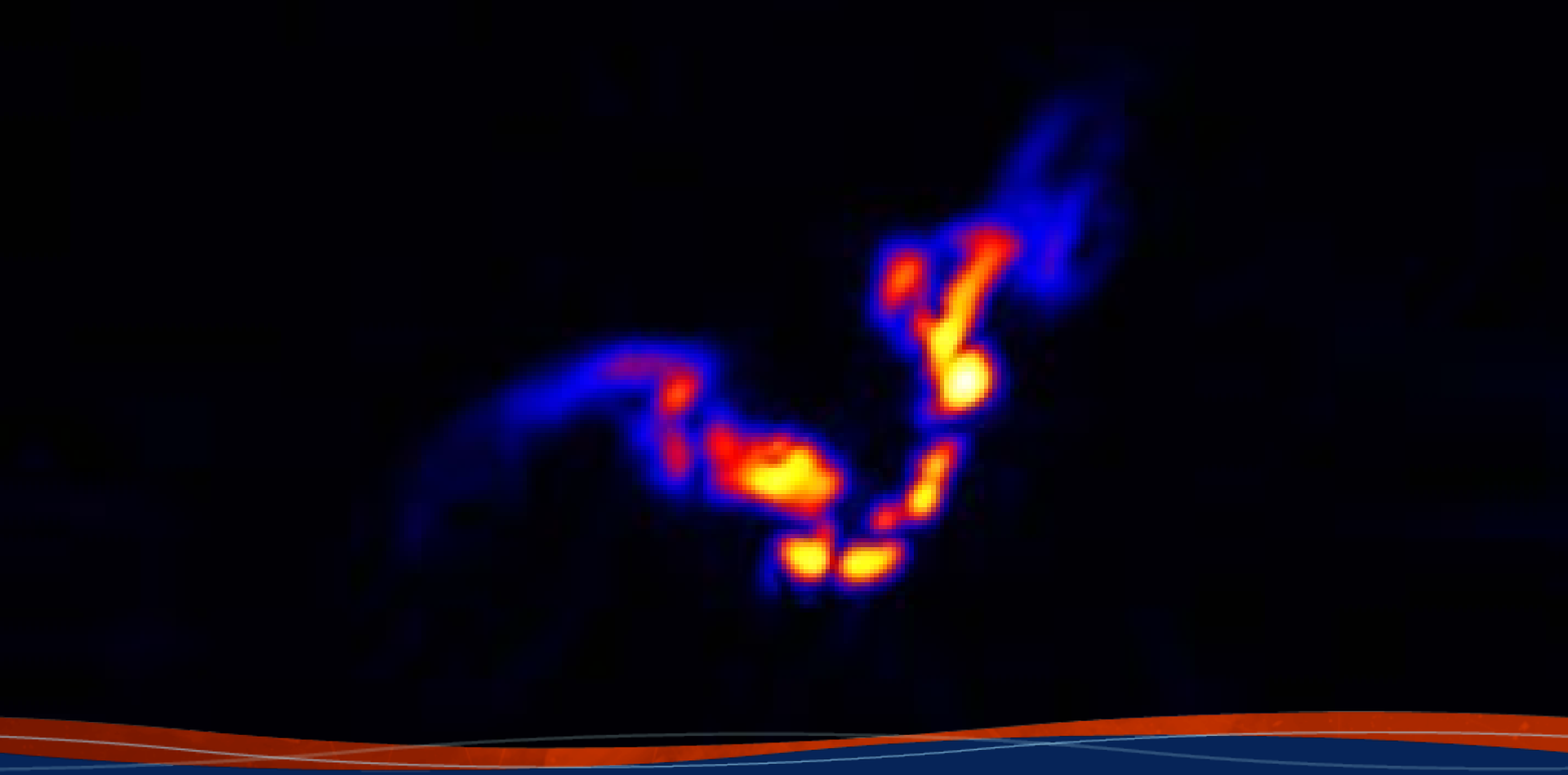


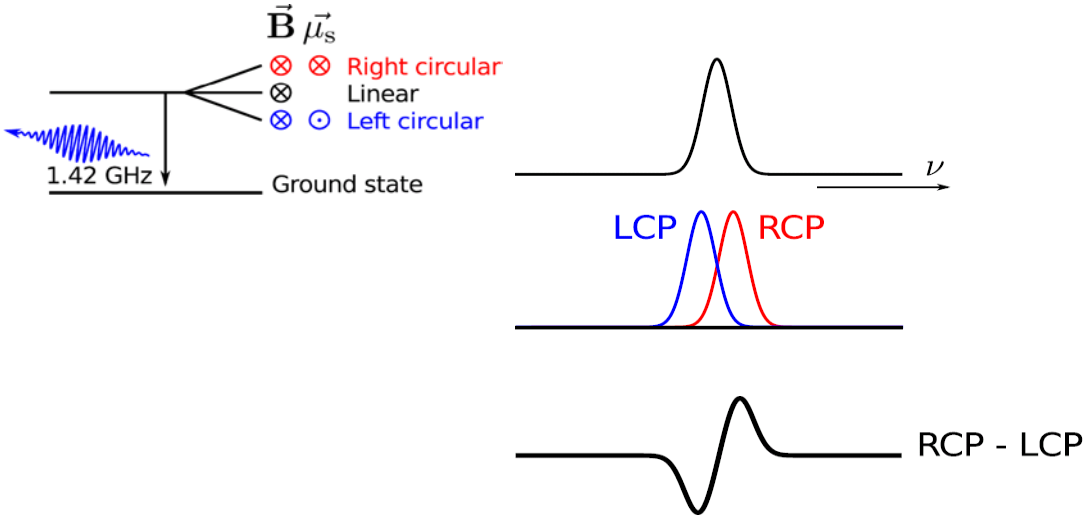
Polarization Calibration

Frank Schinzel (NRAO)

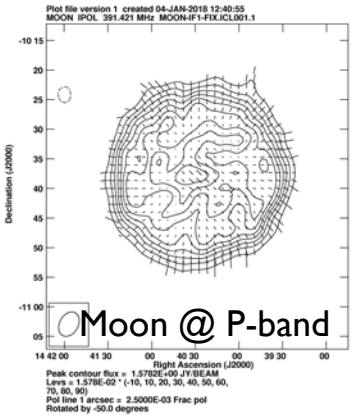
Polarized Radio Emission – Why do we care?

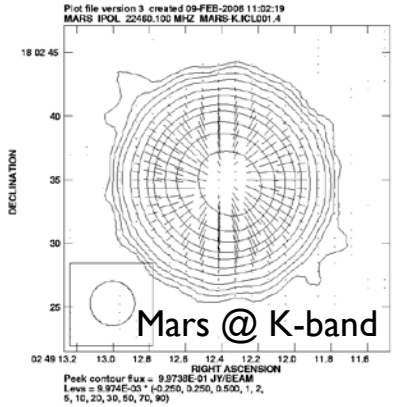
Synchrotron Emission

Zeeman Splitting

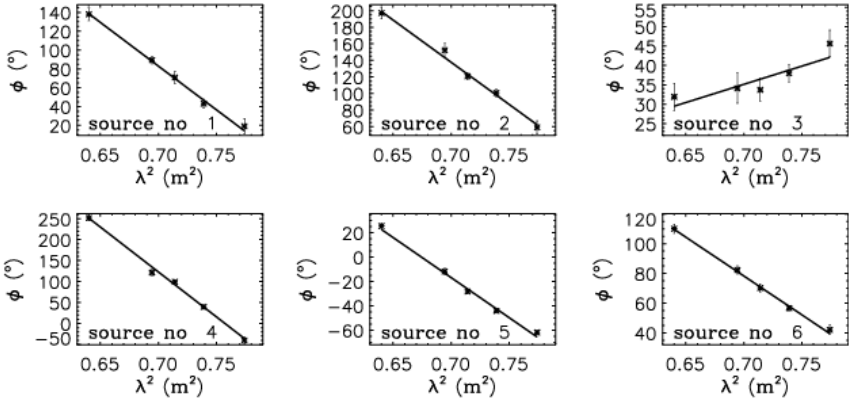


Reflections/Scattering





Faraday Rotation

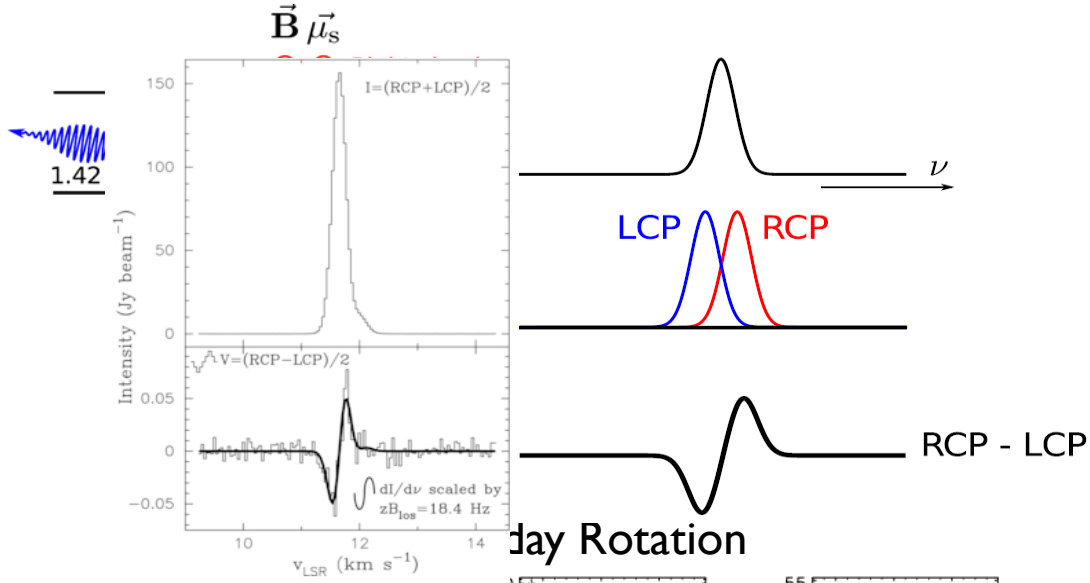


Haverkorn, Katgert, & de Bruyn 2003

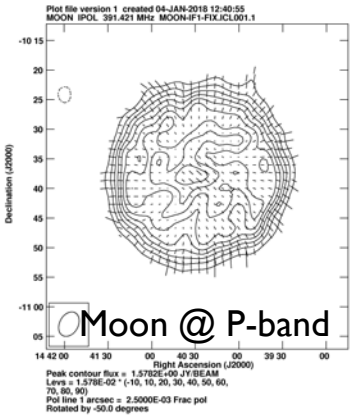
Polarized Radio Emission – Why do we care?

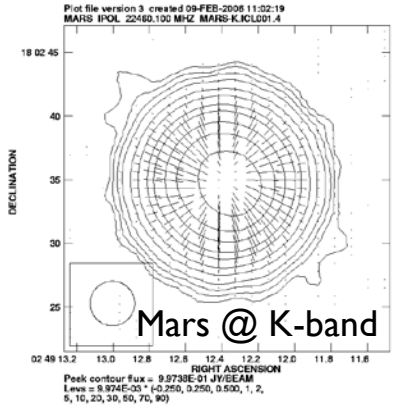
Synchrotron Emission

Zeeman Splitting



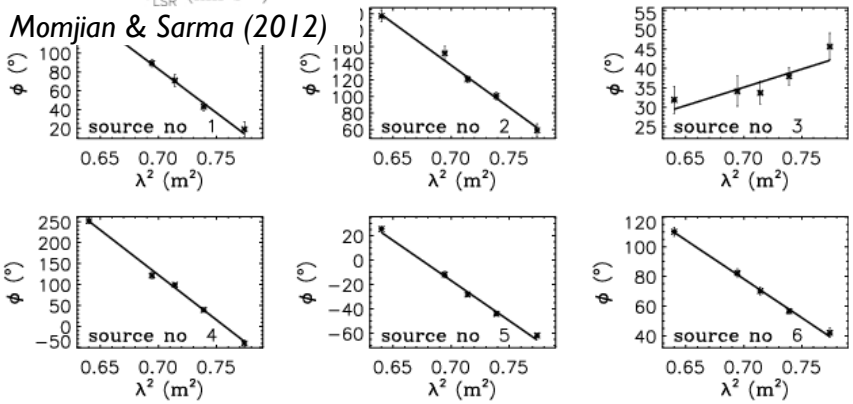
Reflections/Scattering





Faraday Rotation

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: $\chi = 0.5 \cdot \mathrm{atan2}(U/Q)$

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 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 on Tuesday, here we focus on the polarization calibration steps that are universal.

