Karl G. Jansky VLA Data Reduction Tutorial: Continuum calibration and imaging

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Introduction: A CASA 5.3.0 tutorial

- VLA observation in 2010 of the supernova remnant 3C 391
- Array in D-configuration (baselines $\lesssim$ 1 kilometer)
- Frequency band is C-band (4-8 GHz)
- 128-MHz wide spectral window at 4.6 GHz: 64 x 2-MHz
- Full polarization: RR, LL, RL, LR
- Resolution ~ 12 arcsec Primary beam size (FoV) ~ 9 arcmin
- Source angular size ~ 9 arcmin → mosaic! (7 pointings)

- The full tutorial is available at http://casaguides.nrao.edu
(CASA tutorials → Karl G. Jansky VLA Tutorials)

The data set

- You were asked to download a file: [3C391.tar.gz]
- Un-compress the file: `tar –xvfz 3C391.tar.gz`

- The result will be one file and seven sub-directories:
  - 3c391_commands.txt *(text file with commands used in this tutorial)*
  - 3c391_raw.ms *(uncalibrated data set)*
  - 3c391_calibrated.ms *(fully calibrated data set)*
  - 3c391_I_pbcor.image *(multi-scale, primary beam corrected, Stokes I image)*
  - 3c391_IQUV.image *(multi-scale Stokes IQUV image "cube")*
  - 3c391_P_pbcor.image *(linear polarization intensity image)*
  - 3c391_X.image *(polarization position angle image)*
  - (backup_gencal_table.antpos) *(pre-made gencal table if needed)*

Observer logs

- Check the observer logs before starting!
  - Weather (wind, clouds) during the observation
  - Record of antennas that may need a priori flagging
- Observer logs available at the NRAO science data archive.

- Log report:
  - An antenna may not be in the array *(should be absent from data)*
  - Antenna 13 (ea13 in CASA!) has no C-band receiver *(usually need to flag)*
  - Antenna 15 (ea15 in CASA!) has corrupted data *(usually need to flag)*
  - Some antennas will be reported with poor baseline positions
    - common--- run task `gencal` to fix antenna positions
    - if no antenna positions required, `gencal` will not produce output table

CASA startup

```
> casa
==>
========================================
The start-up time of CASA may vary
depending on whether the shared libraries
are cached or not.
========================================

IPython 5.1.0 -- An enhanced Interactive Python

CASA 5.3.0-143  -- Common Astronomy Software Applications

-- > CrashReporter initialized.
Enter doc('start') for help getting started with CASA. . .
Using matplotlib backend: TkAgg

CASA <1>:
```

Initial data examination and flagging

Important CASA tasks are:

- List a summary of the data set: `listobs`
- Make a graphical plot of the antenna positions: `plotants`
- Plot the data: `plotms`
- Flag bad data when necessary: `flagdata`

CASA: *listobs*

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List the summary of the data set: `listobs`

- type `default listobs` in CASA, then hit enter
- type `inp` (to see current input values)
- set the `vis` variable:

```
vis = '3c391_raw.ms'
```

- to run the task, type `listobs` or type `go`
- check the casa logger

Data Set Summary (*listobs*)

```
Time  Priority  Origin          Message
      INFO      …s::summary     Fields: 10
      INFO      …::summary+       ID   Code Name                RA               Decl           Epoch   SrcId      nRows
      INFO      …::summary+       0    N    J1331+3030          13:31:08.287984 +30.30.32.95886 J2000   0          31964
      INFO      …::summary+       1    J    J1822-0938          18:22:28.704200 -09.38.56.83501 J2000   1          39733
      INFO      …::summary+       2    NONE 3C391 C1            18:49:24.244000 -00.55.40.58001 J2000   2         105580
      INFO      …::summary+       3    NONE 3C391 C2            18:49:29.149001 -00.57.48.00001 J2000   3         110533
      INFO      …::summary+       4    NONE 3C391 C3            18:49:19.339000 -00.57.48.00001 J2000   4         110331
      INFO      …::summary+       5    NONE 3C391 C4            18:49:14.434001 -00.55.40.58001 J2000   5         110862
      INFO      …::summary+       6    NONE 3C391 C5            18:49:19.339000 -00.53.33.16000 J2000   6         110546
      INFO      …::summary+       7    NONE 3C391 C6            18:49:29.149001 -00.53.33.16000 J2000   7         109884
      INFO      …::summary+       8    NONE 3C391 C7            18:49:34.054000 -00.55.40.58001 J2000   8         107178
      INFO      …::summary+       9    Z    J0319+4130          03:19:48.160102 +41.30.42.10305 J2000   9           8768
      INFO      …s::summary     Spectral Windows:  (1 unique spectral windows and 1 unique polarization setups)
      INFO      …::summary+       SpwID  Name         #Chans   Frame   Ch0(MHz)  ChanWid(kHz)  TotBW(kHz) CtrFreq(MHz)  Corrs
      INFO      …::summary+       0      Subband:0        64   TOPO    4536.000      2000.000    128000.0    4599.0000  RR  RL  LR  LL
      INFO      …s::summary     Sources: 10
      INFO      …::summary+       ID   Name                SpwId RestFreq(MHz)  SysVel(km/s)
      INFO      …::summary+       0    J1331+3030          0     -              -
      INFO      …::summary+       1    J1822-0938          0     -              -
      INFO      …::summary+       2    3C391 C1            0     -              -
      INFO      …::summary+       3    3C391 C2            0     -              -
      INFO      …::summary+       4    3C391 C3            0     -              -
      INFO      …::summary+       5    3C391 C4            0     -              -
      INFO      …::summary+       6    3C391 C5            0     -              -
      INFO      …::summary+       7    3C391 C6            0     -              -
      INFO      …::summary+       8    3C391 C7            0     -              -
      INFO      …::summary+       9    J0319+4130          0     -              -
      INFO      …s::summary     Antennas: 26:
      INFO      …::summary+       ID   Name  Station   Diam.    Long.         Lat.                 Offset from array center (m)
      INFO      …::summary+                                                                         East         North     Elevation
      INFO      …::summary+       0    ea01  W09       25.0 m   -107.37.25.2  +33.53.51.0       -521.9407     -332.7782     -1.1977
      INFO      …::summary+       1    ea02  E02       25.0 m   -107.37.04.4  +33.54.01.1          9.8247      -20.4292     -2.7808
      INFO      …::summary+       2    ea03  E09       25.0 m   -107.36.45.1  +33.53.53.6        506.0591     -251.8666     -3.5832
      INFO      …::summary+       3    ea04  W01       25.0 m   -107.37.05.9  +33.54.00.5        -27.3562      -41.3030     -2.7418
      INFO      …::summary+       4    ea05  W08       25.0 m   -107.37.21.6  +33.53.53.0       -432.1158     -272.1493     -1.5032
      INFO      …::summary+       5    ea07  N06       25.0 m   -107.37.06.9  +33.54.10.3        -54.0667      263.8720     -4.2292
      INFO      …::summary+       6    ea08  N01       25.0 m   -107.37.06.0  +33.54.01.8        -30.8810       -1.4664     -2.8597
      INFO      …::summary+       7    ea09  E06       25.0 m   -107.36.55.6  +33.53.57.7        236.9058     -126.3369     -2.4443
      INFO      …::summary+       8    ea11  E04       25.0 m   -107.37.00.8  +33.53.59.7        102.8046      -63.7684     -2.6412
```

Summary of the observing strategy

Flux calibrator Bandpass calibrator Polarization angle calibrator	J1331+3030 = 3C286; field id = 0
Complex gain calibrator	J1822-0938; field id = 1
Science target(s)	3C391 C1-C7; field ids = 2-8
Polarization leakage calibrator	J0319+4130 = 3C84; field id = 9

One spectral window in this data set, spw id = 0

- Bracket target fields with complex gain calibrator.
- Observe flux/bandpass/angle calibrator(s) at least once.
- For an unpolarized leakage calibrator (like 3C84): observe once.

CASA: *plotants*

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To make a graphical plot of the antenna positions:

`plotants`

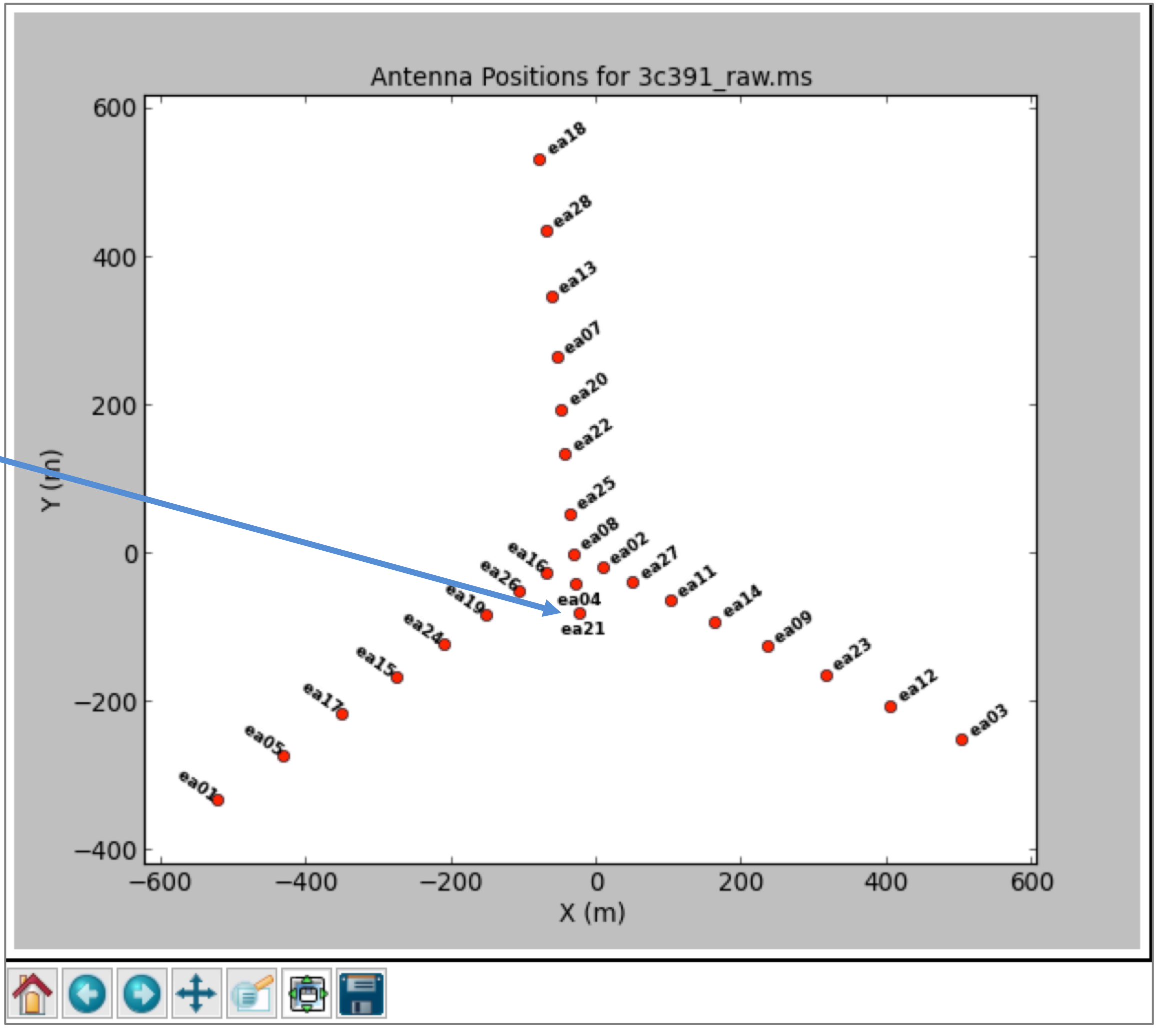
- type `default plotants` in CASA, then hit enter
- type `inp`
- set the relevant variables, e.g.

```
vis = '3c391_raw.ms'
```

