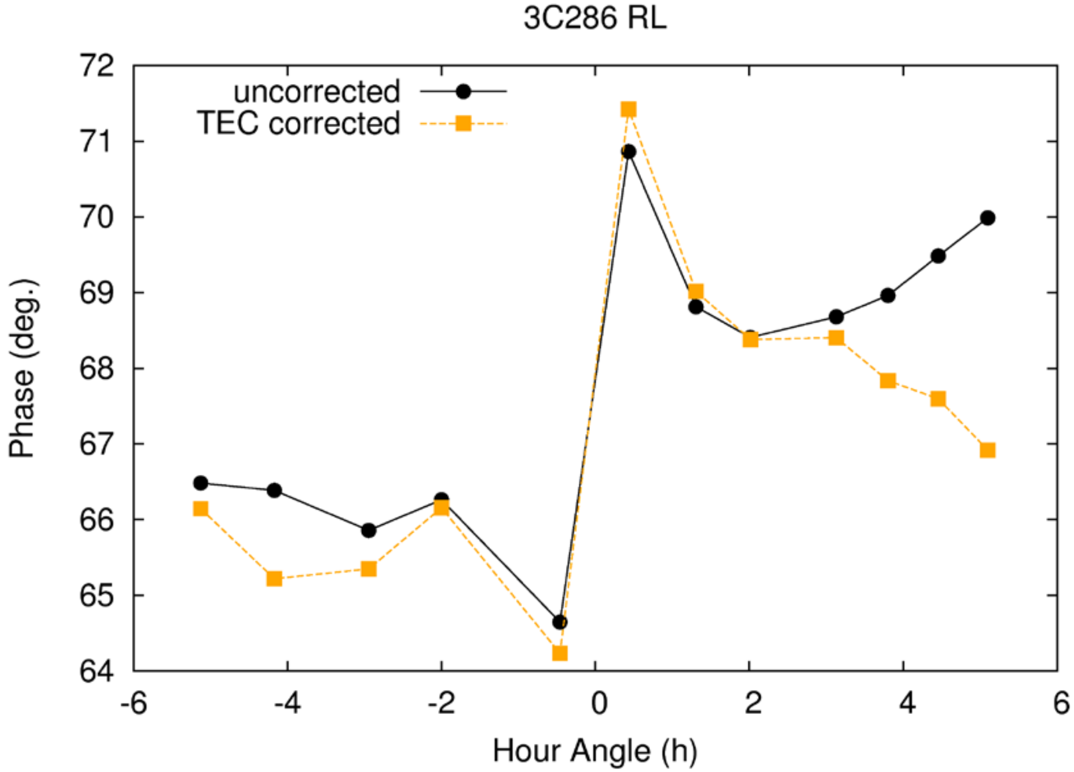


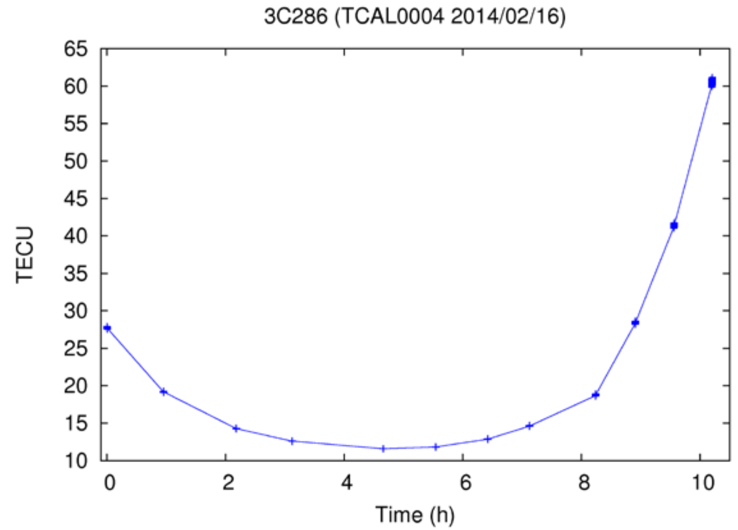
multi-band delay



VLA RL phase stability