Step 0: Preparation

Start CASA 5.4.2-5 & familiarize with scans

To start CASA from the command line type: casa –r 5.4.2-5

- CASA commands for copy & paste and supplemental material can be found in your directory ('commands.py').

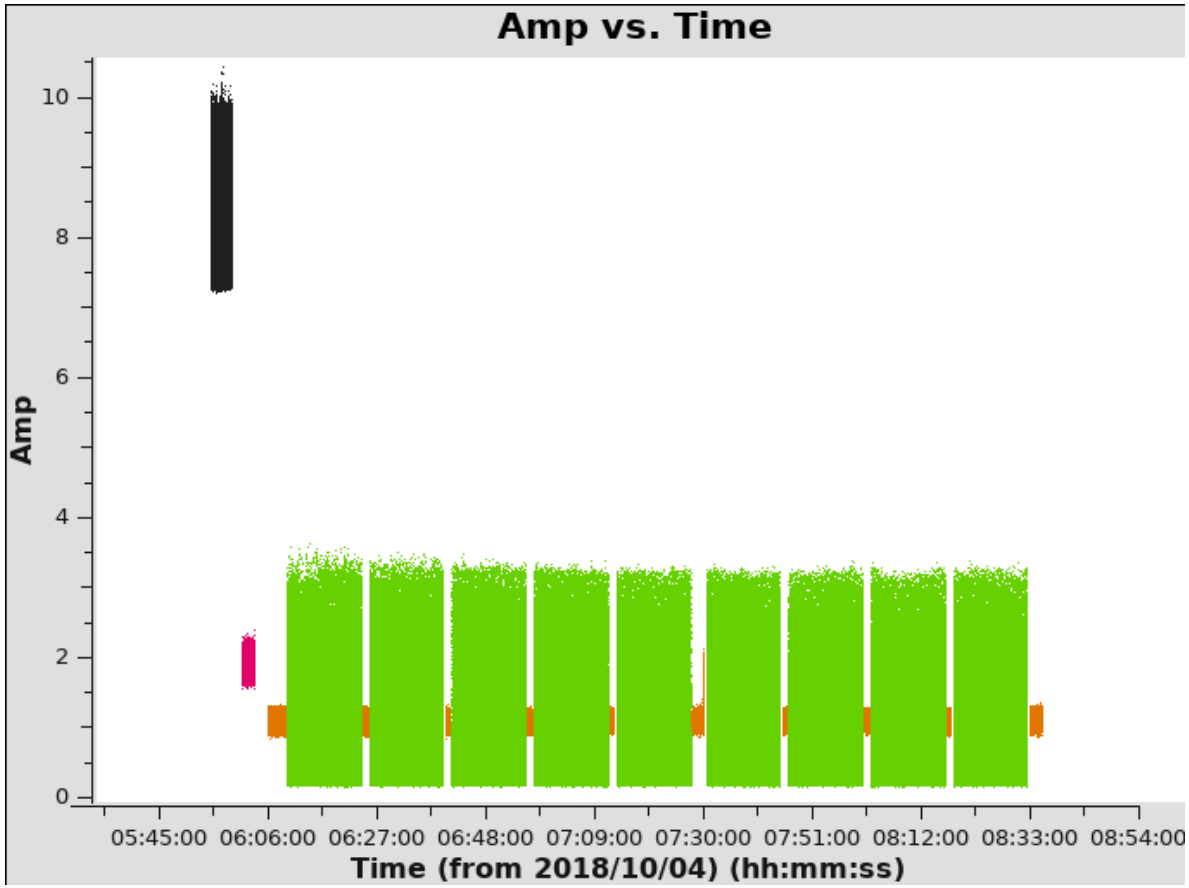
```
# In CASA
listobs(vis = 'TDRW0001_calibrated.ms')
```

- *This dataset: parallel hand calibration applied and split out the corrected column (applycal with parang=False).*
- 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?

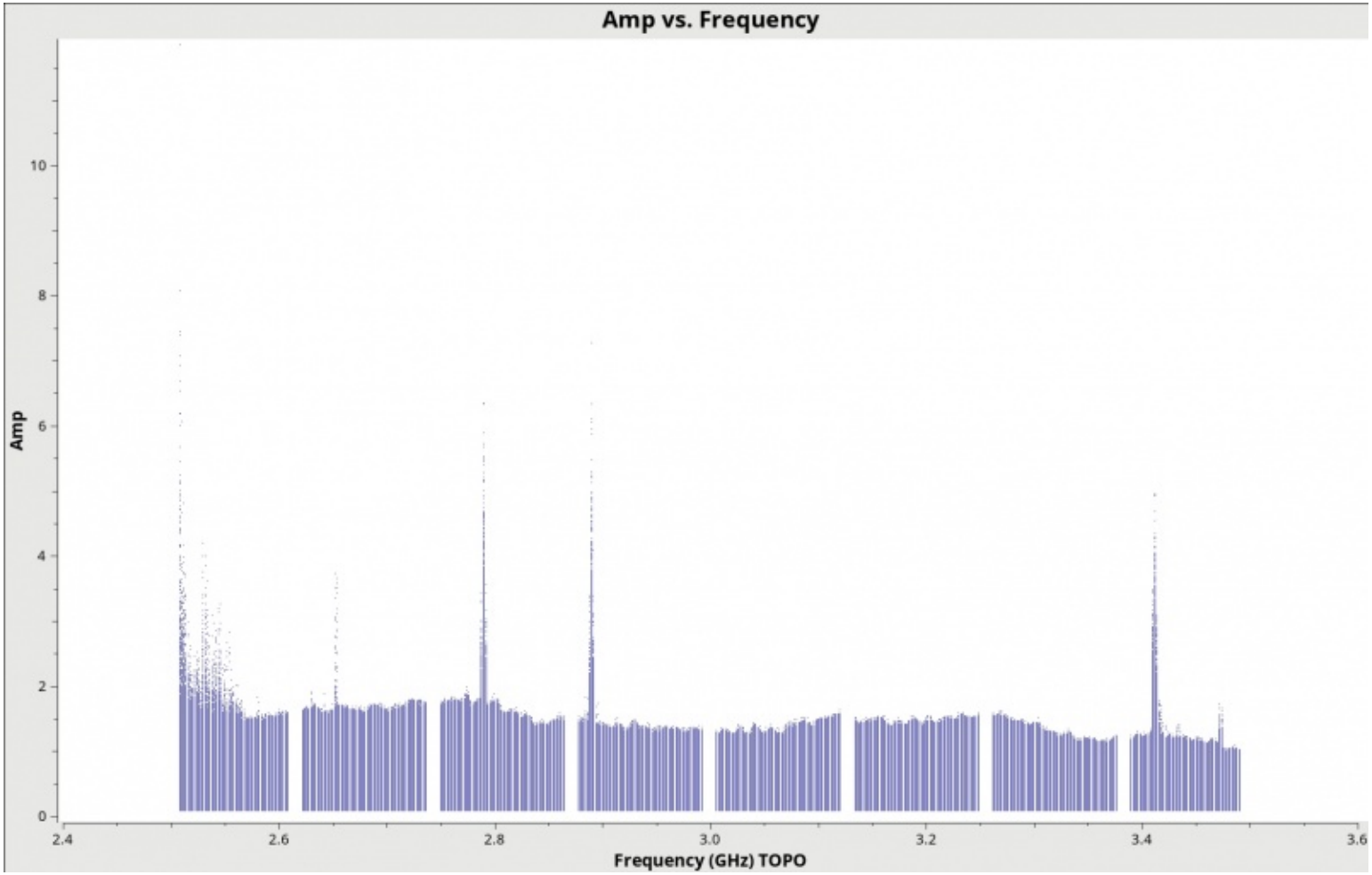
(marked as phase calibrator)

Inspect dataset

```
plotms(vis='TDRW0001_calibrated.ms', selectdata=True,
        correlation='RR', spw='0~7:32', coloraxis='field')
```



Additional flagging for RL/LR



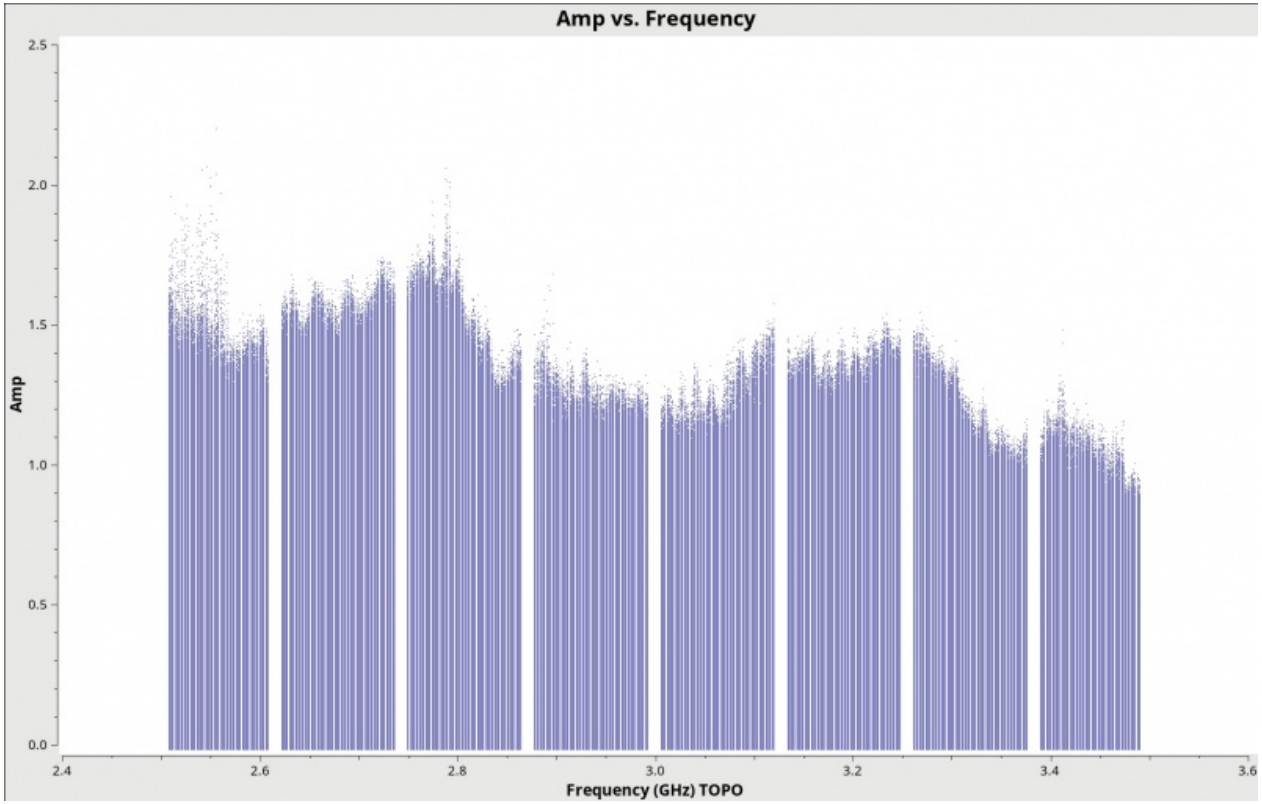
Additional flagging for RL/LR

```
#This has already been done for your dataset to save time.
# 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)
```

Additional flagging for RL/LR

```
plotms(vis='TDRW0001_calibrated.ms', xaxis='frequency', yaxis='amplitude', field='0~2',
        correlation='RL,LR')
```



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
- Additional calibrators monitored through projects TPOL0003 & TCAL0009, currently you have to reduce this data yourself if needed.
- In your directory is the textfile '3C48_2019.dat' that was compiled from the 2019 values for 3C48 that are provided at the above webpages.

CASA task setjy (https://casa.nrao.edu/casadocs-devel/stable/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.