- to run the task, type `plotants` or type `go`

Antenna locations (*plotants*)

Choose a central antenna to be the reference antenna. Tutorial will use `refant = 'ea21'`



CASA: *plotms*

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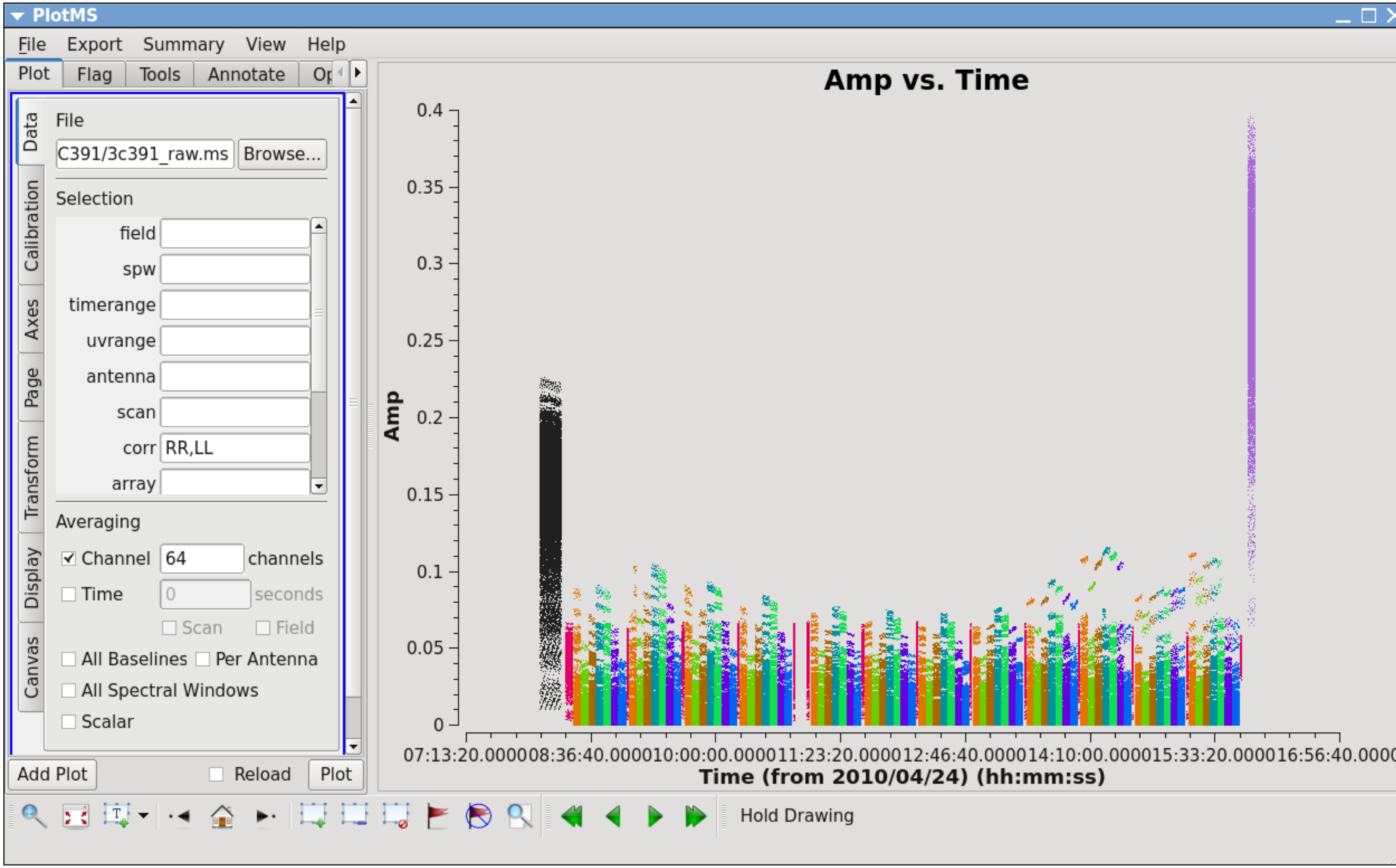
To plot the data using various axes: `plotms`

- Example: amplitude vs. time
  - `default plotms`
  - `inp`
  - Set variables:

```
vis          = '3c391_raw.ms'
xaxis        = 'time'
yaxis        = 'amp'
selectdata   =  True
correlation  = 'RR,LL'
averagedata  =  True
avgchannel   = '64'
coloraxis    = 'field'
```

  - `plotms` or `go`

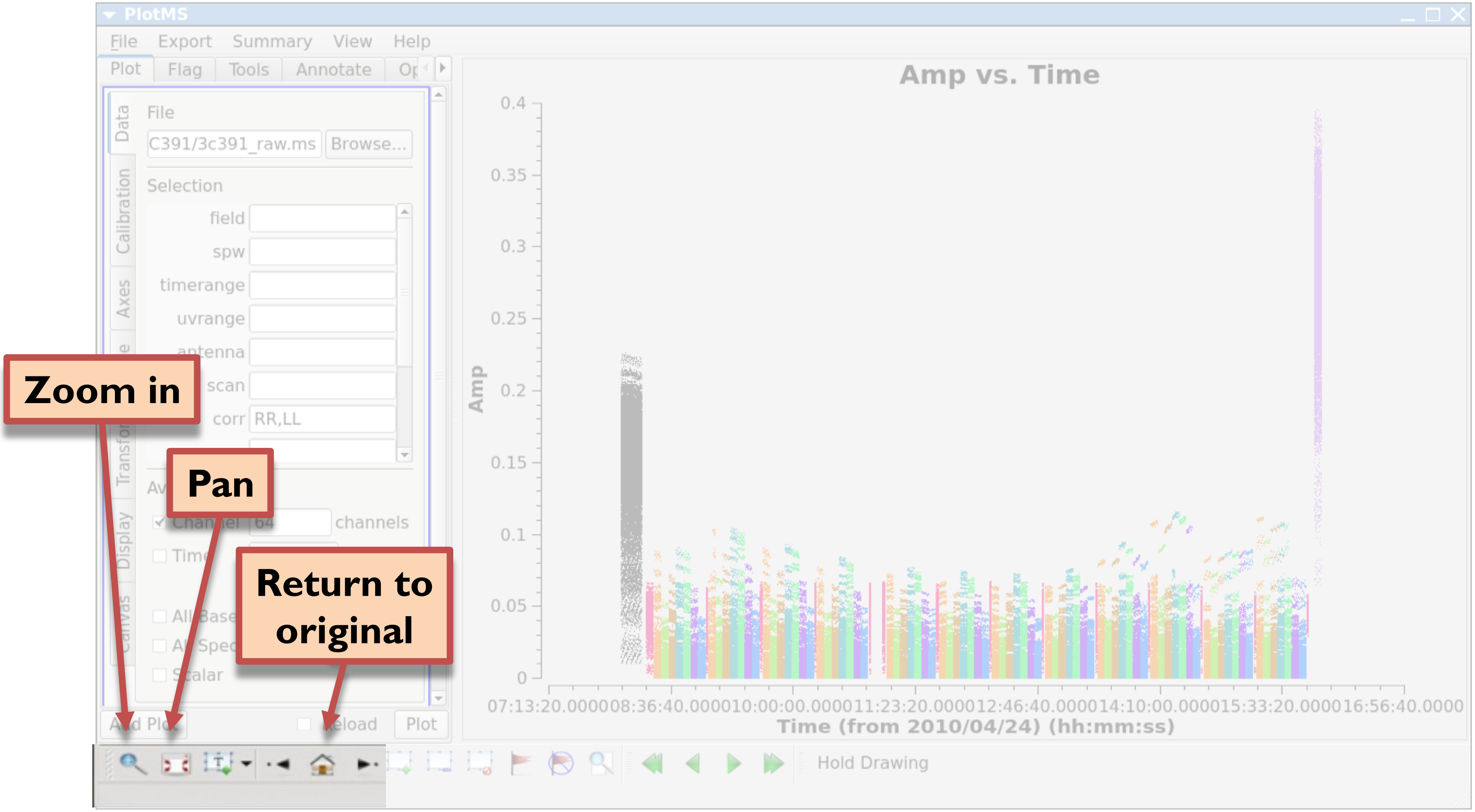
CASA: *plotms*



PlotMS
File Export Summary View Help
Plot Flag Tools Annotate Op
Data Calibration Axes Page Transform Display Canvas
File
C391/3c391_raw.ms Browse...
Selection
field
spw
timerange
uvrange
antenna
scan
corr RR,LL
array
Averaging
Channel 64 channels
Time 0 seconds
Scan Field
All Baselines Per Antenna
All Spectral Windows
Scalar
Add Plot Reload Plot
Amp vs. Time
Amp
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
07:13:20.000008:36:40.000010:00:00.000011:23:20.000012:46:40.000014:10:00.000015:33:20.000016:56:40.0000
Time (from 2010/04/24) (hh:mm:ss)
Hold Drawing