Ionosphere – typically a few degrees at 3GHz

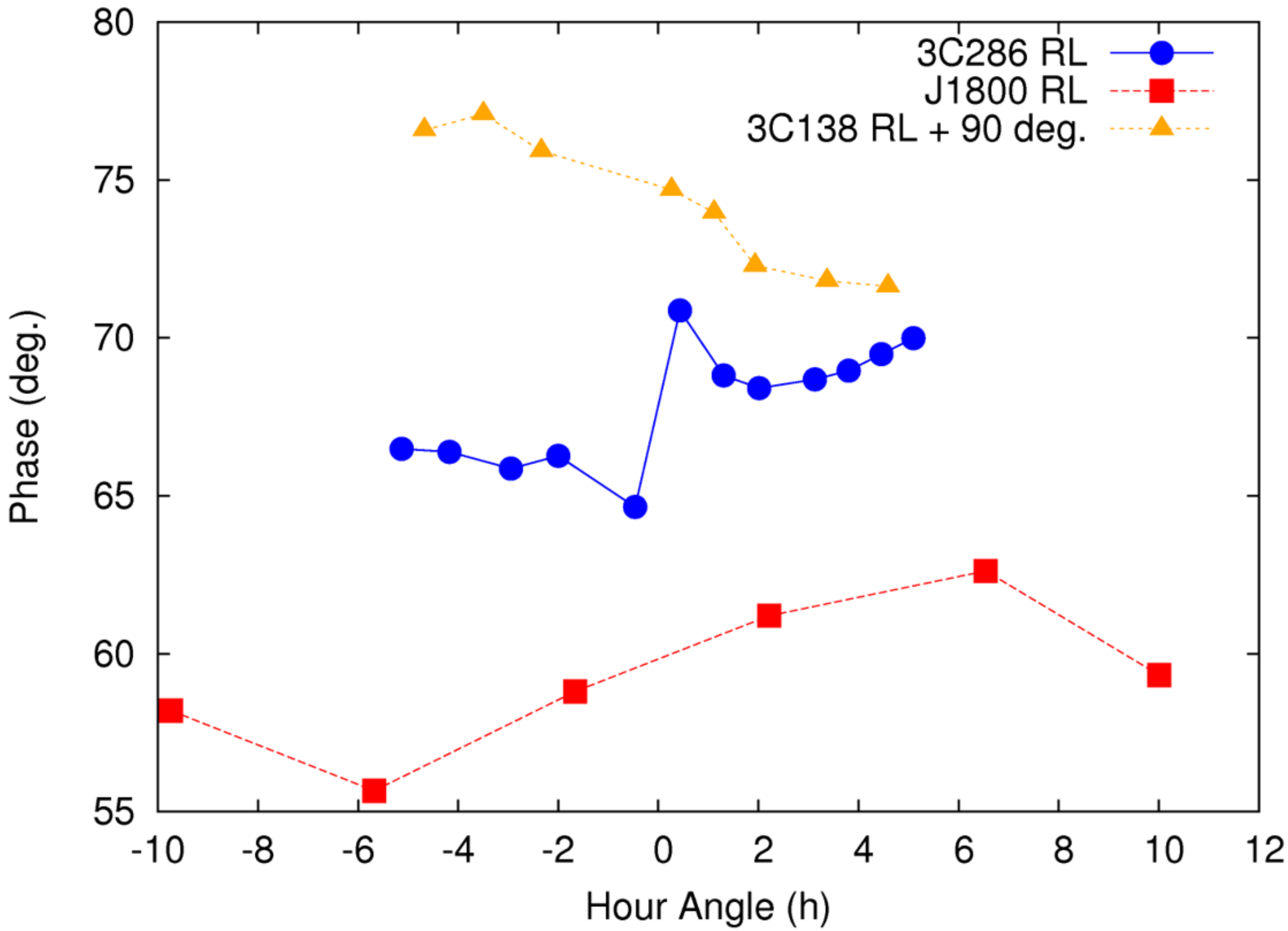




Large dTEC leads to Faraday rotation.