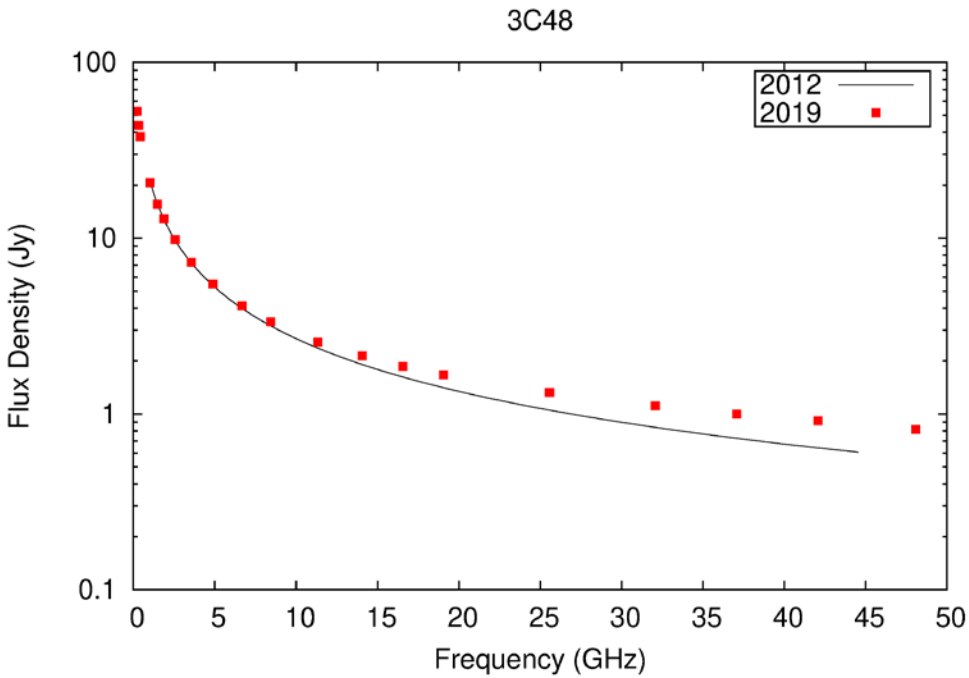
```
standard     =  'manual'      #  Flux density standard
fluxdensity  =  [1, 0, 0, 0]  #  Specified flux density in Jy [I,Q,U,V]
spix         =     []         #  Spectral index (including higher terms) of I fluxdensity
reffreq      =      ''        #  Reference frequency for spix
polindex     =      []   #  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)
```

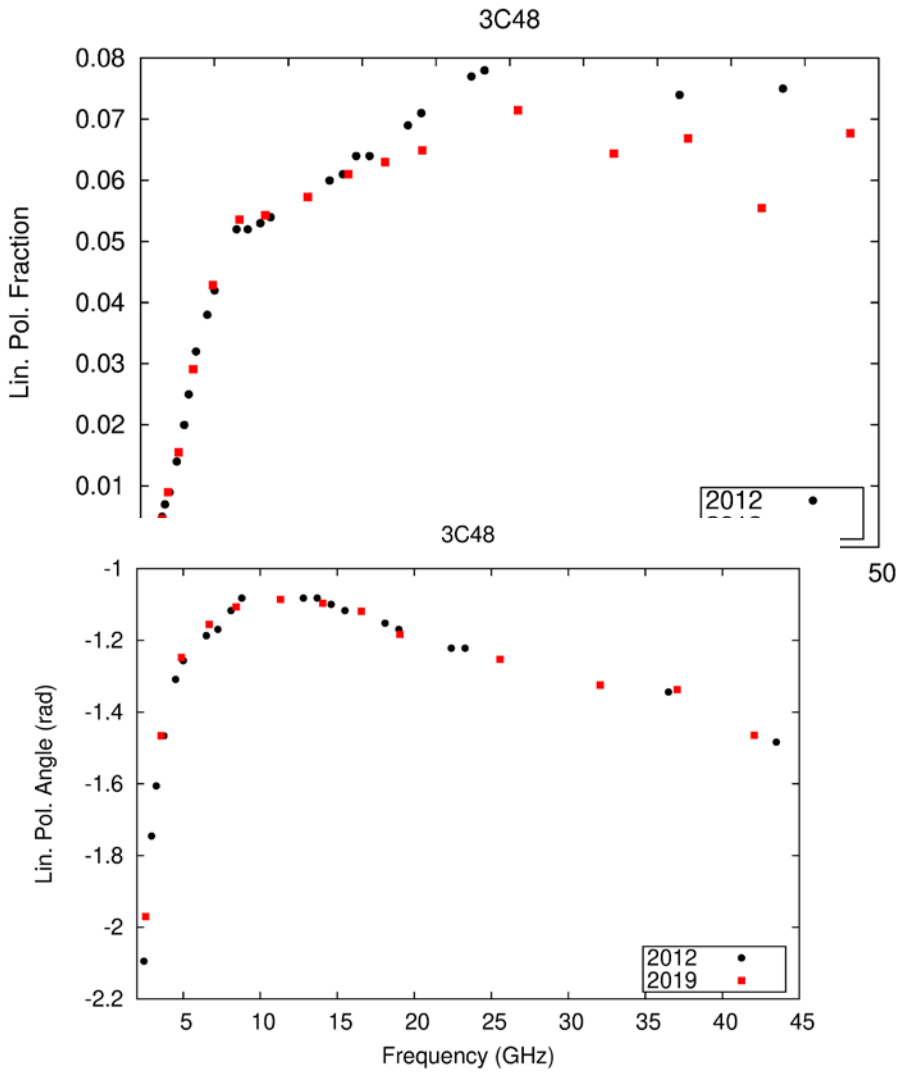
$$S(\nu) = fluxdensity[0] * \frac{\nu}{reffreq}^{spix[0]+spix[1]*log(\nu/reffreq)+..}$$

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

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

3C48: Lin. Pol. Angle Calibrator



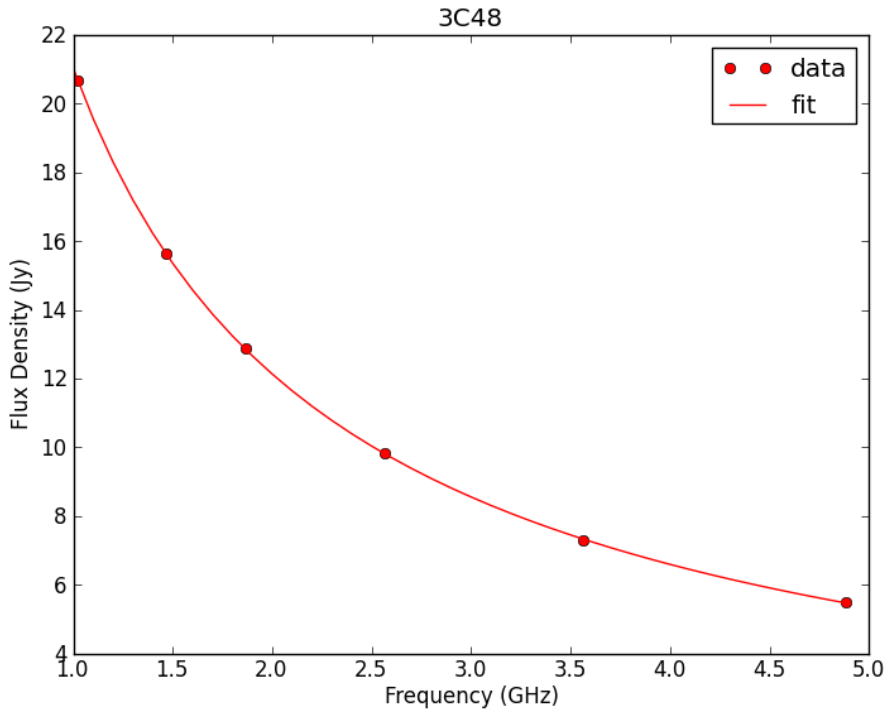


CASA task setjy (https://casa.nrao.edu/casadocs-devel/stable/global-task-list/task_setjy/about)

determining the coefficients for 3C 48 at S-band - Spix

We use known values of 3C48 (3C48_2019.dat) to fit Stokes I and spectral index & curvature.

```
execfile('fit_I.py')
```



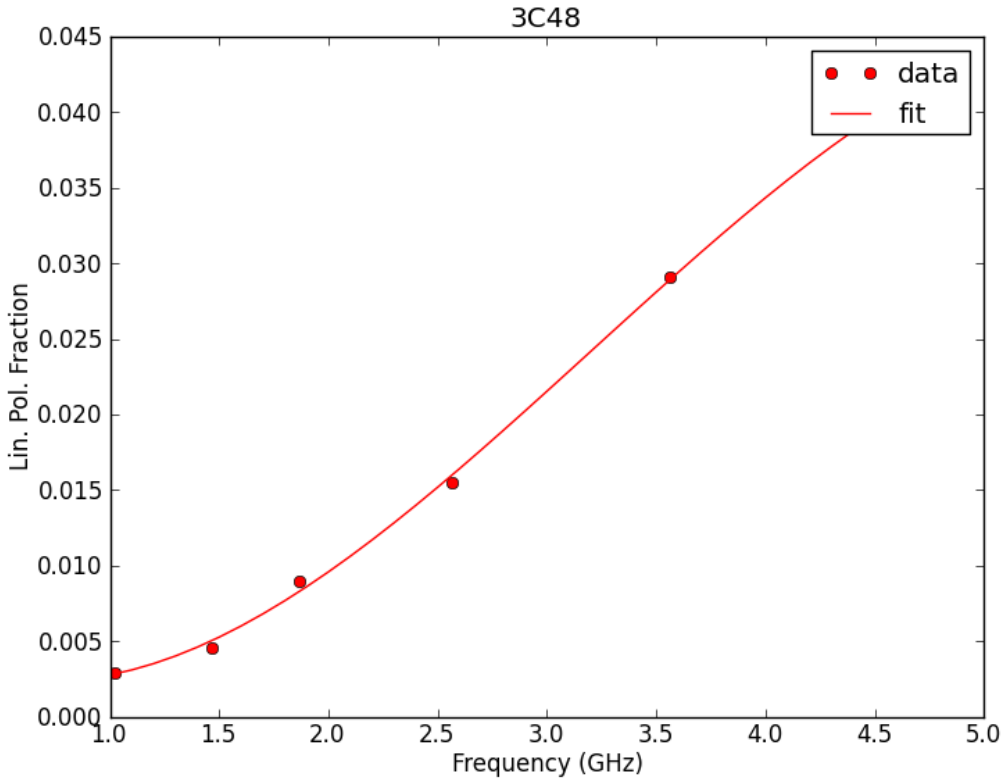
I@3GHz = 8.5555 Jy
spix = [-0.88640,
-0.14323]

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

determining the coefficients for 3C 48 at S-band - polindex

We use known values of 3C48 (3C48_2019.dat) to fit linear polarization fraction.

```
execfile('fit_PF.py')
```



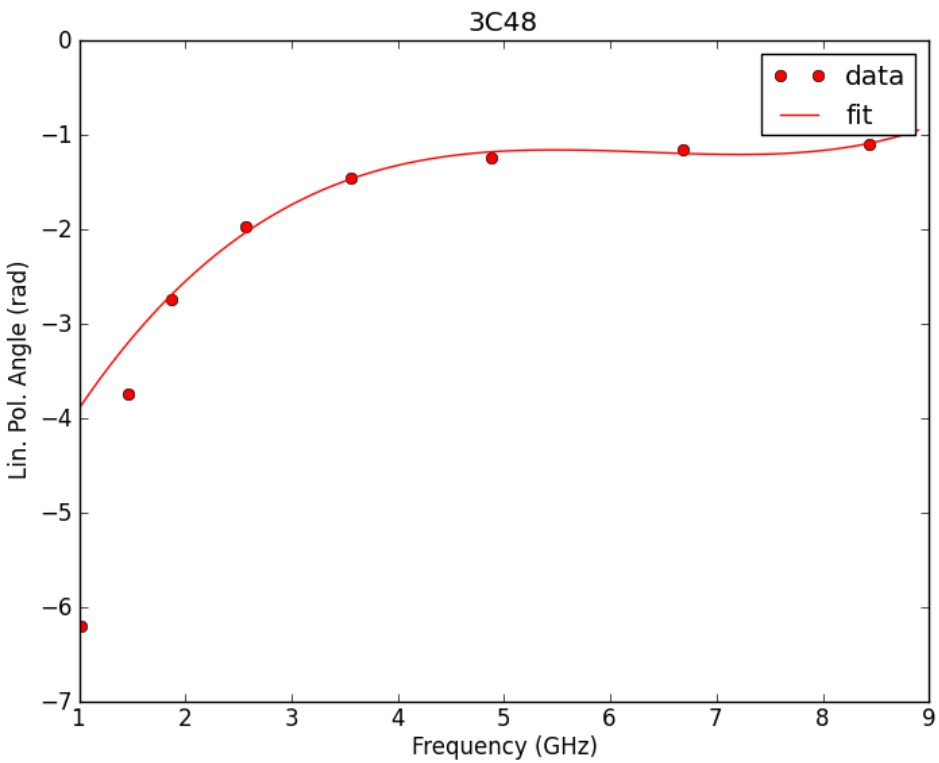

```
polindex = [0.02152579,
            0.03924469,
            0.00382036,
           -0.0192665]
```

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

determining the coefficients for 3C 48 at S-band - polangle

We use known values of 3C48 (3C48_2019.dat) to fit linear polarization angle in radians.

```
execfile('fit_PA.py')
```




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

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

```
%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)
```

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

setjy returns a Python dictionary (CASA record) that reports the Stokes I, Q, U and V terms. If not captured through a variable, here 'mysetjy', it is printed to the command line window.