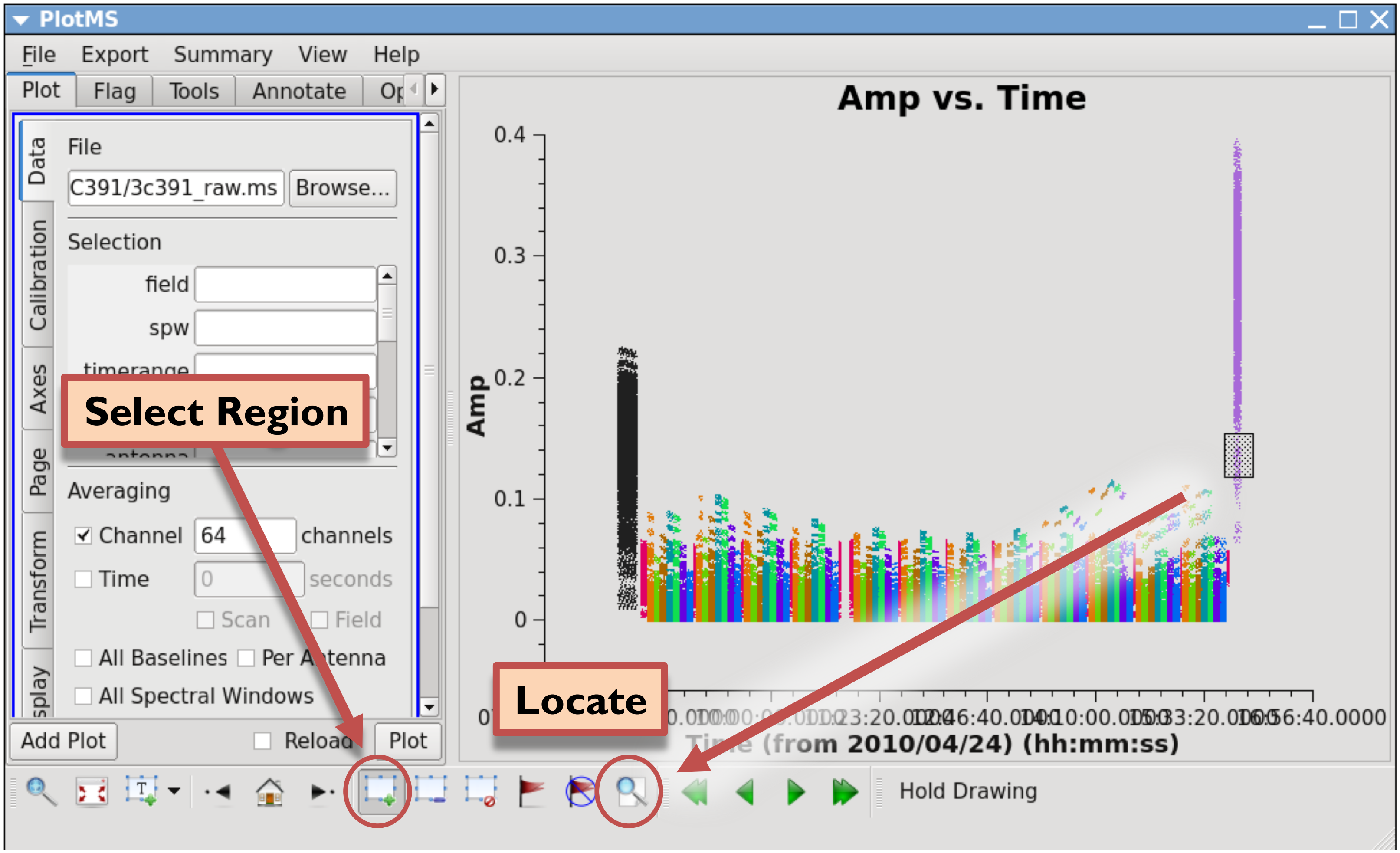
CASA: *plotms*

Navigate using the buttons at the bottom left of the window



CASA: *plotms*

Use the "*Region*" and "*Locate*" tools to identify data points

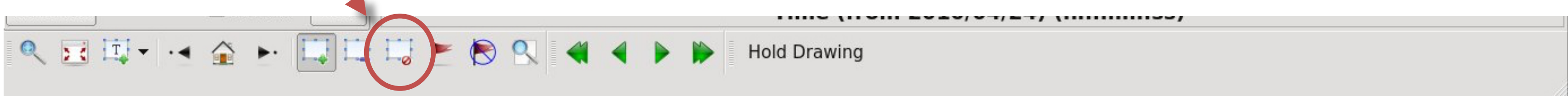


CASA: *plotms*

"Located" data points are reported in the CASA logger.
These data are from Scan=103, Field=J0319+4130, Field id = 9

```
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:55:27.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.135101 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:55:37.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.136288 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:55:47.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.140415 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:55:47.0000 BL=ea19@W04 & ea27@E03[16&24] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.131959 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:55:57.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.135353 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:07.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.13038 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:17.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.140066 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:17.0000 BL=ea19@W04 & ea27@E03[16&24] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.135358 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:27.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.146086 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:27.0000 BL=ea16@W02 & ea20@N05[13&17] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.131846 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:27.0000 BL=ea19@W04 & ea27@E03[16&24] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.129772 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:37.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.141583 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:37.0000 BL=ea19@W04 & ea27@E03[16&24] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.130181 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:47.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.136689 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:47.0000 BL=ea19@W04 & ea27@E03[16&24] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.139761 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:57.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.144551 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:56:57.0000 BL=ea19@W04 & ea27@E03[16&24] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.132943 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:57:07.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.139712 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:57:07.0000 BL=ea19@W04 & ea27@E03[16&24] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.135401 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:57:17.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.134276 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:57:17.0000 BL=ea19@W04 & ea27@E03[16&24] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.144318 Observation=0
…S::locate+  Scan=103 Field=J0319+4130[9] Time=2010/04/24/15:57:27.0000 BL=ea12@E08 & ea16@W02[9&13] Spw=0 Chan=<0~63> Freq=4.599 Corr=LL X=4.77884e+09 Y=0.135183 Observation=0
```

Clear regions in *plotms:*



CASA: *plotms*

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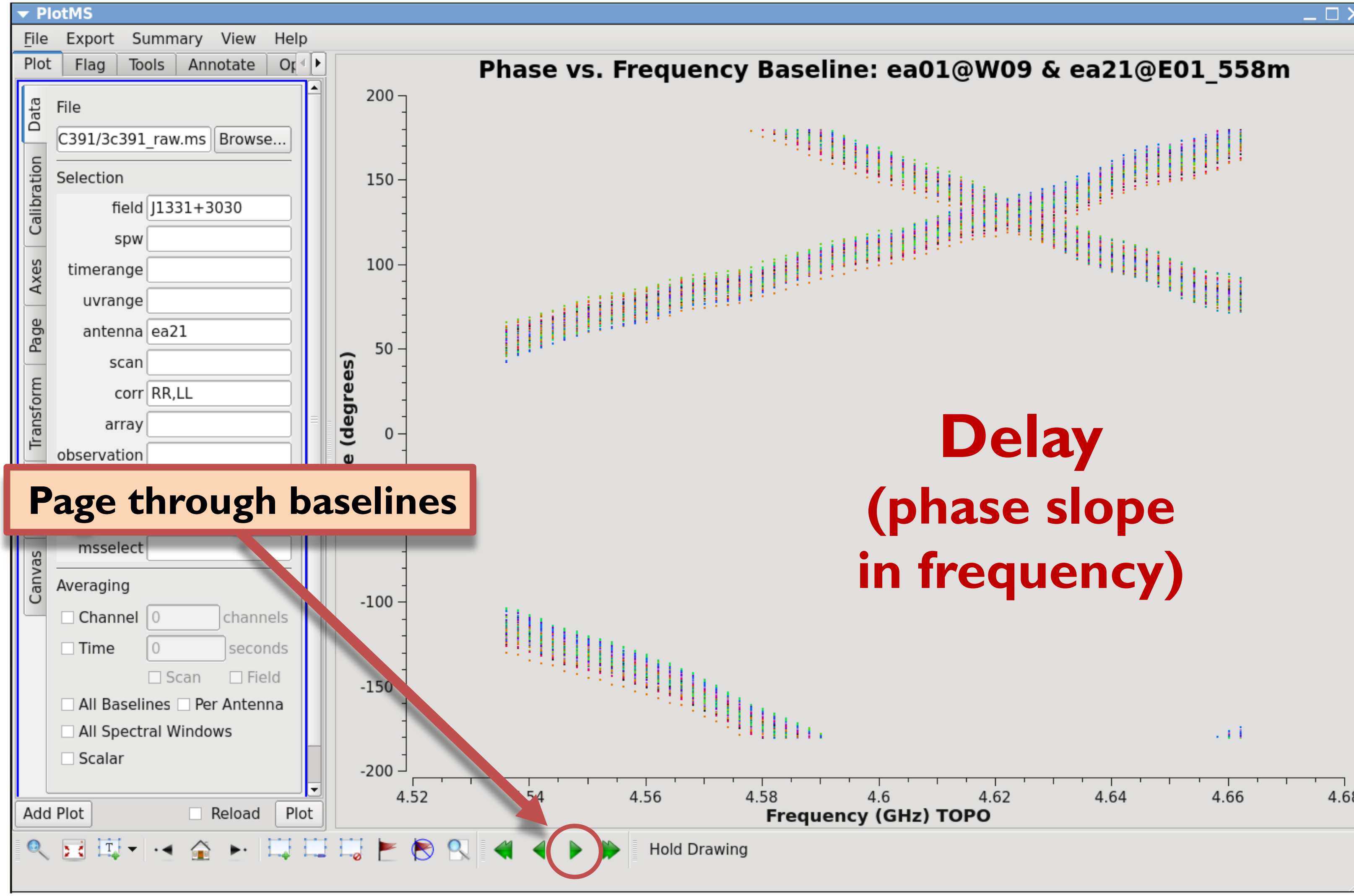
- Another example: phase vs. frequency or channel
  - `tget plotms`
  - Set variables:

```
xaxis          = 'freq'
yaxis          = 'phase'
selectdata     =  True
field          = 'J1331+3030'
antenna        = 'ea21'
averagedata    =  False
iteraxis       = 'baseline'
coloraxis      = 'time'
```

(rerun `inp` to double-check input parameter settings)

  - `plotms` or `go`

CASA: *plotms*


PlotMS
File Export Summary View Help
Plot Flag Tools Annotate Op
Data
Calibration
Axes
Page
Transform
Canvas
File
C391/3c391_raw.ms Browse...
Selection
field J1331+3030
spw
timerange
uvrange
antenna ea21
scan
corr RR,LL
array
observation
msselect
Averaging
Channel 0 channels
Time 0 seconds
Scan Field
All Baselines Per Antenna
All Spectral Windows
Scalar
Add Plot Reload Plot
Hold Drawing
Phase vs. Frequency Baseline: ea01@W09 & ea21@E01_558m
e (degrees)
200
150
100
50
0
-100
-150
-200
4.52
54
4.56
4.58
4.6
4.62
4.64
4.66
4.68
Frequency (GHz) TOPO
Page through baselines
Delay
(phase slope
in frequency)

Calibration Strategy (a priori, bandpass)

- Correct antenna positions: `gencal`
- Set the flux density scale: `setjy`
- For bandpass calibration
  1. Phase-only calibration (short *solint*) on the bandpass calibrator: `gaincal`
  2. Delay calibration (remove slope in phase vs. frequency) while applying solutions from (1):
     `gaincal` (*gaintype*='*K*')
  3. Bandpass calibration while applying solutions from (2): `bandpass`

The calibration table from (1) is ignored in subsequent steps. The calibration tables from (2) and (3) will be applied on-the-fly in subsequent calibration steps.

CASA: *gencal* (to correct antenna positions)

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The *gencal* task is for antenna-specific corrections.
For antenna positions, it will perform an automated lookup in the position corrections database online (requires internet connection):

`gencal`

- `default gencal` and `inp`
- Set variables:

```
vis      = '3c391_raw.ms'
caltype  = 'antpos'
caltable = 'cal.antpos'
```

- `gencal` or `go`

Corrections are reported in CASA logger.