VLA RL phase stability

Instrumental – limit to ~5 deg. absolute accuracy



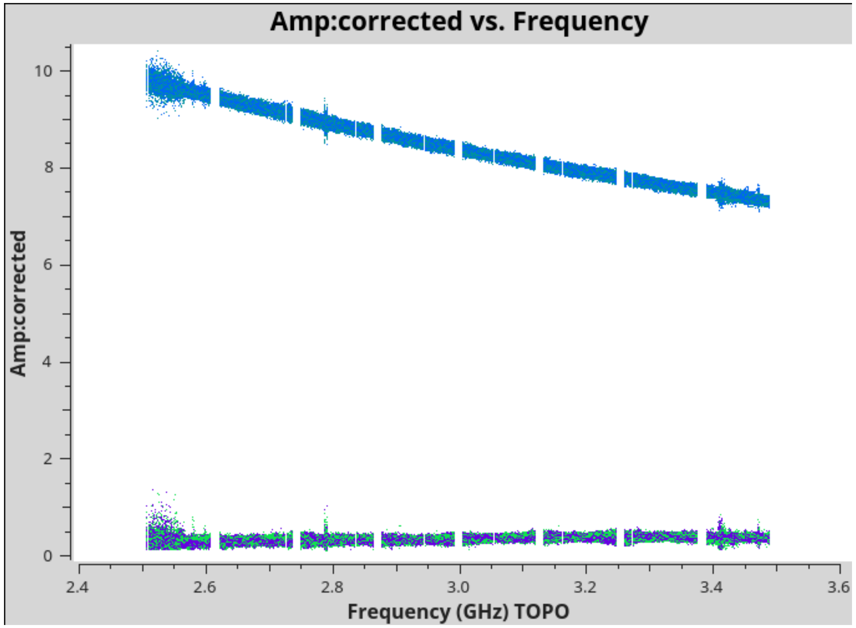
Step 4: Apply Calibration & Inspect

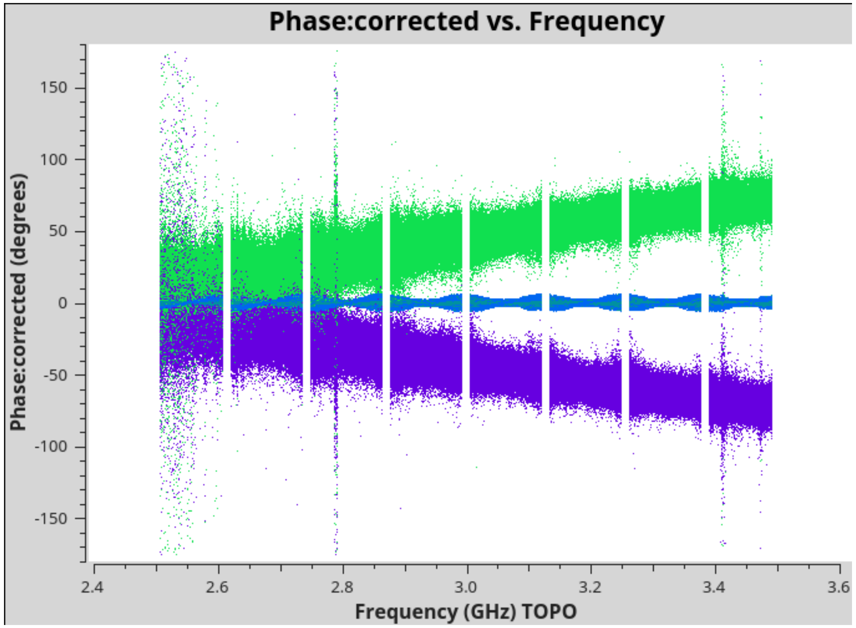
Finally let's apply the calibration

applycal(vis = 'TDRW0001_calibrated.ms',
field='',
gainfield=['', '', ''],
flagbackup=True,
interp=['', '', ''],
gaintable=[**kcross_mbd,dtab_J0259,xtab**],
spw='0~7',
calwt=[False, False, False],
applymode='**calflagstrict**',
antenna='*&*',
spwmap=[[**0,0,0,0,0,0,0,0**],[],[]],
parang=True)

Inspect calibration – 3C48

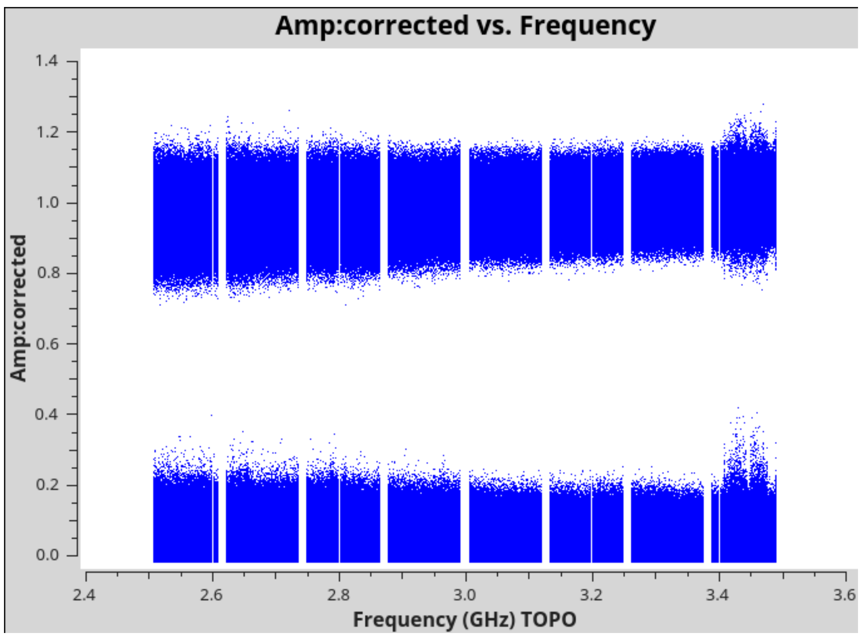
```
plotms(vis='TDRW0001_calibrated.ms',field='0',correlation='',
    timerange='',antenna='',avgtime='60',
    xaxis='frequency',yaxis='amp',ydatacolumn='corrected',
    coloraxis='corr')

plotms(vis='TDRW0001_calibrated.ms',field='0',correlation='',
    timerange='',antenna='',avgtime='60',
    xaxis='frequency',yaxis='phase',ydatacolumn='corrected',
    plotrange=[-1,-1,-180,180],coloraxis='corr')
```