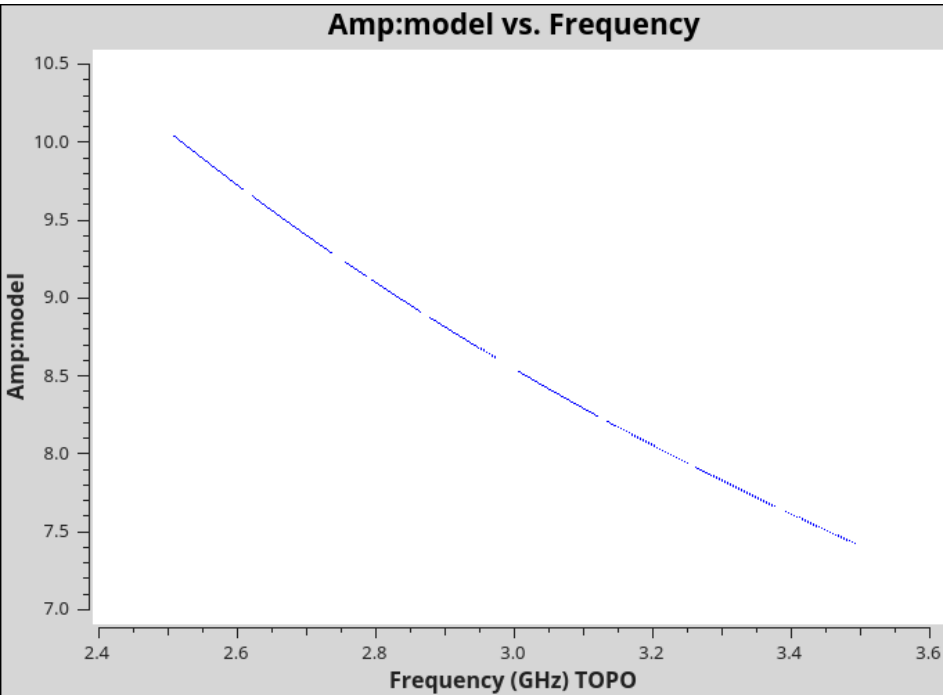
```
print mysetjy
```

Check that the model is set correctly

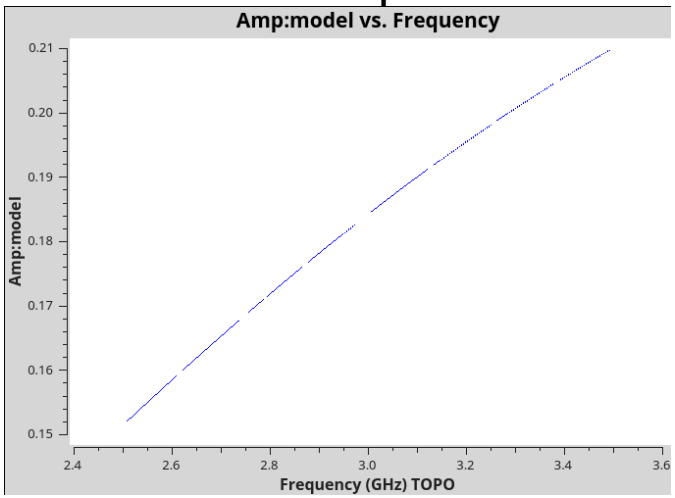
```
# Flux density
plotms(vis='TDRW0001_calibrated.ms', field='0', correlation='RR', timerange='',
            antenna='ea01&ea02', xaxis='frequency', yaxis='amp', ydatacolumn='model')
# RL amplitudes
plotms(vis='TDRW0001_calibrated.ms', field='0', correlation='RL', timerange='',
            antenna='ea01&ea02', xaxis='frequency', yaxis='amp', ydatacolumn='model')
# RL phase
plotms(vis='TDRW0001_calibrated.ms', field='0', correlation='RL', timerange='',
            antenna='ea01&ea02', xaxis='frequency', yaxis='phase', ydatacolumn='model')
```

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

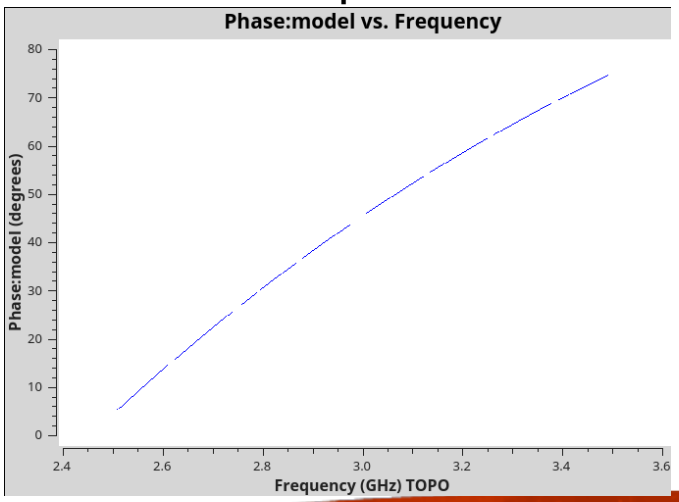
RR amplitude



RL amplitude



RL phase



Scale D-term calibrators (J0259+0747; J2355+7828)

In order to obtain the correct amplitude scaling for instrumental polarization calibration, we need to also specify the Stokes I model that was used for the D-term calibrator(s).

*The model values of the two D-term calibrators can be obtained from the pipeline weblog under the task hifv_fluxboot2 inside the CASA log.

Fitted spectrum for J2355+4950 with fitorder=2: Flux density = 1.76852 +/- 0.000723163 (freq=2.98457 GHz) spidx=-0.603023 +/- 0.00307991 curv=-0.20303 +/- 0.0750626

Fitted spectrum for J0259+0747 with fitorder=2: Flux density = 0.970631 +/- 0.000745372 (freq=2.98457 GHz) spidx=0.172459 +/- 0.00531882 curv=-0.191716 +/- 0.140254

Scale D-term calibrators (J0259+0747; J2355+7828)

```
%cpaste
setjy(vis='TDRW0001_calibrated.ms',
        field='J2355+4950', standard='manual',
        fluxdensity = [1.76852,0,0,0],
        spix = [-0.603023, -0.20303],
        reffreq = '2.98457GHz',
        polindex=[], polangle=[],
        usescratch=True )

setjy(vis='TDRW0001_calibrated.ms',
        field='J0259+0747', standard='manual',
        fluxdensity = [0.970631,0,0,0],
        spix = [0.172459,-0.191716],
        reffreq = '2.98457GHz',
        polindex=[], polangle=[],
        usescratch=True )
```

Step 1: Determine R-L delay

Solving for the cross-hand delays

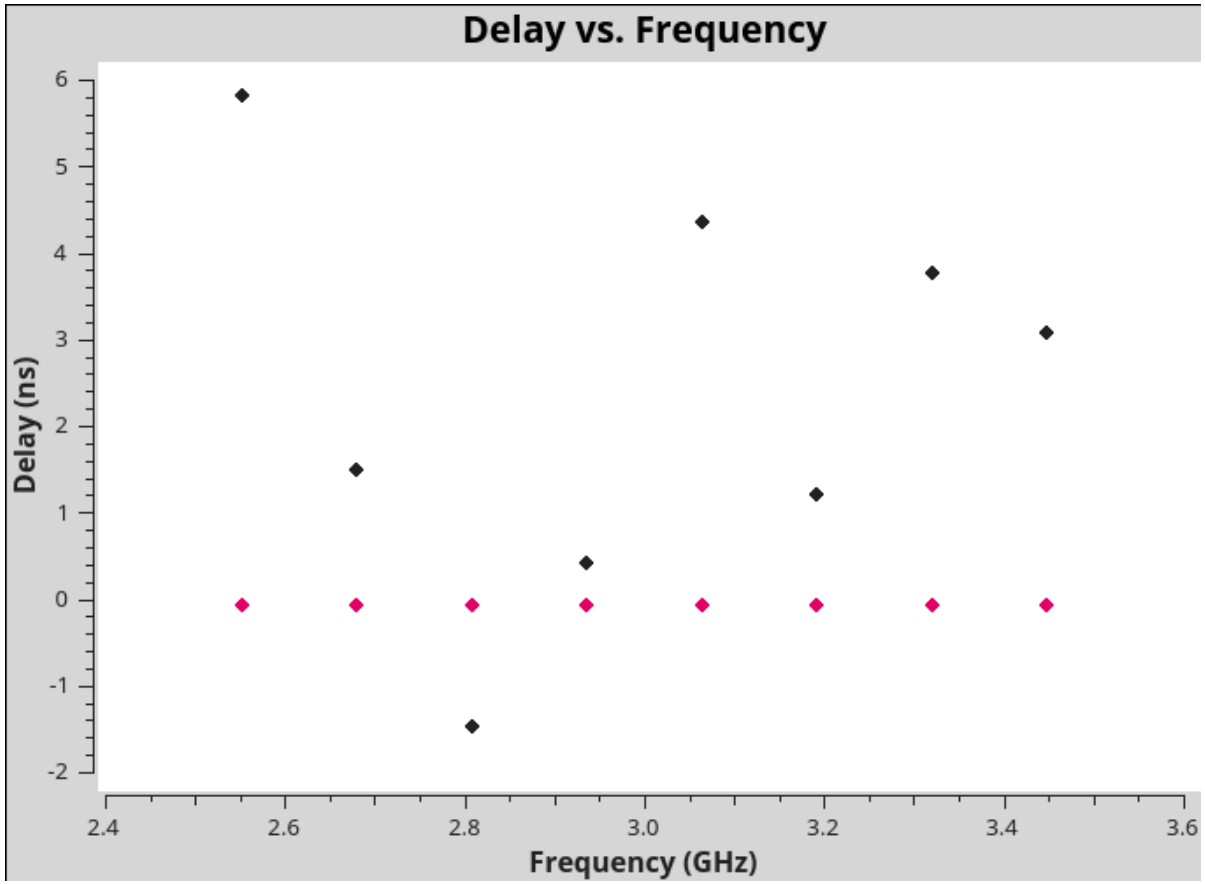
```
# solve using Single Band Delay
%cpaste
kcross_sbd = 'TDRW0001_calibrated.Kcross_sbd'
gaincal(vis='TDRW0001_calibrated.ms',
    caltable=kcross_sbd,
    field='0137+331=3C48',
    spw='0~7:5~58',                    # ignore edge channels
    refant='ea10',                     # same reference antenna 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:
Time=2018/10/04/05:51:12.0 Spw=0 Global cross-hand delay=5.71477 nsec
Time=2018/10/04/05:51:10.6 Spw=1 Global cross-hand delay=1.51269 nsec
Time=2018/10/04/05:51:11.8 Spw=2 Global cross-hand delay=-1.36895 nsec
Time=2018/10/04/05:51:11.5 Spw=3 Global cross-hand delay=0.468607 nsec
Time=2018/10/04/05:51:10.5 Spw=4 Global cross-hand delay=4.29537 nsec
Time=2018/10/04/05:51:10.6 Spw=5 Global cross-hand delay=1.23363 nsec
Time=2018/10/04/05:51:10.4 Spw=6 Global cross-hand delay=3.72454 nsec
Time=2018/10/04/05:51:10.5 Spw=7 Global cross-hand delay=3.04475 nsec

Solving for the cross-hand delays
visualize resulting delays

```
plotms(vis=kcross_sbd,xaxis='frequency',yaxis='delay',antenna='ea10',coloraxis='corr')
```



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)
```