CASA: *setjy* (to set flux density scale)

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- Flux density calibration using J1331+3030 = 3C 286.
- This source requires a model.
- Use task `setjy`.
- To find out if a model is available (`default setjy`):

  `listmodels = True`

- `setjy` or `go`

- The C-band model for 3C286 is: `3C286_C.im`

CASA: *setjy* (to set flux density scale)

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Now set the *setjy* variables:

```
vis         = '3c391_raw.ms'
listmodels  =  False
field       = 'J1331+3030'
model       = '3C286_C.im'
```

Run the task with `setjy` or `go`

The CASA logger will report many lines. The most important:

J1331+3030 (fld ind 0) spw 0 [I=7.6677, Q=0, U=0,V=0] Jy @ 4.536e+09Hz, (Perley-Butler 2013)

Scaling spw(s) [0]'s model image by channel to I = 7.66874, 7.59784, 7.53052 Jy @(4.535e+09, 4.601e+09, 4.665e+09)Hz …

Capture output from `setjy` (Stokes I) with e.g. `output=setjy()`

CASA: *gaincal*

- The *gaincal* task solves for variations in antenna complex gains (amp, phase) as a function of time.
- At different stages of calibration, we use it to correct for:
  - variations of phase vs. time throughout the scan on the bandpass calibrator (before doing bandpass calibration)
  - antenna-based delays, compared to a reference antenna (before doing bandpass calibration)
  - atmospheric/antenna-gain changes with time (traced by the complex gain calibrator, to be applied to the target sources)

CASA: *gaincal*

- First perform an initial phase calibration (with short *solint*) on the bandpass calibrator to solve for short timescale phase variations. Applying this table "on-the-fly" when solving for bandpass calibration prevents phase decorrelation in the bandpass solutions.

- It is standard to do this initial phase calibration on the bandpass calibrator before solving for the bandpass solution.

- In this tutorial, we will use this technique on *all* calibrators (not just the bandpass calibrator) as a quality assurance step.

CASA: *gaincal* (for phase variation with time)

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`default gaincal`, then `inp`, then:

```
vis        = '3c391_raw.ms'
caltable   = 'cal.G'
field      = '0,1,9'         # examine all calibrator fields
refant     = 'ea21'
spw        = '0:27~36'       # small range to avoid decorrelation
gaintype   = 'G'
calmode    = 'p'             # solve for phases
solint     = 'int'           # solution interval = integration
minsnr     =  5              # minimum signal-to-noise ratio
gaintable  = 'cal.antpos'
```

(rerun `inp` to double-check input parameter settings)

`gaincal` or `go`

CASA: *plotcal* *(deprecated from CASA 5.4 onward)*

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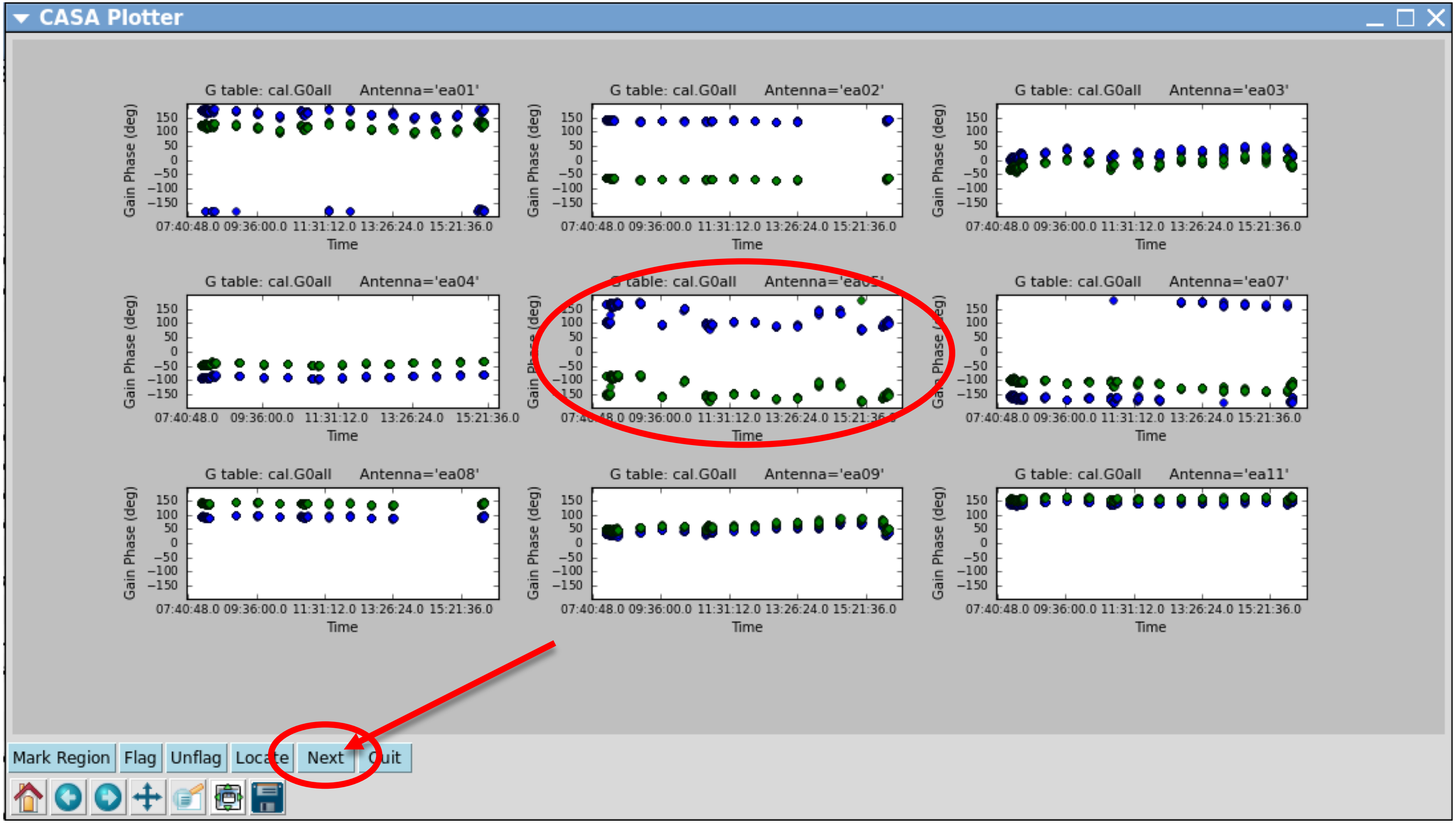
- *gaincal* made the calibration table `cal.G`
- Examine the calibration solutions: `plotcal`

```
default plotcal
    caltable     = 'cal.G'
    xaxis        = 'time'
    yaxis        = 'phase'
    subplot      =  331              # display 3x3 plots per screen
    iteration    = 'antenna'         # iterate through antennas
    plotrange    = [-1,-1,-180,180]  # [xmin,xmax,ymin,ymax]
plotcal or go
```

CASA: *plotcal* *(deprecated from CASA 5.4 onward)*



CASA: *plotms*

Use `plotms` instead of `plotcal` to examine caltables

– (use from CASA 5.4 onward; for 5.3 stick with `plotcal`)

```
default plotms
    vis         = 'cal.G'
    xaxis       = 'time'
    yaxis       = 'phase'
    gridrows    =  3         # display 3x3 plots per screen
    gridcols    =  3
    iteraxis    = 'antenna'     # iterate through antennas
    coloraxis   = 'corr'
    plotrange   = [-1,-1,-180,180] # [xmin,xmax,ymin,ymax]
plotms or go
```

CASA: *flagdata*

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Flag bad data when you find it, in this case antenna ea05

`flagdata`

- `default flagdata`
- `inp`
- Set variables:

```
vis          = '3c391_raw.ms'
mode         = 'manual'
antenna      = 'ea05'
flagbackup   =  True
```

- `flagdata` or `go`

Calibration Strategy (a priori, bandpass)

- ✓ Correct antenna positions: `gencal`
- ✓ Set the flux density scale: `setjy`
- For bandpass calibration
  1. ✓ Phase-only calibration (short *solint*) on the bandpass calibrator: `gaincal`
  2. Delay calibration (remove slope in phase vs. frequency) while applying solutions from (1):
     `gaincal` (*gaintype*='*K*')
  3. Bandpass calibration while applying solutions from (1) and (2): `bandpass`

  The calibration table from (1) is ignored in subsequent steps. The calibration tables from (2) and (3) will be applied on-the-fly in subsequent calibration steps.

CASA: *gaincal* (to calibrate the delays)

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`default gaincal`, then `inp`, then:

```
vis        = '3c391_raw.ms'
caltable   = 'cal.K'
field      = '0'                # a bright calibrator (e.g., bandpass cal)
refant     = 'ea21'
spw        = '0:5~58'           # all (non-edge) channels
gaintype   = 'K'                # solve for antenna-based delays
solint     = 'inf'              # infinite: average all times in a scan
minsnr     =  5                 # minimum signal-to-noise ratio
gaintable  = ['cal.antpos', 'cal.G']
gainfield  = ['', '0']          # which field's solutions to apply
```

`gaincal` or `go`

CASA: *bandpass*

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Bandpass calibration: `bandpass`

```
default bandpass
    vis         =  '3c391_raw.ms'
    caltable    =  'cal.BP'
    field       =  '0'       # can reference by field id
    solint      =  'inf'     # infinite
    refant      =  'ea21'
    gaintable   = ['cal.antpos','cal.G','cal.K']
    gainfield   = ['', '0', '']  # which field's solutions to apply
bandpass or go
```

CASA: *plotcal*

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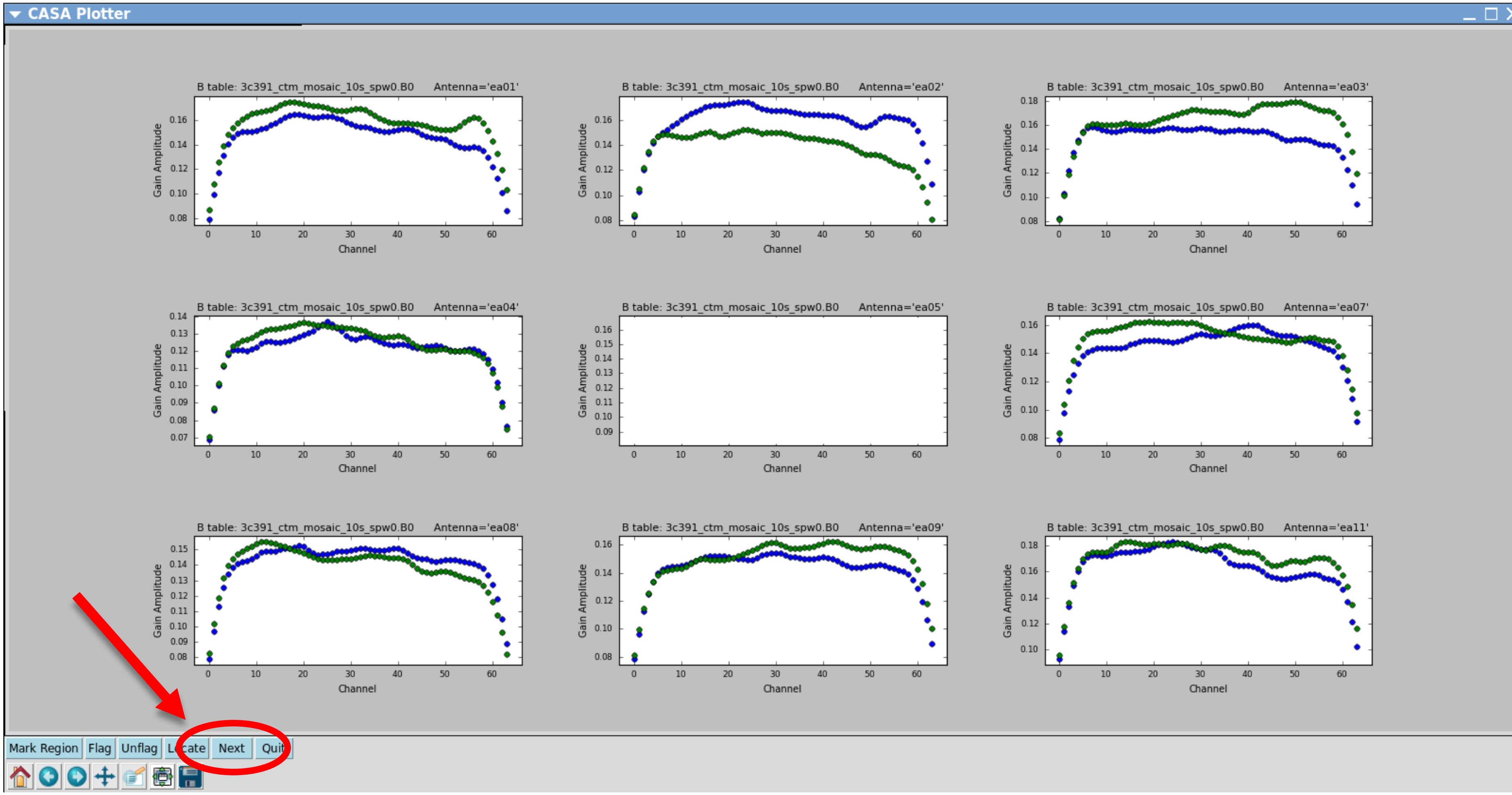
- *bandpass* made the calibration table `bandpass.bpcal`
- Plot the derived amplitude solutions: `plotcal`

```
default plotcal
    caltable    = 'cal.BP'
    xaxis       = 'chan'
    yaxis       = 'amp'
    subplot     =  331
    iteration   = 'antenna'
plotcal or go
```