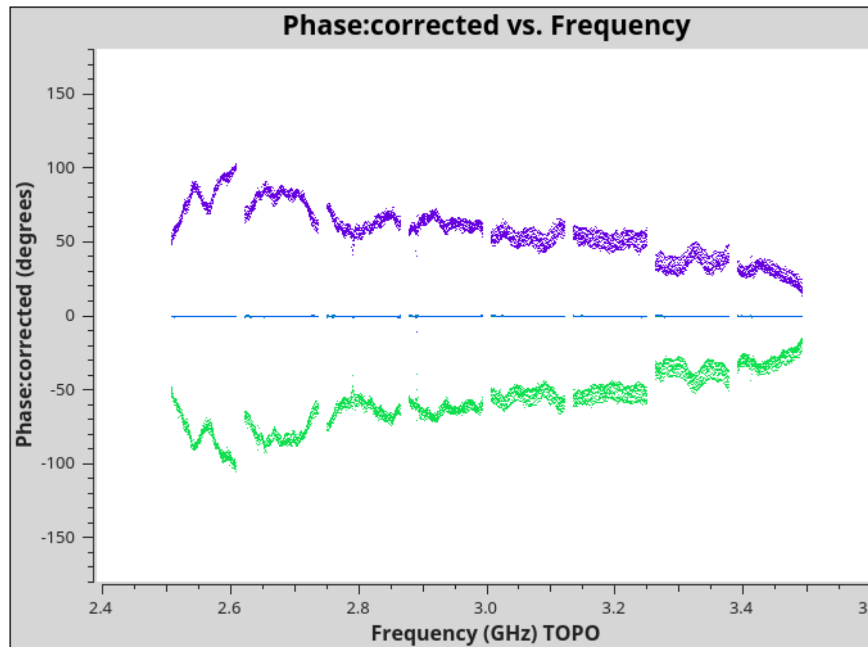




Inspect calibration – J0529+4950

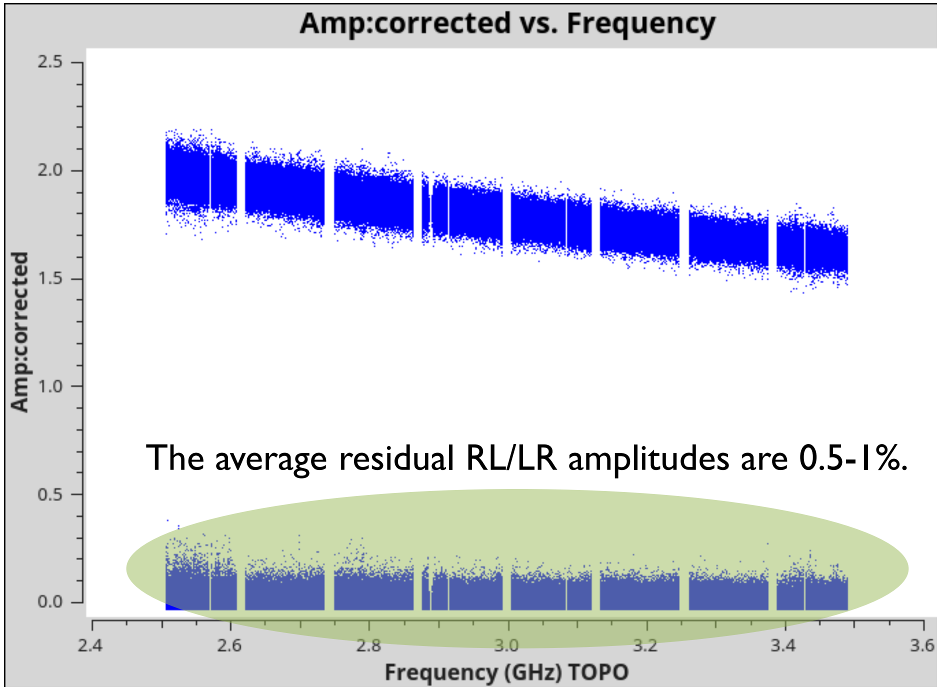
```
plotms(vis='TDRW0001_calibrated.ms',field='1',correlation='',
     timerange='',antenna='',avgtime='60',
     xaxis='frequency',yaxis='amp',ydatacolumn='corrected',
     coloraxis='corr')

plotms(vis='TDRW0001_calibrated.ms',field='1',correlation='RR,LL',
     timerange='',antenna='',avgtime='60',
     xaxis='frequency',yaxis='phase',ydatacolumn='corrected',
     plotrange=[-1,-1,-180,180],coloraxis='corr')
```