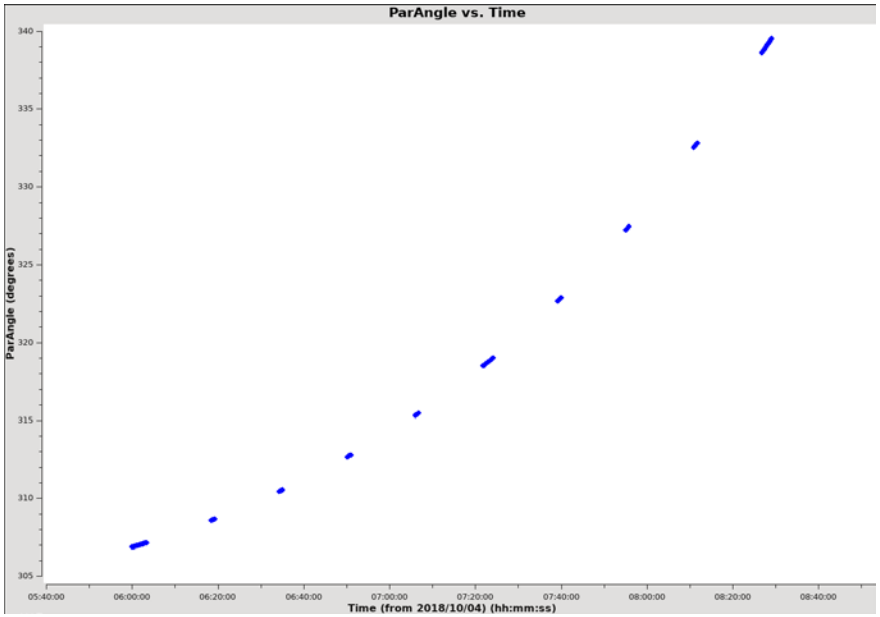
Solving for the cross-hand delays
Output printed in the logger

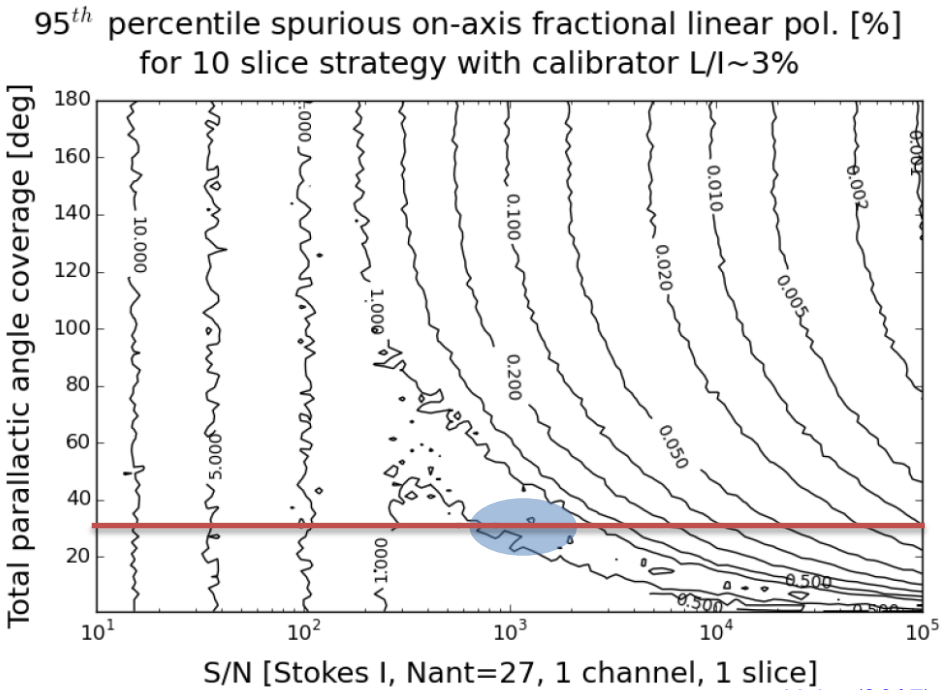
For single band delay there are 8 solutions:
Time=2018/10/04/05:51:12.0 Spw=0 Global cross-hand delay=5.71477 nsec
Time=2018/10/04/05:51:10.6 Spw=1 Global cross-hand delay=1.51269 nsec
Time=2018/10/04/05:51:11.8 Spw=2 Global cross-hand delay=-1.36895 nsec
Time=2018/10/04/05:51:11.5 Spw=3 Global cross-hand delay=0.468607 nsec
Time=2018/10/04/05:51:10.5 Spw=4 Global cross-hand delay=4.29537 nsec
Time=2018/10/04/05:51:10.6 Spw=5 Global cross-hand delay=1.23363 nsec
Time=2018/10/04/05:51:10.4 Spw=6 Global cross-hand delay=3.72454 nsec
Time=2018/10/04/05:51:10.5 Spw=7 Global cross-hand delay=3.04475 nsec

For multiband delay there is one solution:
Time=2018/10/04/05:51:10.9 Multi-band cross-hand delay=3.68198 nsec

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

Solving for instrumental polarization
J0259+0747





Hales (2017)

~33 degrees parallactic angle coverage
10 scans/slices; Flux density ~0.9 Jy

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

```
plotms(vis='TDRW0001_calibrated.ms', field='J0259+0747', xaxis='time',yaxis='parang')
```

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

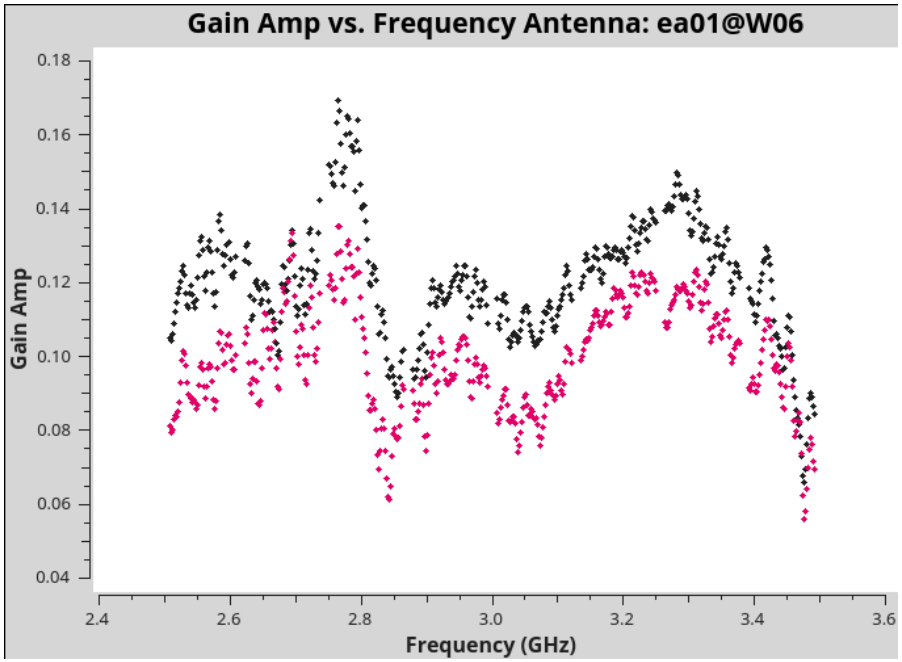
Check output in logger:

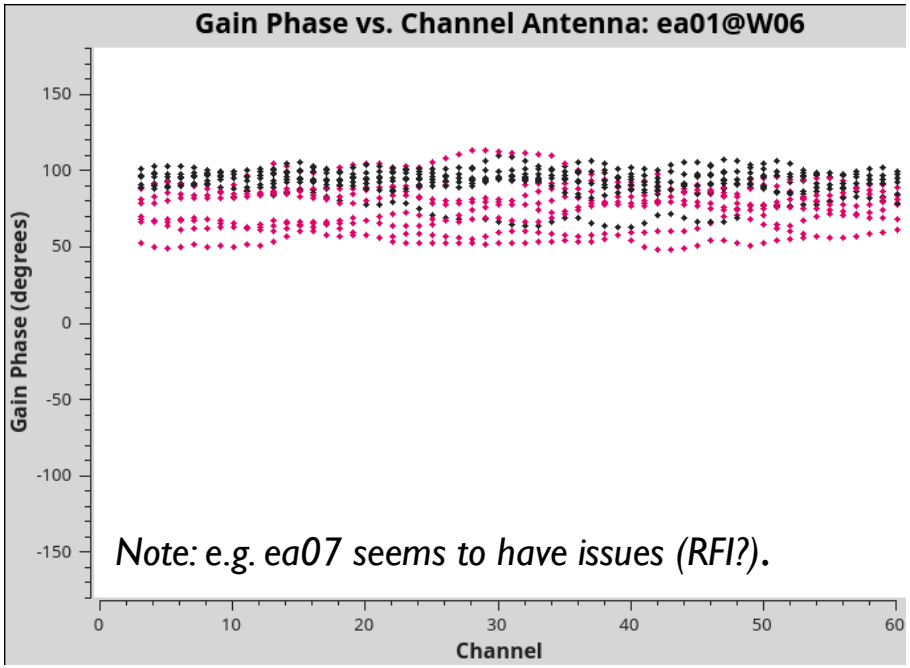
Fractional polarization solution for J0259+0747 (spw = 0): : Q = 0.0261594, U = 0.0334233 (P = 0.0424432, X = 25.9754 deg)
Fractional polarization solution for J0259+0747 (spw = 1): : Q = 0.0145776, U = 0.038399 (P = 0.041073, X = 34.6057 deg)
Fractional polarization solution for J0259+0747 (spw = 2): : 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

```
# Amplitude solutions
plotms(vis=dtab_J0259,xaxis='freq',yaxis='amp', iteraxis='antenna',coloraxis='corr')
# Phase solutions
plotms(vis=dtab_J0259,xaxis='chan',yaxis='phase', iteraxis='antenna',coloraxis='corr')
```



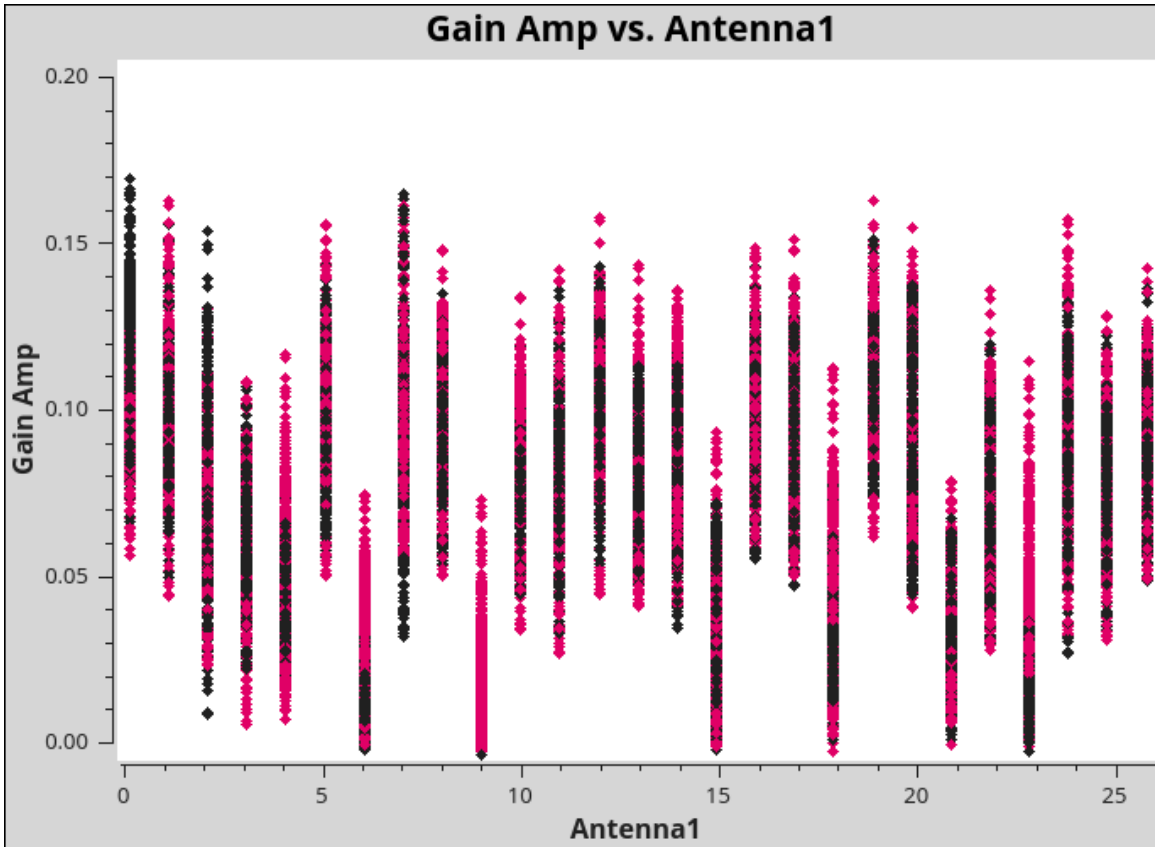


Note: e.g. ea07 seems to have issues (RFI?).