CASA: *plotcal*



Calibration strategy (amplitudes, phases)

- Solve for phases and normalized amplitudes:

  `gaincal` (scan-based *solint*='*inf*') for phase and amplitude calibration on all calibrators

  (insert polarization calibration strategy here)

- Bootstrap the flux density of the secondary calibrator:

  `fluxscale` using table from the above *gaincal* call as input. This will correct the amplitude solutions of that table, and replace it with a new table.

CASA: *gaincal* (to calibrate for atmosphere)

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`default gaincal`, then `inp`, then:

```
vis        = '3c391_raw.ms'
caltable   = 'cal.G1'
field      = '0,1,9'      # all calibrator fields
refant     = 'ea21'
spw        = '0:5~58'     # non-edge channels
gaintype   = 'G'
solint     = 'inf'        # infinite: average all times in a scan
gaintable  = ['cal.antpos', 'cal.K', 'cal.BP']
gainfield  = ['', '', '']
```

`gaincal` or `go`

Calibration strategy (polarization)

- Requirements for polarization calibration:
  - One observation of a position angle calibrator *(3C 286)*
    - Flux density model *(with info from previous `setjy` ouput)*
    - Known fractional polarization *(11.2% in C-band at time of observations)*
    - Known polarization angle East of North *(33° at most frequencies)*

    Get polarization properties from literature and/or NRAO monitoring:

    http://go.nrao.edu/vla-pol

  - To solve for instrumental polarization, either:
    - One observation of a known unpolarized source *(3C 84)*

    OR

    - ≥3 observations of any source over large parallactic angle range (~60°)

Calibration strategy (polarization)

- To calibrate for (linear) polarization:
  - Set the polarization model for the polarization-angle calibrator: `setjy`
  - Solve for cross-hand (RL, LR) delays: residual delay difference between right-handed (R) and left-handed (L) polarization: `gaincal`
  - Solve for the instrumental polarization ("leakage" "D-terms"): `polcal`
  - Solve for the polarization position angle: `polcal`

- MUST use only ONE reference antenna for all polarization calibrations. Check `refant` reporting in CASA logger.

Polarization: set the model

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- Get 3C 286 Stokes `I` from earlier `setjy` output:

  [I=7.6677, Q=0, U=0, V=0] Jy @ 4.536e+09Hz
  I = 7.66874, 7.59784, 7.53052 Jy @(4.535e+09, 4.601e+09, 4.665e+09)Hz …

```
alpha = log(7.53052/7.6677) / log(4665.0/4536.0)
```

- 3C 286 polarization from VLA Observing Guide (or literature)

```
default setjy
    vis          = '3c391_raw.ms'
    field        = 'J1331+3030'
    standard     = 'manual'           # set the model manually
    spw          = '0'
    fluxdensity  = [7.667,0,0,0]      # at reference frequency
    spix         = [alpha,0]          # multiple Taylor terms allowed!
    reffreq      = '4536.0MHz'        # reference frequency
    polindex     = [0.112,0]          # polarization fraction 11.2%
    polangle     = [33*pi/180,0]      # polarization angle in radians
    scalebychan  =  True              # important to scale by channel!
```

Polarization: solve for cross-hand delays

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```
default gaincal
        vis          =  '3c391_raw.ms'
        caltable     =  'cal.Kcross'
        field        =  'J1331+3030'
        spw          =  '0:5~58'
        gaintype     =  'KCROSS'    # for cross-hand polarization calibration
        solint       =  'inf'       # one solution over entire observing run
        combine      =  'scan'      # one solution over entire observing run
        refant       =  'ea21'
        gaintable    = ['cal.antpos','cal.K','cal.BP','cal.G1']
        gainfield    = ['', '', '', '0']
        parang       =   True
gaincal or go
```

Polarization: solve for leakage terms

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With unpolarized calibrator 3C 84 = J0319+4130:

```
default polcal
        vis          = '3c391_raw.ms'
        caltable     = 'cal.D'
        field        = 'J0319+4130'
        spw          = '0:5~58'
        refant       = 'ea21'
        poltype      = 'Df'      # for leakages (D) on per-channel basis (f)
        solint       = 'inf'   } # one solution over entire observing run
        combine      = 'scan'  }
        gaintable    = ['cal.antpos', 'cal.K', 'cal.BP',
                        'cal.G1', 'cal.Kcross']
        gainfield    = ['', '', '', '9', '']     # J0319+4130 field
polcal or go
```

Polarization: solve for R-L polarization angle

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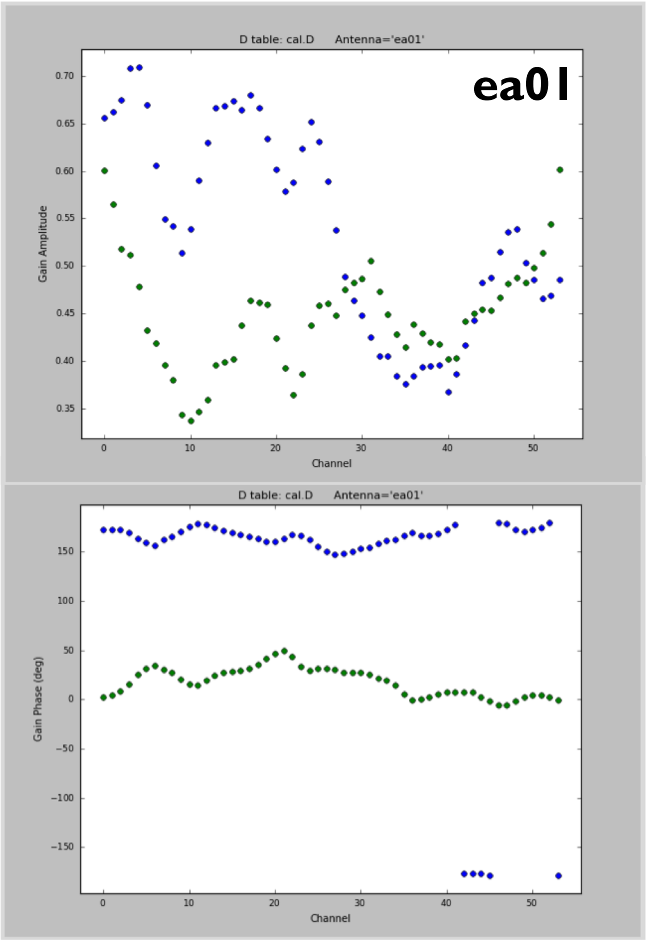
```
default polcal
        vis         =  '3c391_raw.ms'
        caltable    =  'cal.X'
        field       =  'J1331+3030'
        poltype     =  'Xf'        # angle (X) with frequency dependence (f)
        combine     =  'scan'  } # one solution over entire observing run
        solint      =  'inf'   }
        gaintable   = ['cal.antpos','cal.K','cal.BP',
                       'cal.G1','cal.Kcross','cal.D']
        gainfield   = ['', '', '', '0', '', '']
polcal or go
```

Polarization calibration solutions: examples

Leakage solutions (cal.D)

Gain Amplitude

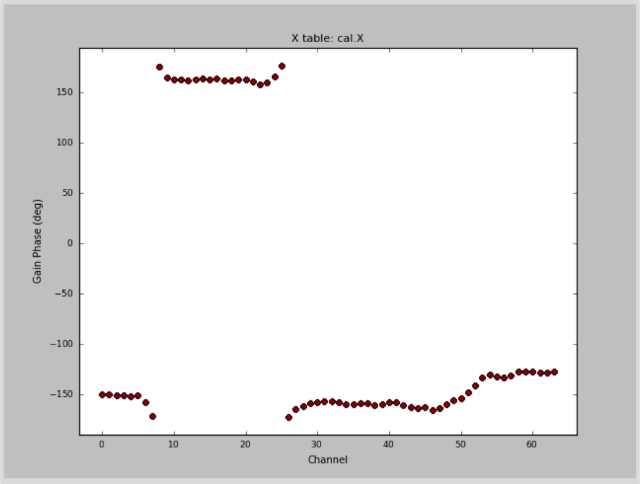
Gain Phase



Channel #

R-L angle solutions (cal.X)

Gain Phase



Channel #

Calibration strategy

- Apply the calibration tables to the target sources:
  - CASA task `applycal`
  - Apply the calibration tables that are relevant to the target, e.g.:
    - The antenna position table
    - The bandpass table
    - The delay calibration table
    - The complex gain calibration table
    - The amplitude calibration table (written by *fluxscale*)
    - The cross-hand delay calibration table (for polarization)
    - The polarization leakage calibration table (for polarization)
    - The polarization angle calibration table (for polarization)
  - The calibrated data is written into the "*corrected*" column of the measurement set (immediately stored on disk)

Calibration strategy

- Examine the calibrated data with `plotms`
- Identify bad data (e.g., RFI) and/or antennas. Flag (`flagdata`) and redo all the calibration.
- Redo `applycal` and examine again.
- Repeat flagging, calibration, applycal, examination until everything looks good. Then:
  - `split` the *corrected* column for the target source into its own new ms (for convenience when imaging)
    - for a mosaic (this tutorial), split all target fields into a single new ms
    - for multiple sources, split each target into its own new ms

Imaging

- The relevant CASA task is `tclean`
  - Iteratively deconvolves sources in the "residual" image

- We will go through some relevant examples for the data set:
  - `3c391_calibrated.ms`

- For more examples, including many advanced techniques, see the Topical CASAguide on imaging:
  https://casaguides.nrao.edu/index.php/VLA_CASA_Imaging

Imaging strategy (general)

- Recommend "*robust*" ("*Briggs*") weighting: provides a balance between resolution (*uniform* weighting) and sensitivity (*natural* weighting)
- Choose a pixel (cell) size such that 3-5 pixels fit across the synthesized beam (resolution element)
- Image size:
  - for a single-pointing, image at least the whole primary beam (FWHM), plus extra padding to reduce aliasing
  - for a mosaic (multiple pointings), image full target + padding
  - for efficiency, choose an image size (in number of pixels) equal to $2^n \times 3^m \times 5$ for some numbers n, m

Imaging strategy: pixel and image sizes

- Cell size (pixel size)*:
  - resolution is 12 arcsec
  - choose cellsize = 2.5 arcsec → ~5 pixels per synthesized beam
- Image size:
  - Supernova remnant has diameter ~9 arcmin = 216 pixels
  - Choose imsize = 480 x 480 pixels (480 = 2^5 x 3^1 x 5)

*Hint: in practice, the resolution depends on which data were flagged. You can find the actual resolution by:

- examining the baseline distribution in *plotms*
- running an initial clean with *niter=0*; no cleaning will be done but the synthesized beam size will be reported in the CASA logger

Imaging strategy: multi-scale

- Standard *tclean* uses one scale [0] --- assumes sky emission is made up of Dirac Delta functions
- Multi-scale algorithm/gridder simultaneously fits/cleans emission at different angular scales (e.g., [0, 3, 10, 30] in pixel units)
  - general guideline: use scales of 0, 2xbeam, 5xbeam, etc., up to scales up to half of the minor axis of the largest structure
  - guideline: use *smallscalebias* to give added weight to the larger scales (which tend to have lower surface brightness)

CASA: *tclean*

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```
default tclean
    vis             =  '3c391_calibrated.ms'
    imagename       =  '3c391_I_multiscale'
    imsize          =  [480,480]
    cell            = ['2.5arcsec','2.5arcsec']
    specmode        =  'mfs'
    gridder         =  'mosaic'
    deconvolver     =  'multiscale'
    scales          =  [0,6,18,54]      # [0, 15, 45, 135] arcsec
    smallscalebias  =   0.9
    weighting       =  'briggs'  # allows compromise of natural vs uniform
    niter           =   5000   # total number of iterations in minor cycles
    threshold       =  '1.0mJy'
    cycleniter      =   500   # maximum iterations before next major cycle
    interactive     =   True
tclean or go
```