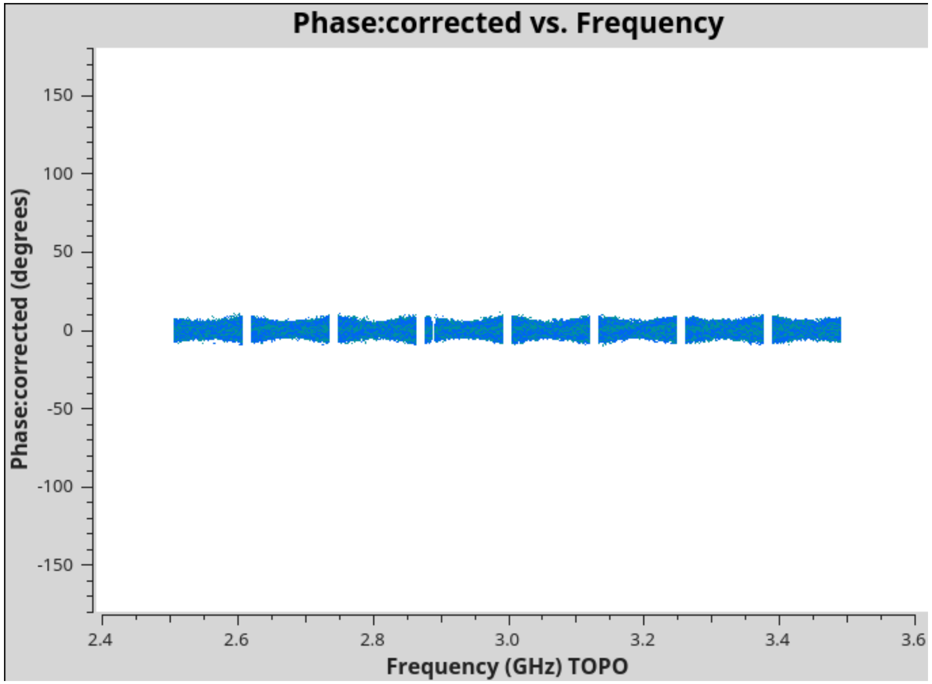


Inspect calibration – J2355+4950

```
plotms(vis='TDRW0001_calibrated.ms',field='2',correlation='',
    timerange='',antenna='',avgtime='60',
    xaxis='frequency',yaxis='amp',ydatacolumn='corrected',
    coloraxis='corr')

plotms(vis='TDRW0001_calibrated.ms',field='2',correlation='',
    timerange='',antenna='',avgtime='60',
    xaxis='frequency',yaxis='phase',ydatacolumn='corrected',
    plotrange=[-1,-1,-180,180],coloraxis='corr',avgbaseline=True)
```



The average residual RL/LR amplitudes are 0.5-1%.



Polarization Calibration

some words on circular polarization

- Beam squint – R/L beams are offset from each other
- No calibrator with Stokes V=0?
- Also no known V>0 calibrator.
- Stokes V good diagnostic for issues in linear polarization calibration.
- plotms cannot plot Stokes yet.

Further Information

- **Polarization CASA guide:** https://casaguides.nrao.edu/index.php?title=CASA_Guides:Polarization_Calibration_based_on_CASA_pipeline_standard_reduction:_The_radio_galaxy_3C75-CASA5.6.2
- **VLA Polarimetry:** https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/pol
- **CASA Polarimetry:** https://casa.nrao.edu/casadocs/casa-6.1.0/calibration-and-visibility-data/synthesis-calibration/instrumental-polarization-calibration
- **RL phase stability memo:** https://library.nrao.edu/public/memos/evla/EVLAM_205.pdf
- **CASA Pipeline Requirements & Design Specifications for Polarization:** https://library.nrao.edu/public/memos/evla/EVLAM_201.pdf

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