Solving for instrumental polarization

J0259+0747 / Df+QU – polarized – inspect results

```
plotms(vis=dtab_J0259,xaxis='antenna1',yaxis='amp',coloraxis='corr')
```



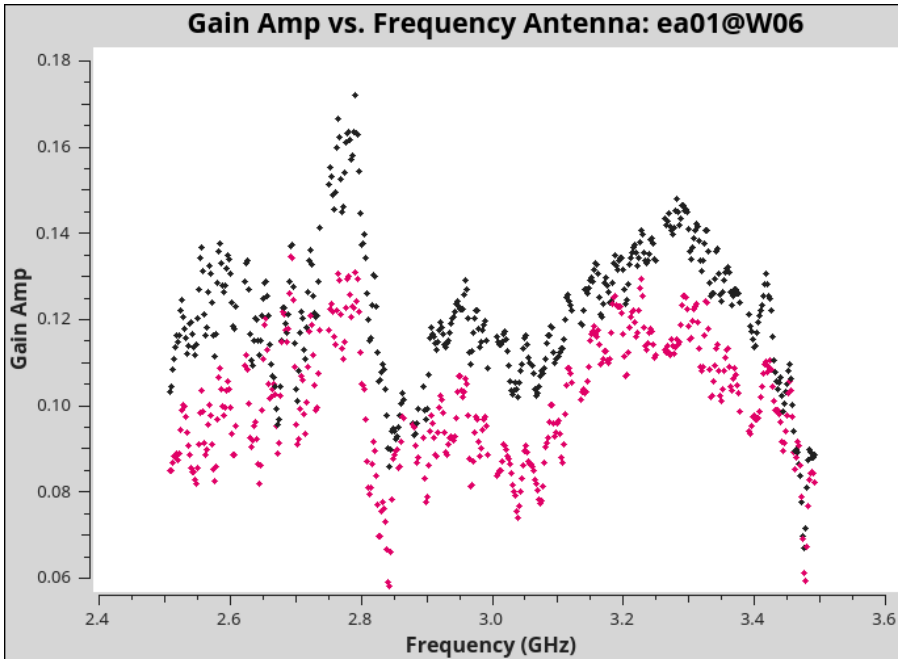
Solving for instrumental polarization
J2355+4950 / Df - unpolarized

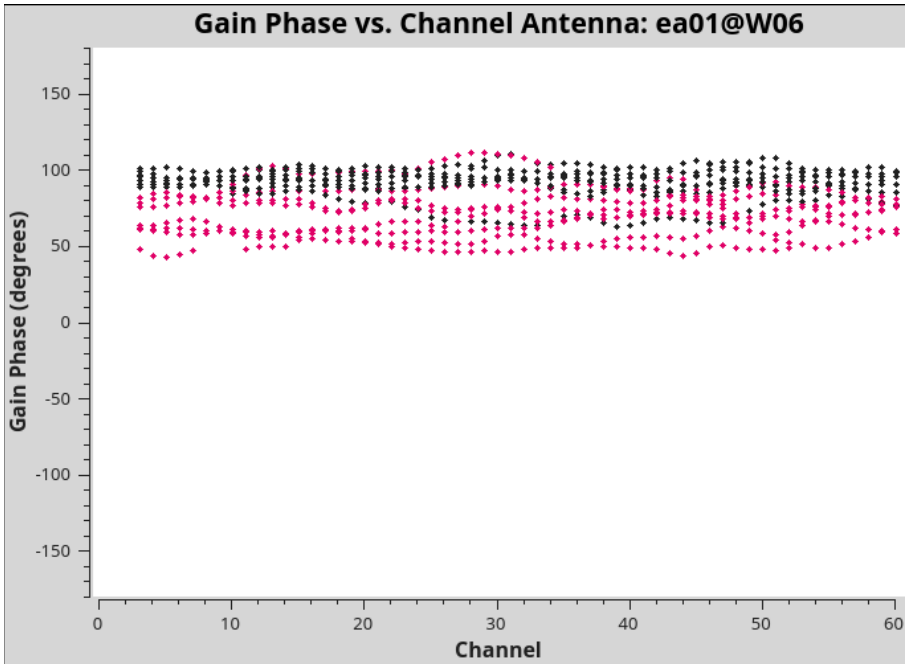
```
%cpaste
dtab_J2355 = 'TDRW0001_calibrated.Df'
polcal(vis='TDRW0001_calibrated.ms',
       caltable=dtab_J2355,
       field='J2355+4950',
       spw='0~7',
       refant='ea10',
       poltype='Df',
       solint='inf,2MHz',
       combine='scan',
       gaintable=[kcross_mbd],
       gainfield=['],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

Solving for instrumental polarization

J2355+4950 / Df – unpolarized – inspect results

```
# Amplitude solutions
plotms(vis=dtab_J2355,xaxis='freq',yaxis='amp', iteraxis='antenna',coloraxis='corr')
# Phase solutions
plotms(vis=dtab_J2355,xaxis='chan',yaxis='phase', iteraxis='antenna',coloraxis='corr')
```

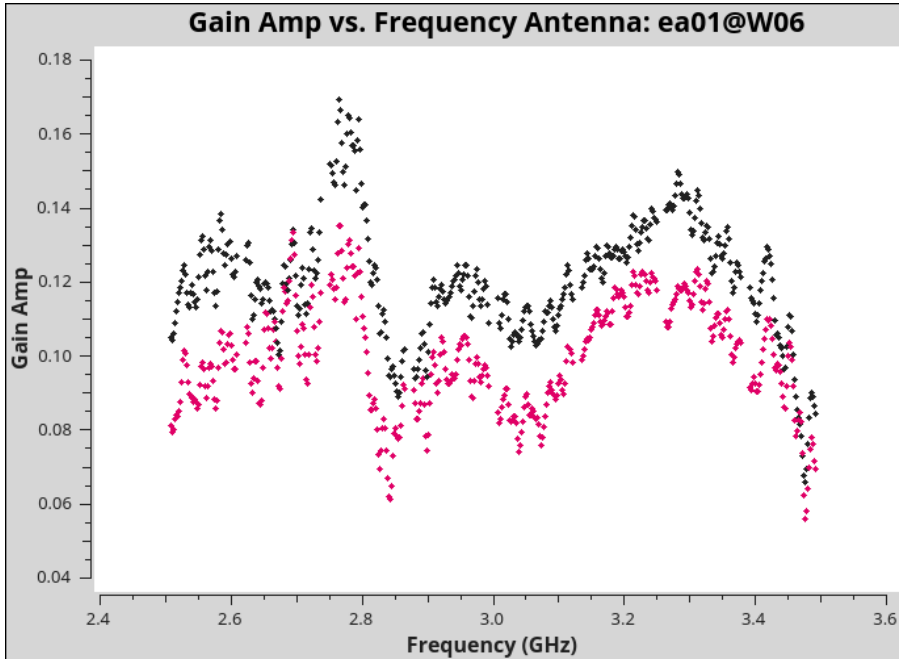




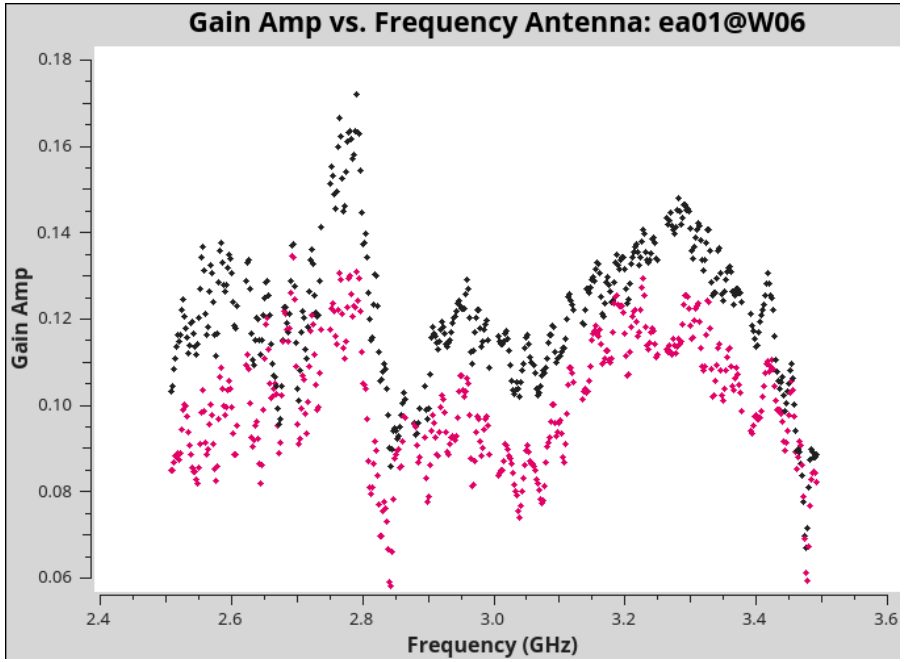
Solving for instrumental polarization

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.

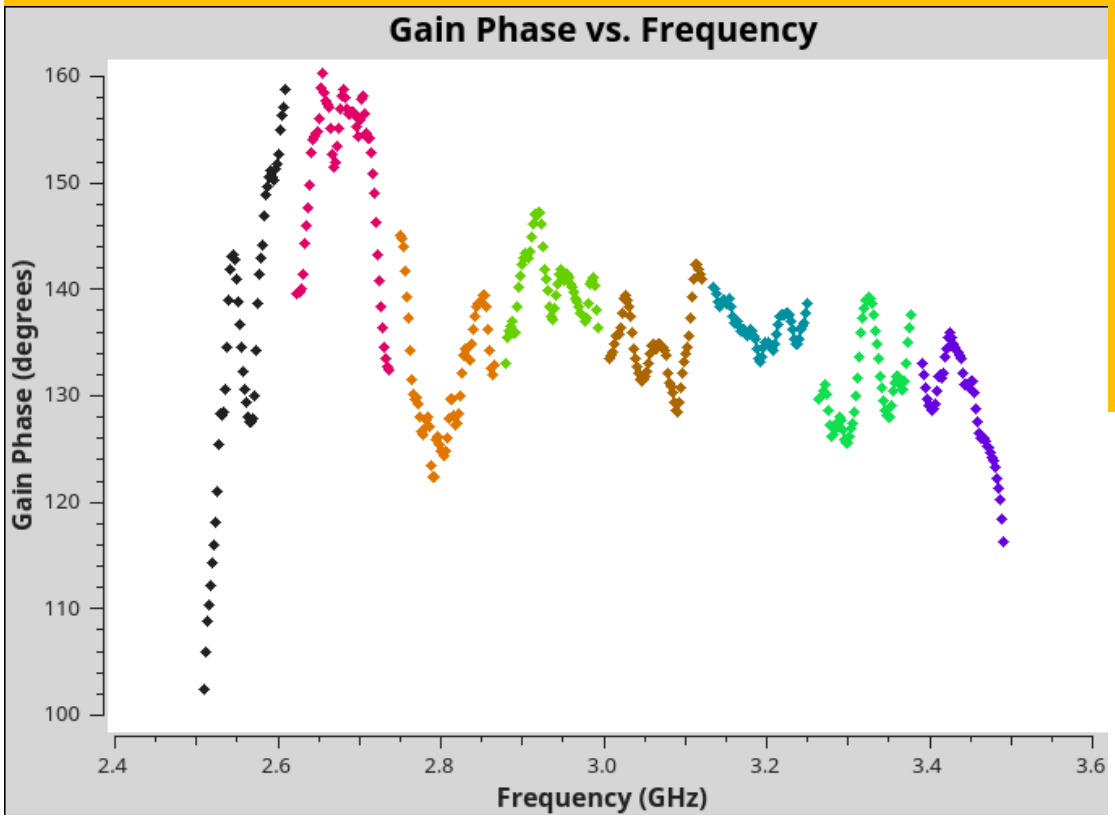
```
%cpaste
xtab = 'TDRW0001_calibrated.Xf'
polcal(vis='TDRW0001_calibrated.ms',
       caltable=xtab,
       spw='0~7',
       field='0137+331=3C48',
       solint='inf,2MHz',
       combine='scan',
       poltype='Xf',
       refant = 'ea10',
       gaintable=[kcross_mbd,dtab_J0259],
       gainfield=['',''],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