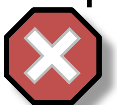
CASA: *tclean*

Interactive = True

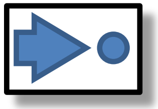
- Make a region
- Double-click inside to activate (green outline turns white)
- Start the clean:

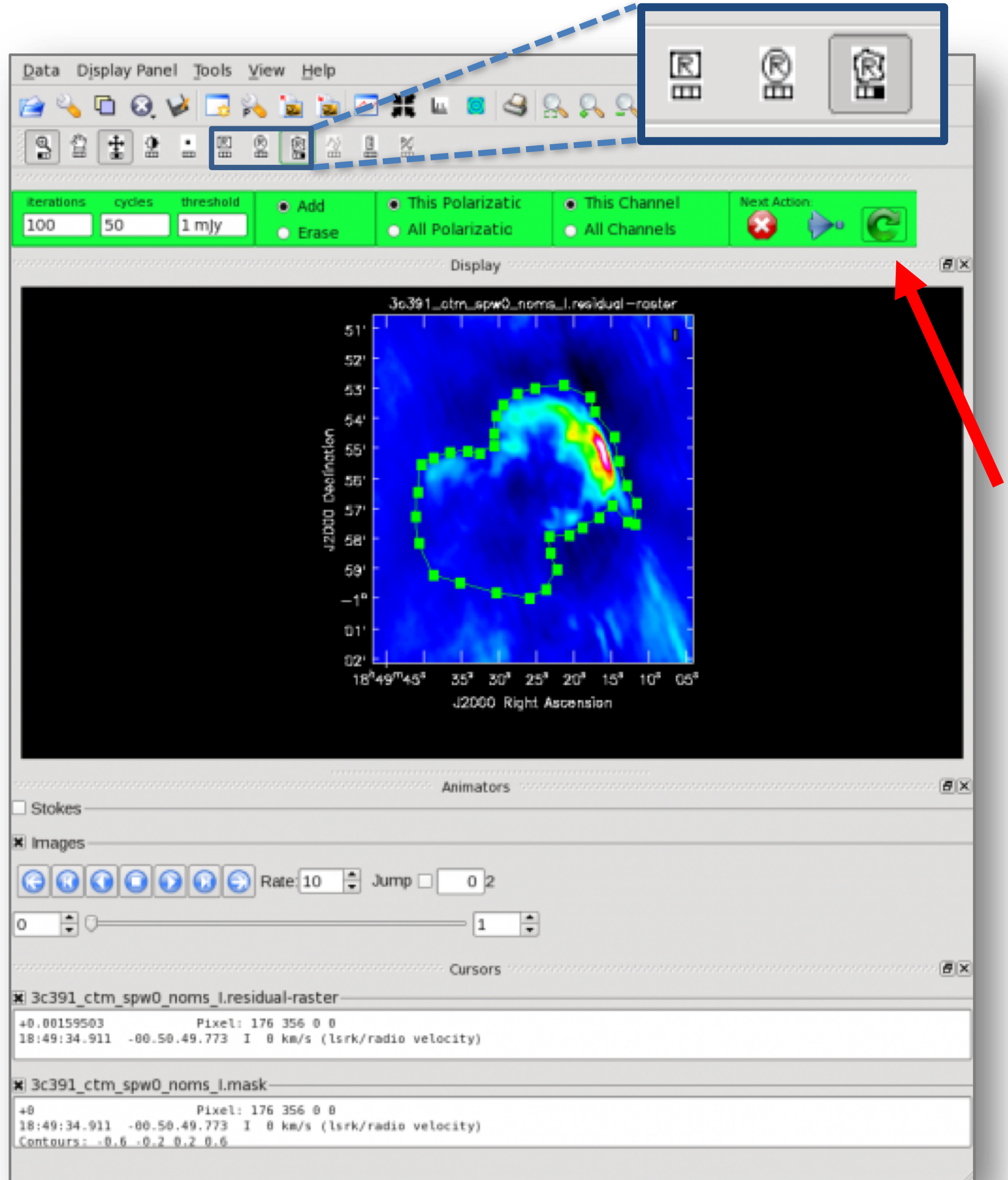
- Adjust regions and continue:

- To stop interactive clean:



- If happy with regions, let it clean until it's done:





CASA: *viewer*

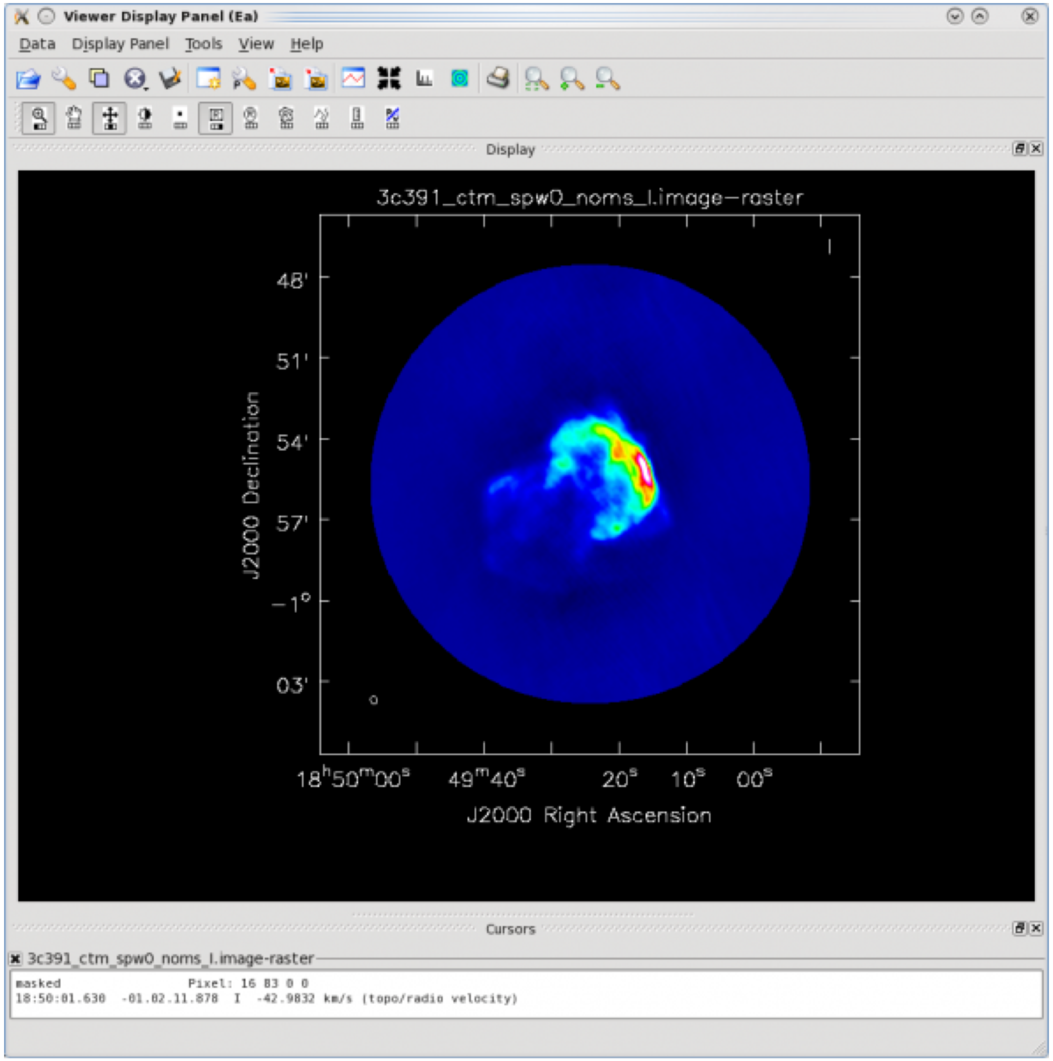
View CASA images, fits files:

`viewer` or

`!casaviewer&`

- Select your image:

`'3c391_I_multiscale.image'`



** You can also load the viewer from outside CASA, by typing `casaviewer` at a terminal command line.

Image analysis: peak brightness, noise level

CASA command line

```
imstat(<image>)
```

or

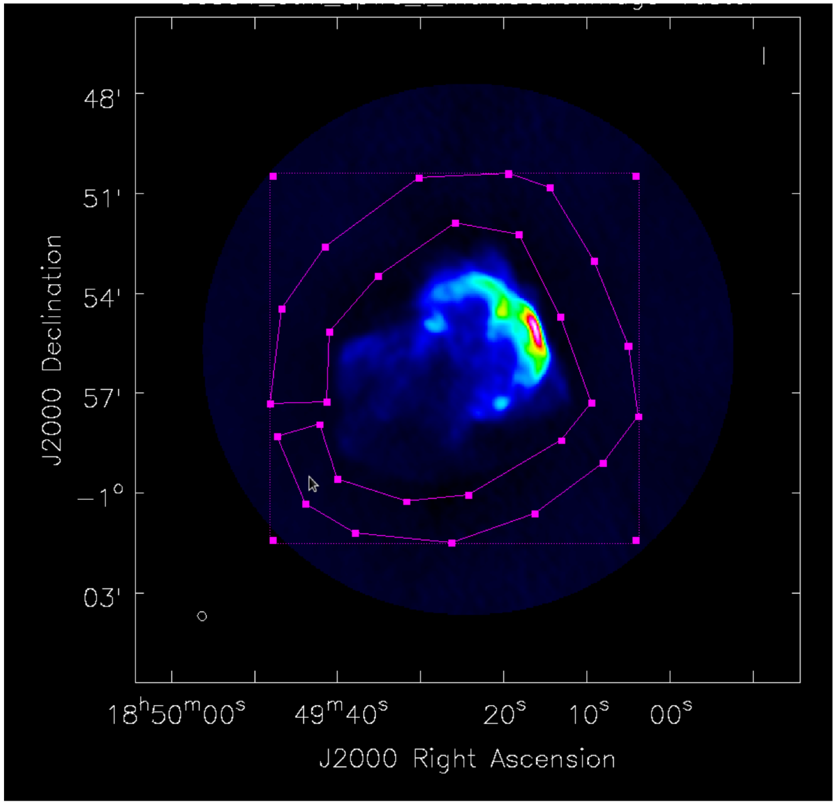
```
mystat = imstat(<image>)
```

reports to CASA logger and returns a Python dictionary:

```
{'blc': array([0, 0, 0, 0], dtype=int32),
 'blcf': '18:50:04.251, -01.05.40.567, I, ...
 'flux': array([ 7.53265832]),
 'max': array([ 0.15447657]),
 'maxpos': array([288, 256, 0, 0],
dtype=int32),
 'maxposf': '18:49:16.243, -00.55.00.579, ...
 'mean': array([ 0.00081497]),
 'medabsdevmed': array([ 0.00016437]),
 'median': array([ 1.00343077e-05]),
 'min': array([-0.00607492]),
 'minpos': array([239, 413, 0, 0], ...
 'minposf': '18:49:24.411, -00.48.28.080, ...
 'npts': array([ 481828.]),
...
```

CASA *viewer* (!casaviewer)

Draw a region with one of the region tools. Double-click inside the region.



Primary beam correction: *impbcor*

- Interferometry images include the antenna primary beam response, roughly a 2-D Gaussian. To correct, *divide* the final cleaned image by the primary beam response (*imagename.flux*)
  - `tclean` task will do this for you if parameter `pbcor = True`
  - task `impbcor`

```
imagename    = '3c391_I_multiscale.image'
pbimage      = '3c391_I_multiscale.flux'
outfile      = '3c391_I_multiscale.pbimage'
```

  - for wide-band** (nterms > 1), use task `widebandpbcor`

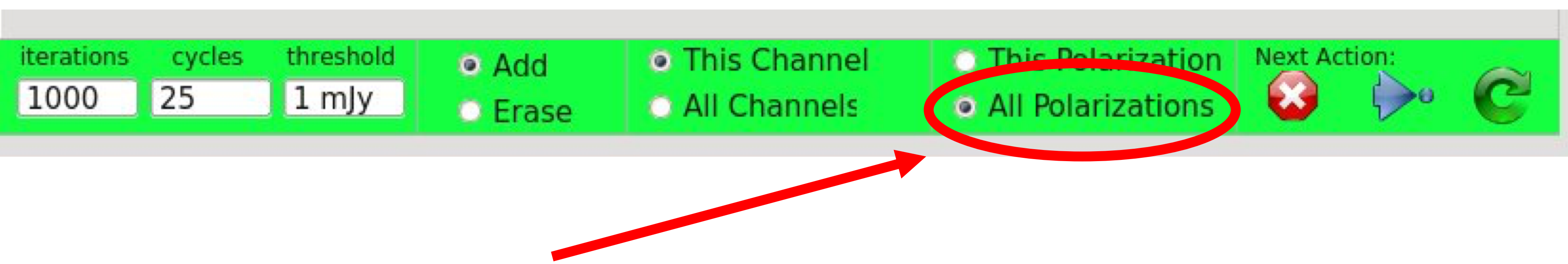
    (**caveat: for wide-band *mosaics*, use pbcor=True in tclean)

- Primary beam corrected images have increased noise at the edges, and at interstices of mosaic pointings

CASA: *tclean* for Stokes IQUV image

```
tget tclean        # set variables to values from previous run
    imagename    = '3c391_IQUV'
    stokes       = 'IQUV'        # or 'I', 'QU', 'Q', 'U', 'V'
    pbcor        =  True         # primary beam correction
```

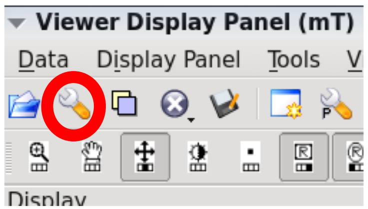
Select the "All Polarizations" button ***before*** making regions!



Polarized images (IQUV)

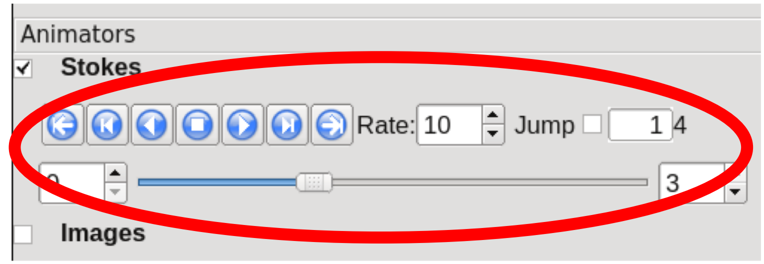
```
viewer('3c391_IQUV.image')
```

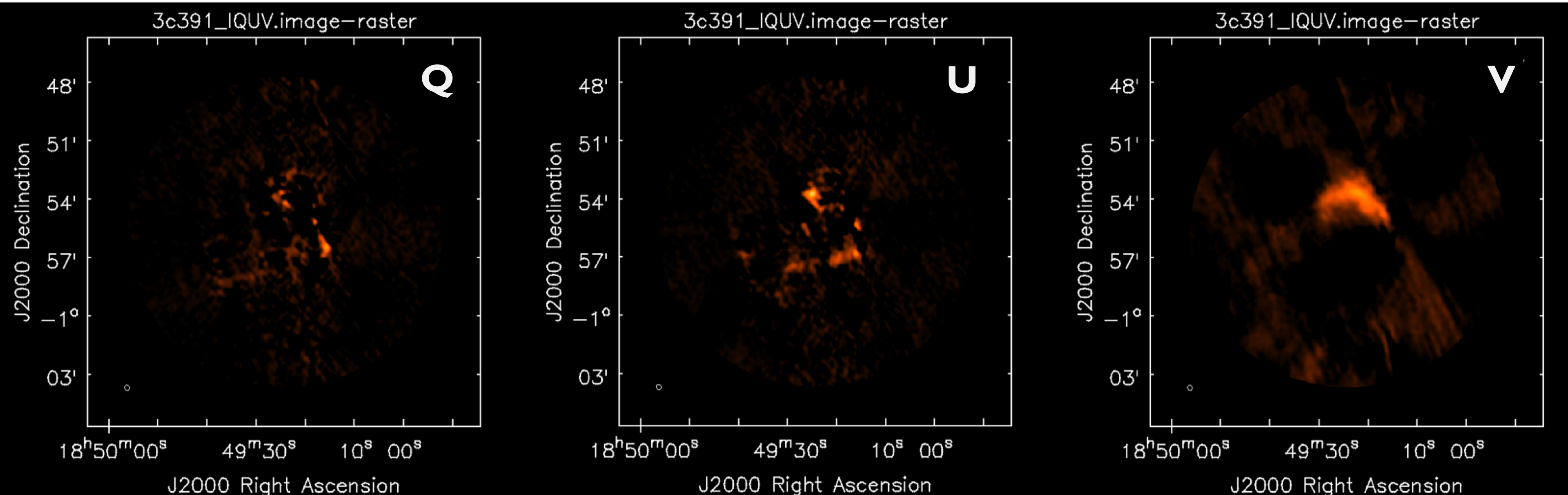
Change scaling through the Data Display Options:



Global Color Settings
Data Range: [0, 0.002]
Scaling Power Cycles: 0.5
Color Map: Hot Metal 1

Iterate through the Stokes cube:





Polarization Intensity and Angle Images

- The CASAguide shows the use of task `immath` to calculate:
  - Linear polarization image "P"

$$\mathrm{P} = \sqrt{Q^2 + U^2}$$

  - Polarization position angle image "X"

$$\tan\left(2\,X\right) = U/Q$$

  - Example:

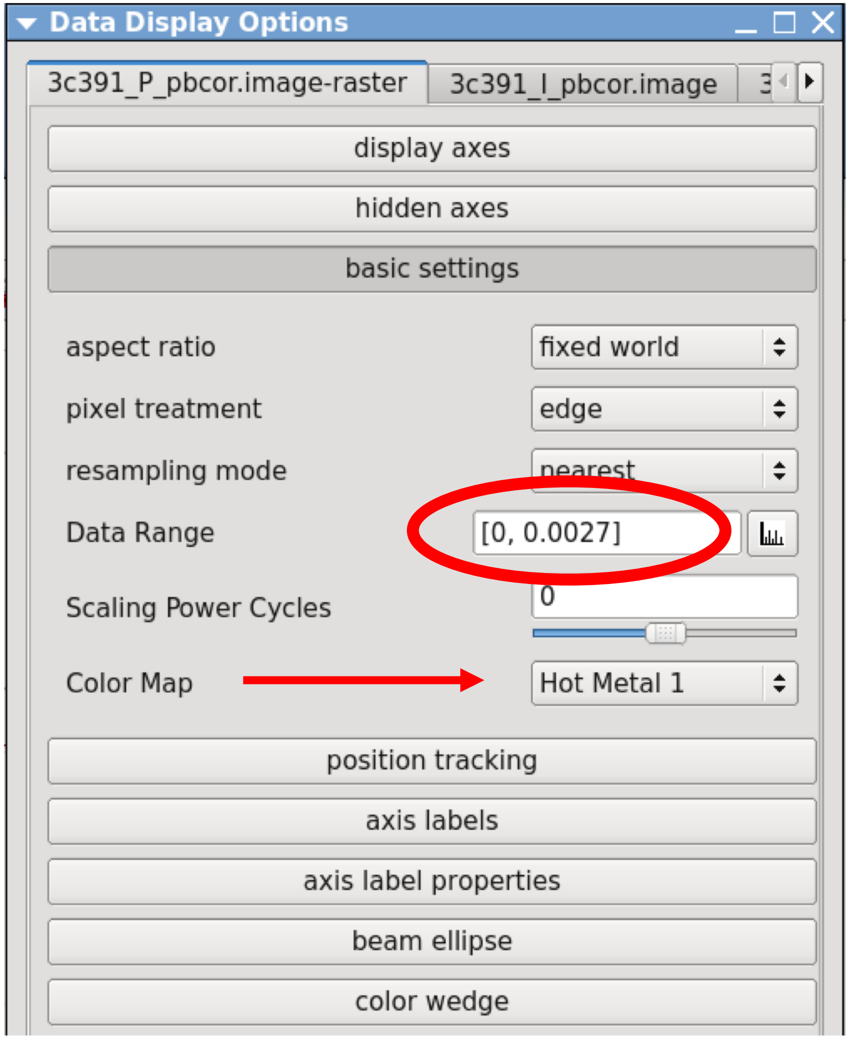
```
immath(outfile     =  '3c391_polX.image',
       mode        =  'pola',
       imagename   = ['3c391.Qimage','3c391.Uimage'],
       polithresh  =  '0.2mJy/beam')
```

Polarization Intensity and Angle Images

1. Load the linear polarization intensity image as a **raster**:
   `3c391_P_pbcor.image`

   Click on the Wrench icon to open the Data Display Options.

   Modify the Data Range and choose a nice Color Map.

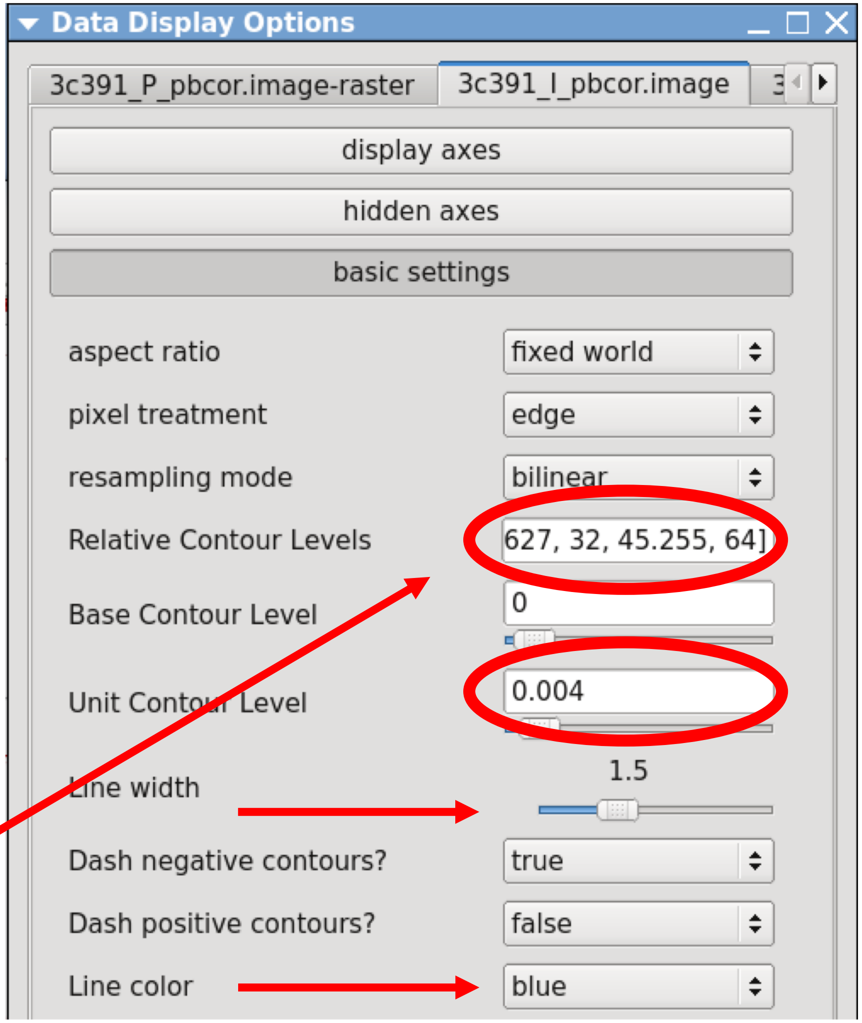


Polarization Intensity and Angle Images 21

2. Load the primary-beam corrected total intensity image as a **contour map**:
`3c391_I_pbcor.image`

Modify Unit Contour Level:
~ 5**σ** = 0.004 Jy/beam

Modify Relative Contour Level:
use $\sqrt{2}$ and a few negative values to demonstrate image quality:
`[-1.414, -1, 1, 1.414, 2, 2.828, 4, 5.657, 8, 11.314, 16, 22.627, 32, 45.255, 64]`



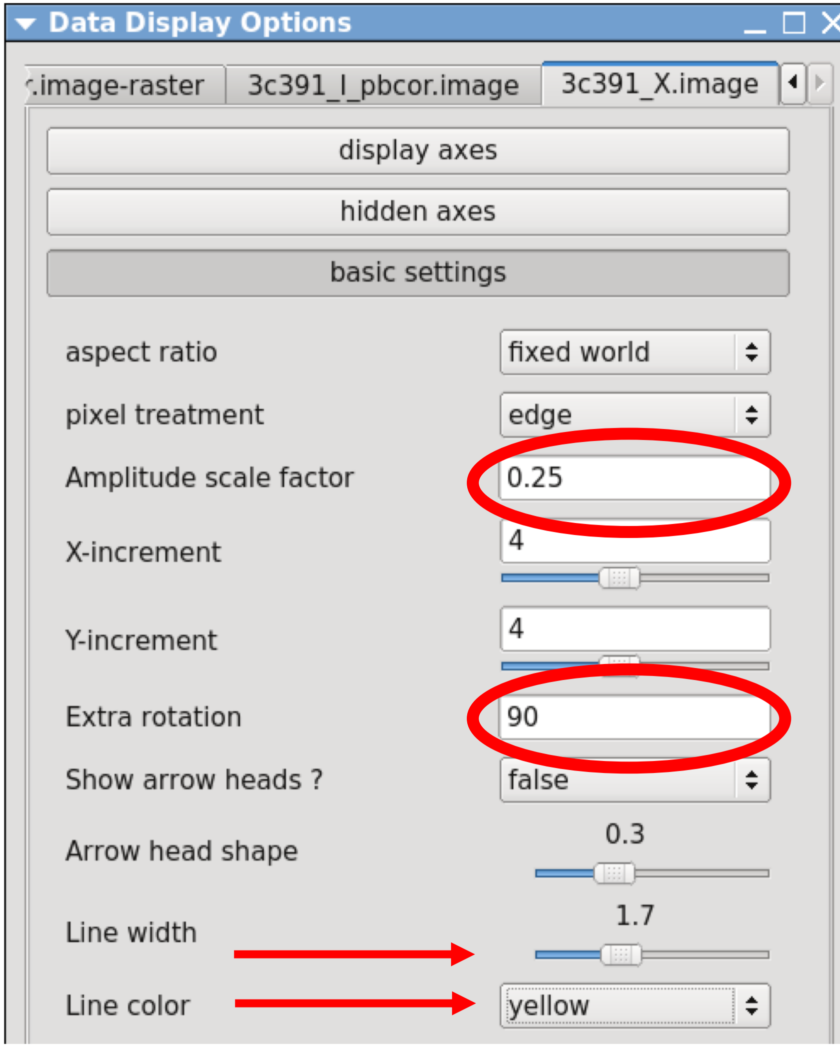
Polarization Intensity and Angle Images

3. Load the polarization position angle image as a **vector map**:

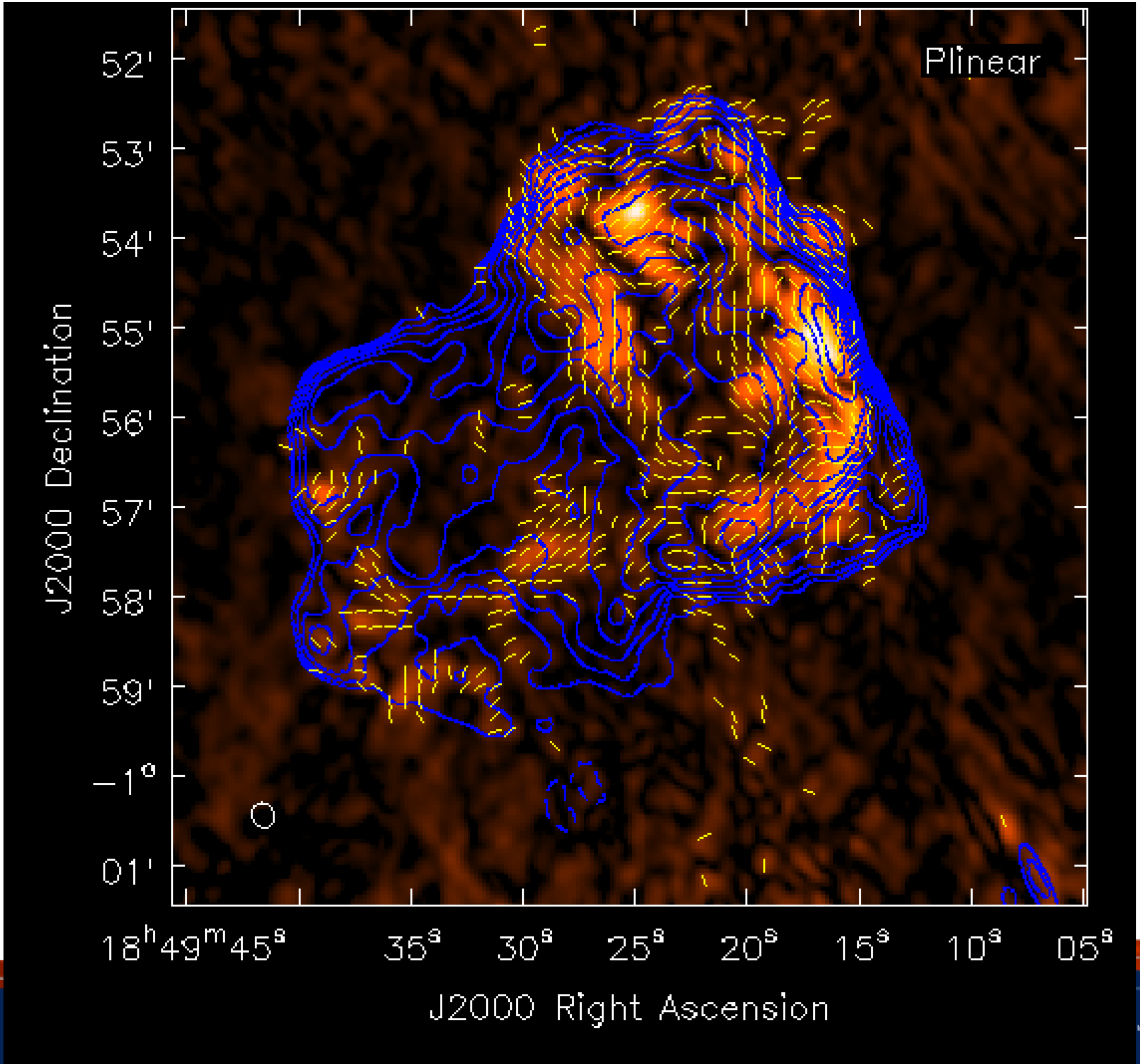
`3c391_X.image`

Modify the Amplitude scale factor (vector length) and choose a nice Line color.

Hint: polarization angle is for the electric vector. To show magnetic field orientation, rotate vectors by 90°.



Voila!


Plinear
52'
53'
54'
55'
56'
57'
58'
59'
−1°
01'
J2000 Declination
$18^h49^m45^s$
35^s
30^s
25^s
20^s
15^s
10^s
05^s
J2000 Right Ascension

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