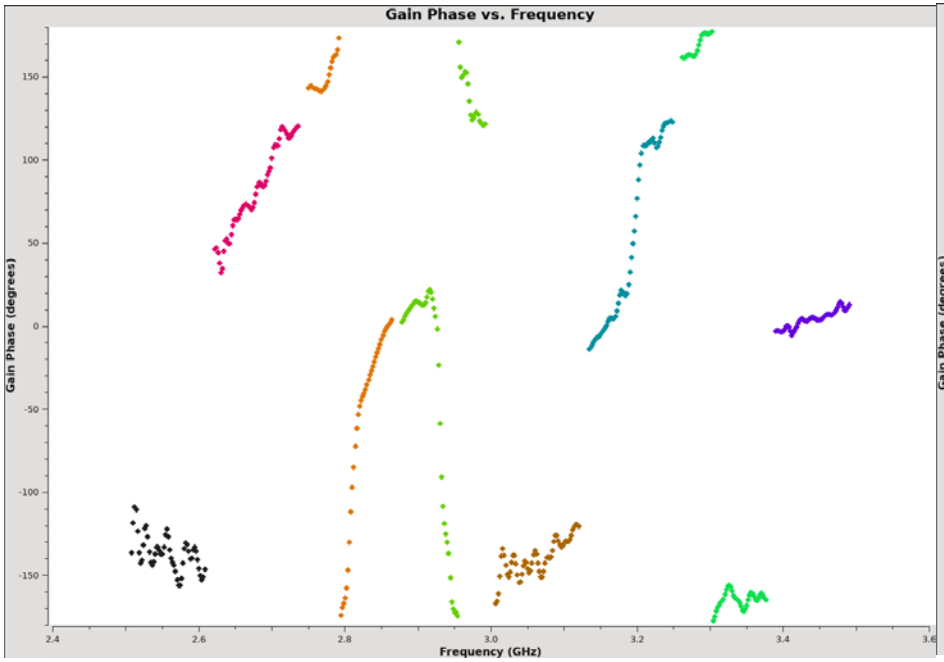



```
plotms(vis=xtab,
       xaxis='frequency',
       yaxis='phase',
       coloraxis='spw')
```

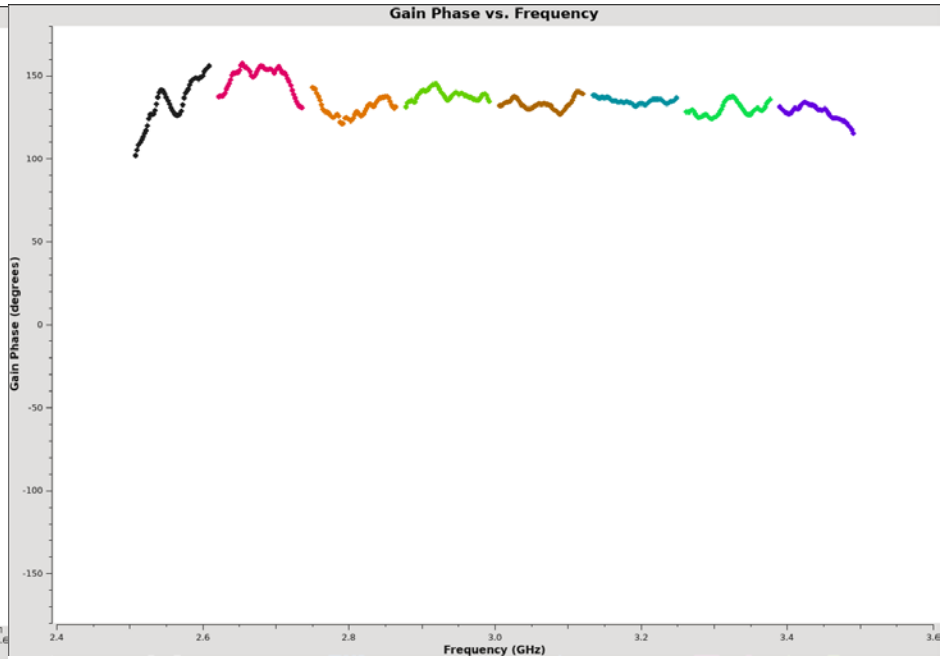
Setting R-L phase

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



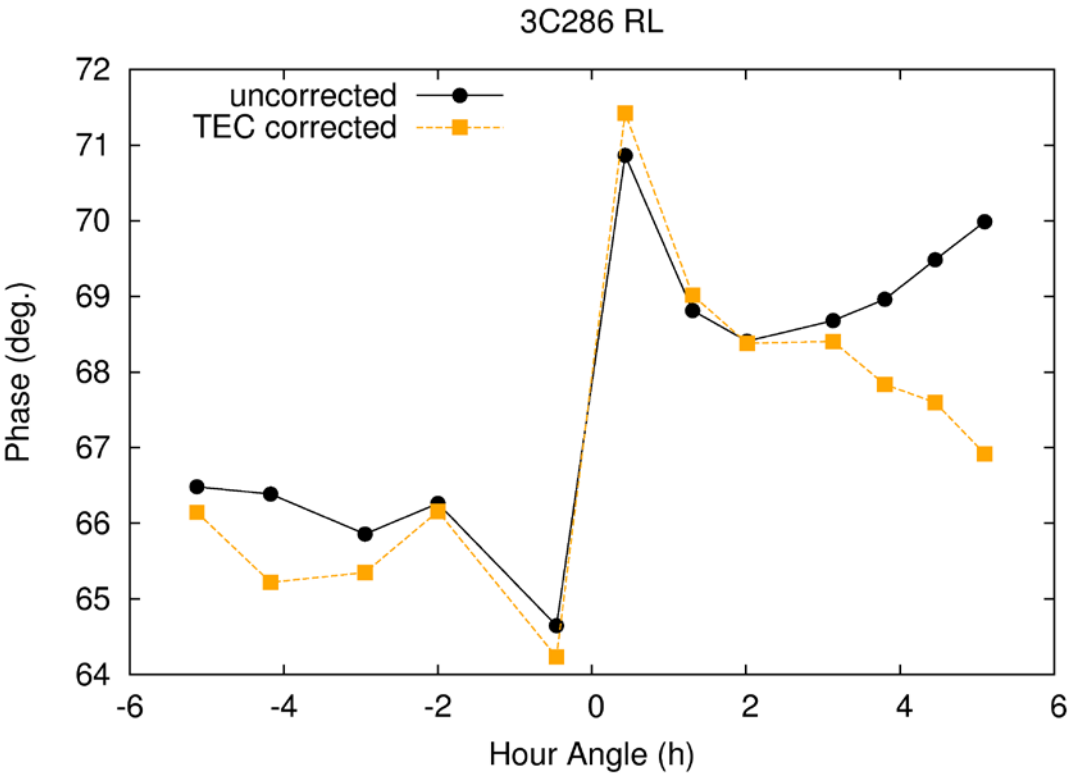
Step 4: Apply Calibration & Inspect

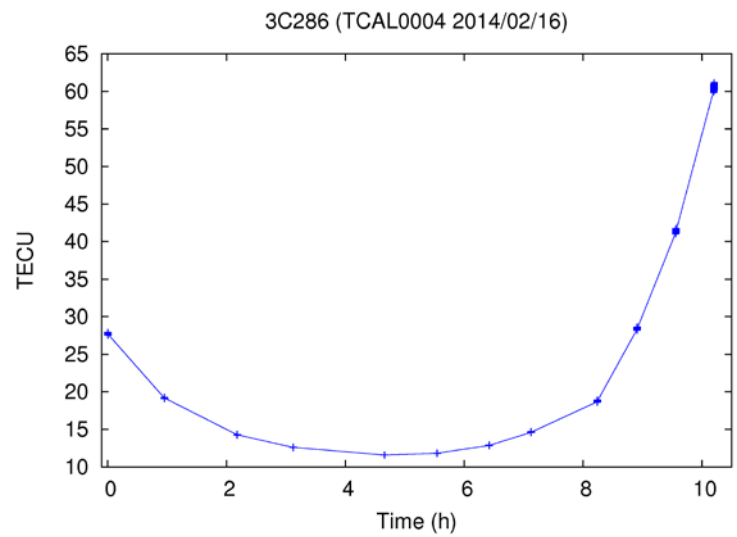
Finally let's apply the calibration

```
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)
```

VLA RL phase stability

Ionosphere – typically a few degrees at 3GHz

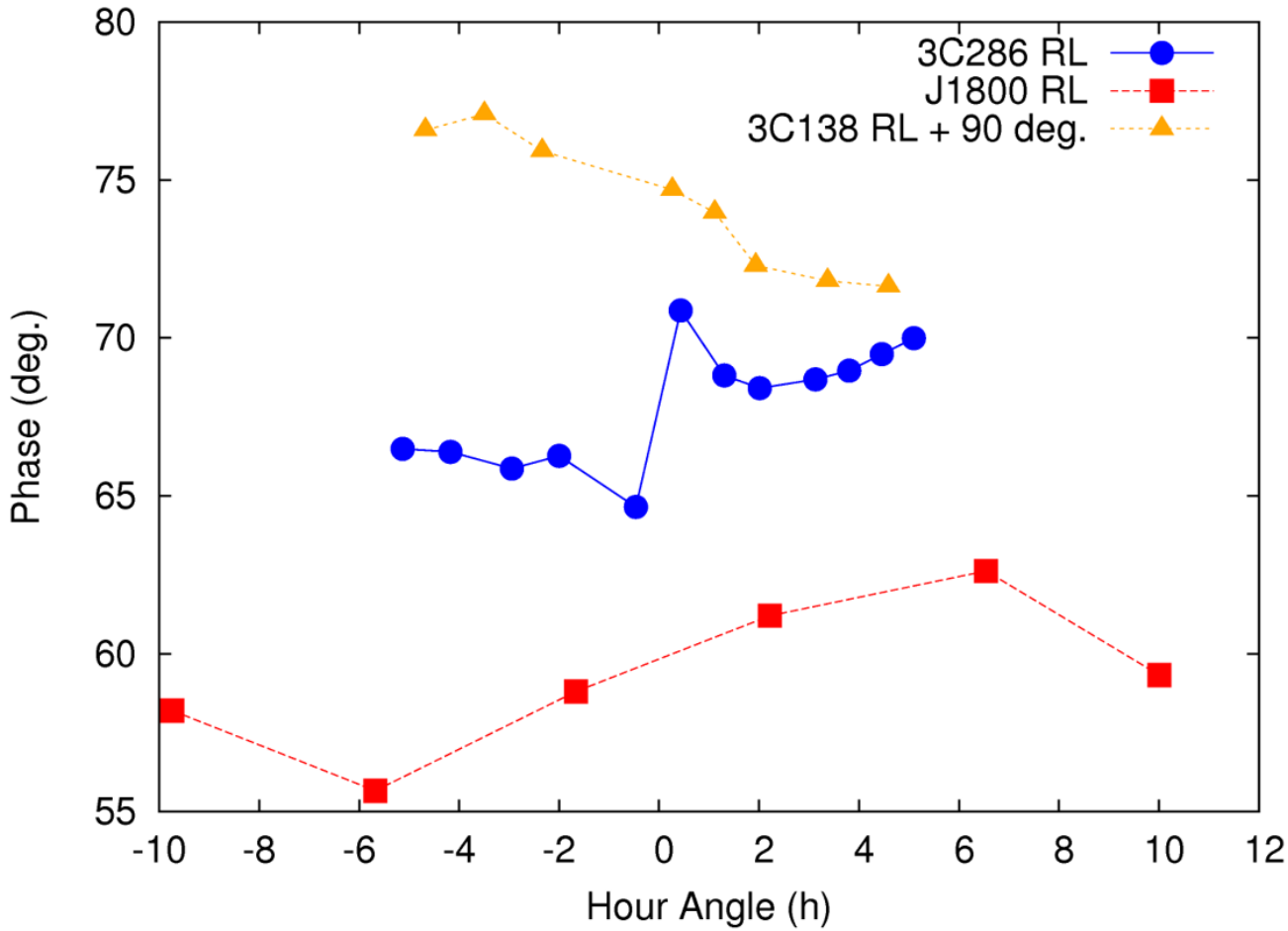




Large dTEC leads to Faraday rotation.

VLA RL phase stability

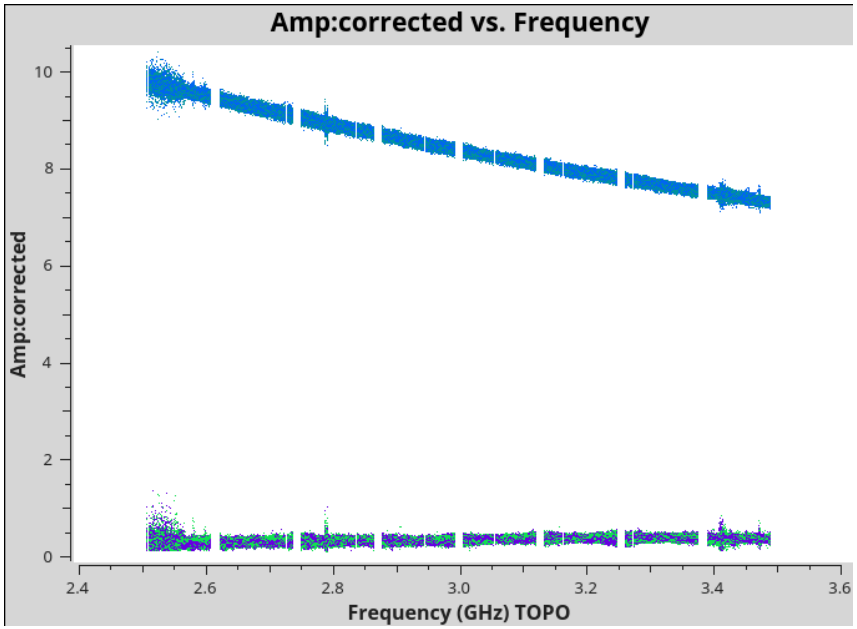
Instrumental – limit to ~5 deg. absolute accuracy

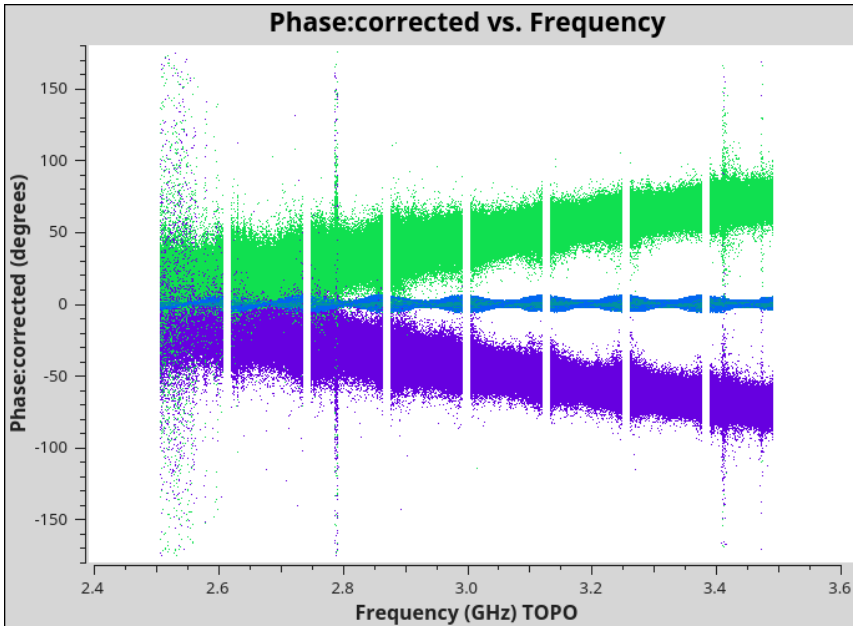


Inspect calibration – 3C48

```
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')
```

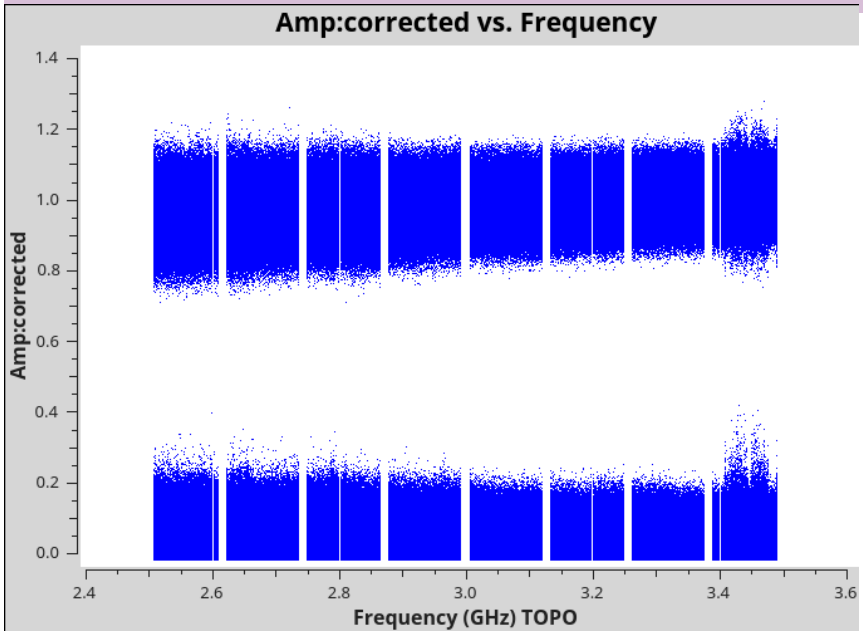


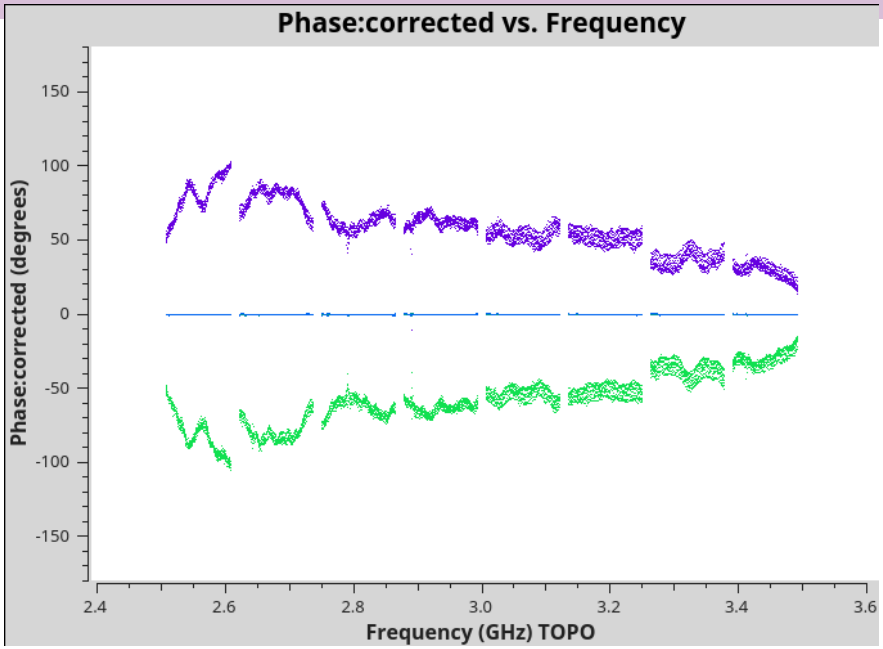


Inspect calibration – J0529+4950

```
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')
```

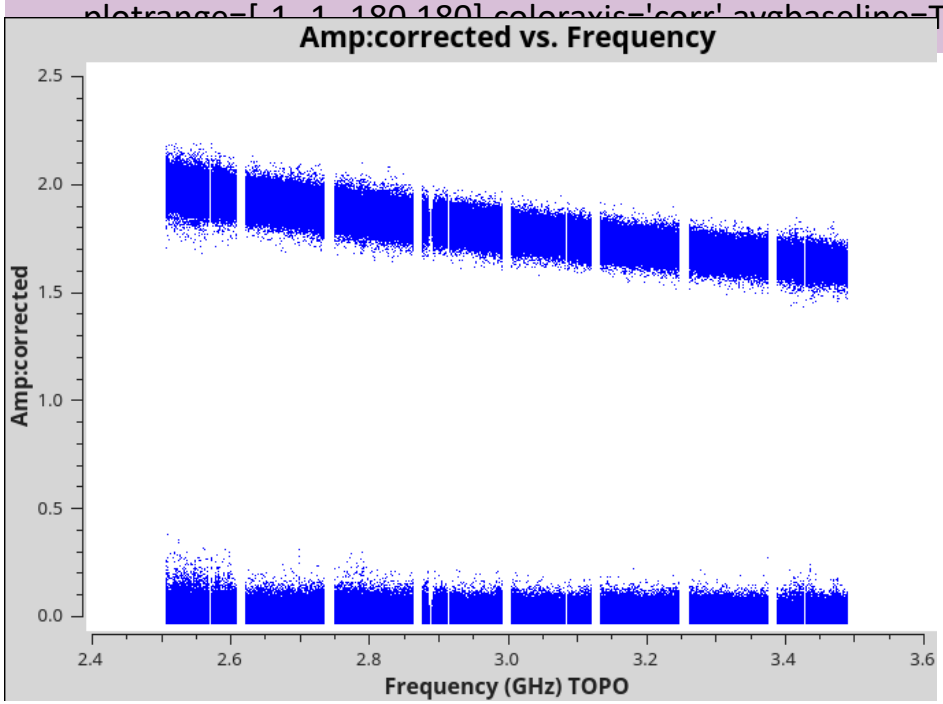


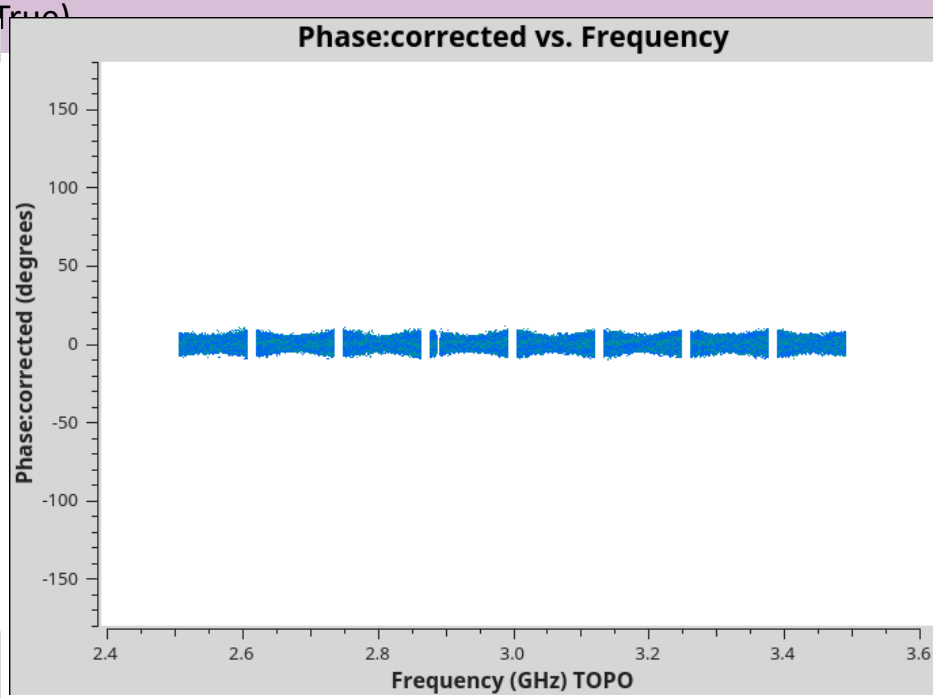


Inspect calibration – J2355+4950

```
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)
```





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/Polarization_Calibration_based_on_CASA_pipeline_standard_reduction:_The_radio_galaxy_3C75-CASA4.5.2
- **VLA Polarimetry:** https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/pol
- **CASA Polarimetry:**
- https://casa.nrao.edu/casadocs/casa-5.4.0/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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