



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

Amy Kimball (NRAO)



Introduction: A CASA 4.7.2 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 $\rightarrow$ mosaic! (7 pointings)
- The full tutorial is available at <http://casaguides.nrao.edu>
(CASA tutorials $\rightarrow$ Karl G. Jansky VLA Tutorials)

The data set

- You were asked to download a file: [3C391.tar](#)
- Un-compress the file: `tar -xvf 3C391.tar`
- The result will be one file and six 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)*

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 (4.7.2 version)

```
> casa
```

```
==>
```

```
=====
```

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

```
=====
```

CASA Version 4.7.2-REL (r39762)

Compiled on: Wed 2017/03/08 12:39:14 UTC

For help use the following commands:

tasklist	- Task list organized by category
taskhelp	- One line summary of available tasks
help taskname	- Full help for task
toolhelp	- One line summary of available tools
help par.parametername	- Full help for parameter name

Activating auto-logging. Current session state plus future input saved.

Filename : ipython-20170310-231528.log

Mode : backup

Output logging : False

Raw input log : False

Timestamping : False

State : active

*** Loading ATNF ASAP Package...

*** ...ASAP (rev#38164:) import complete ***

CASA <3>:

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	...	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	...	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	...	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	...	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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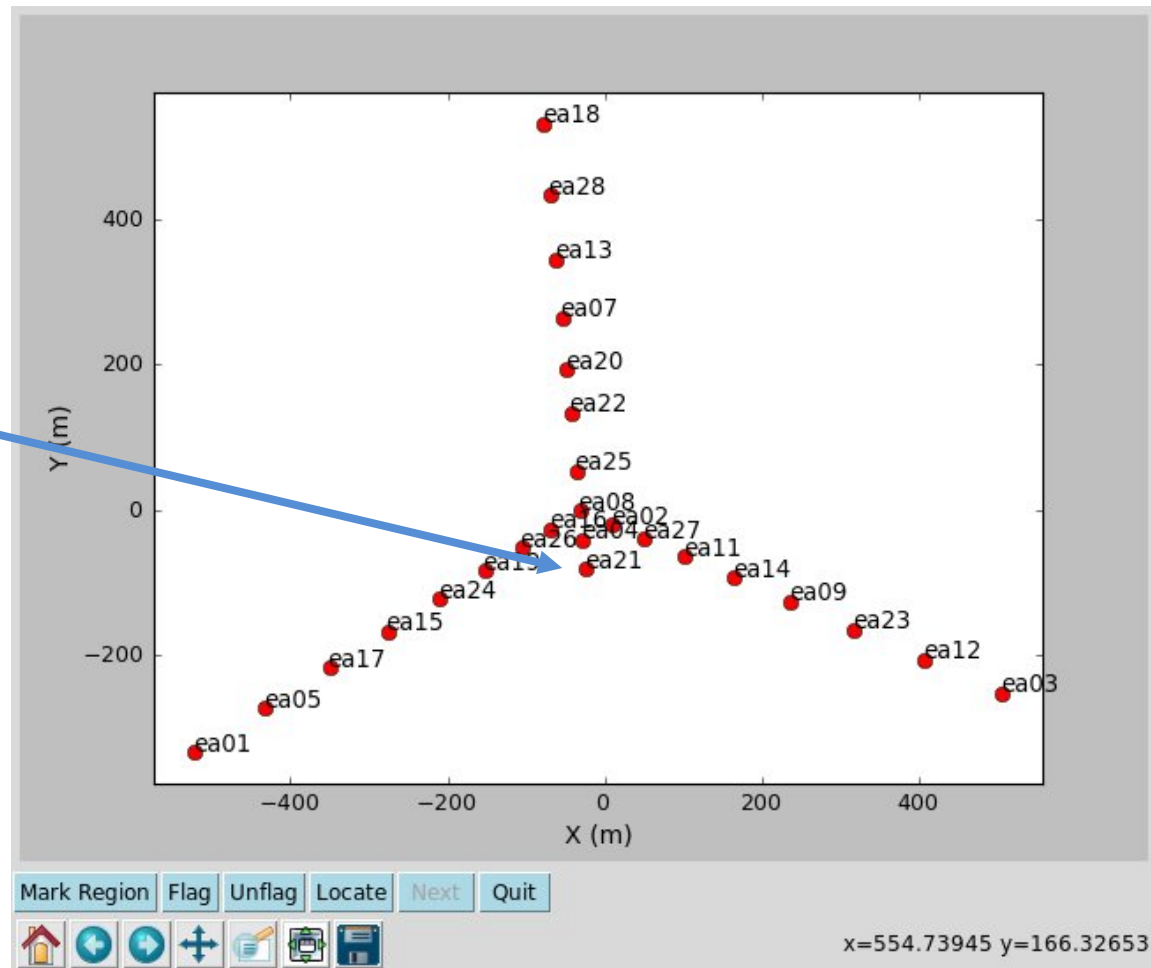
To make a graphical plot of the antenna positions:

`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'



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'`

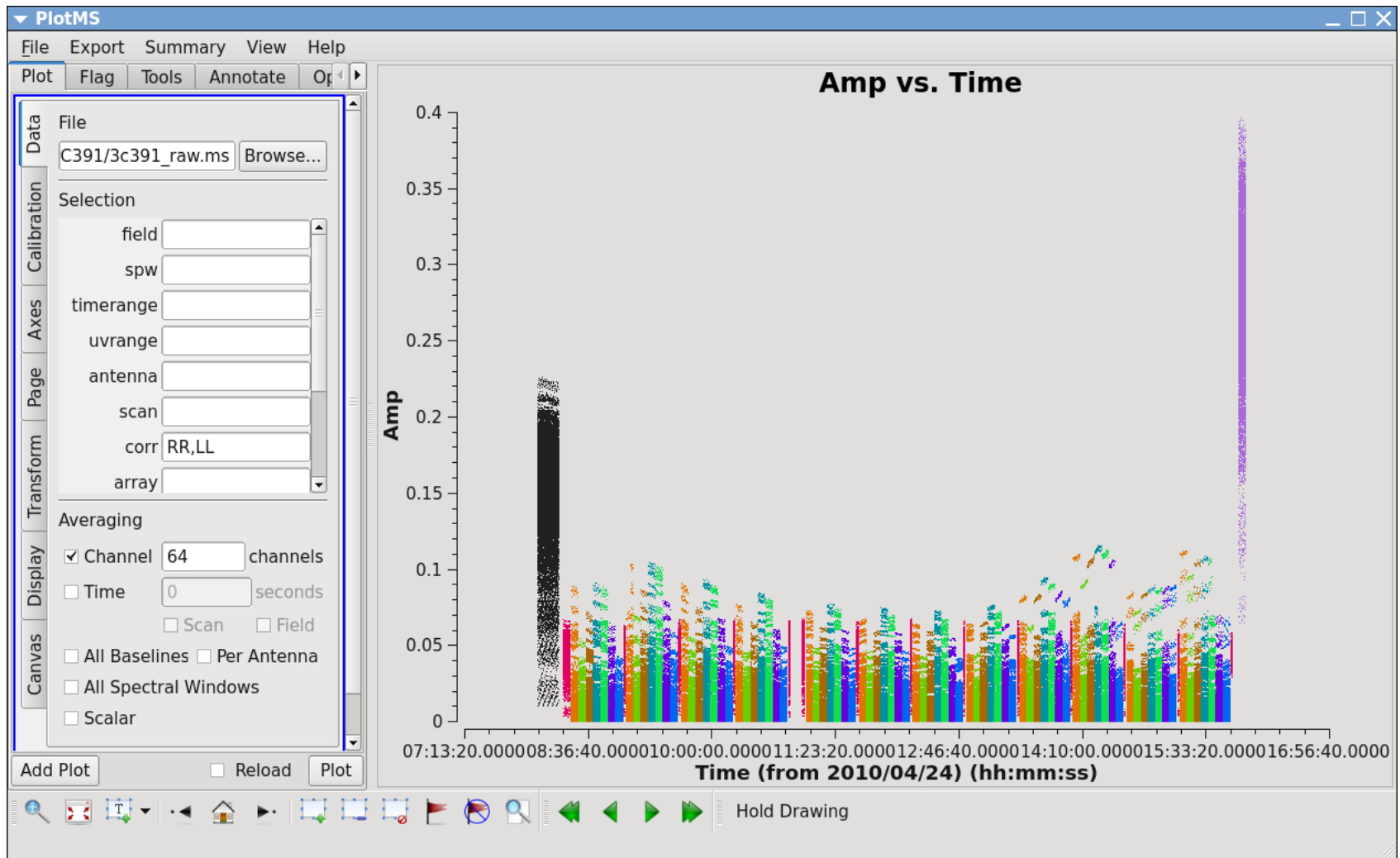
- `averagedata` = `True`

- `avgchannel` = `'64'`

- `coloraxis` = `'field'`

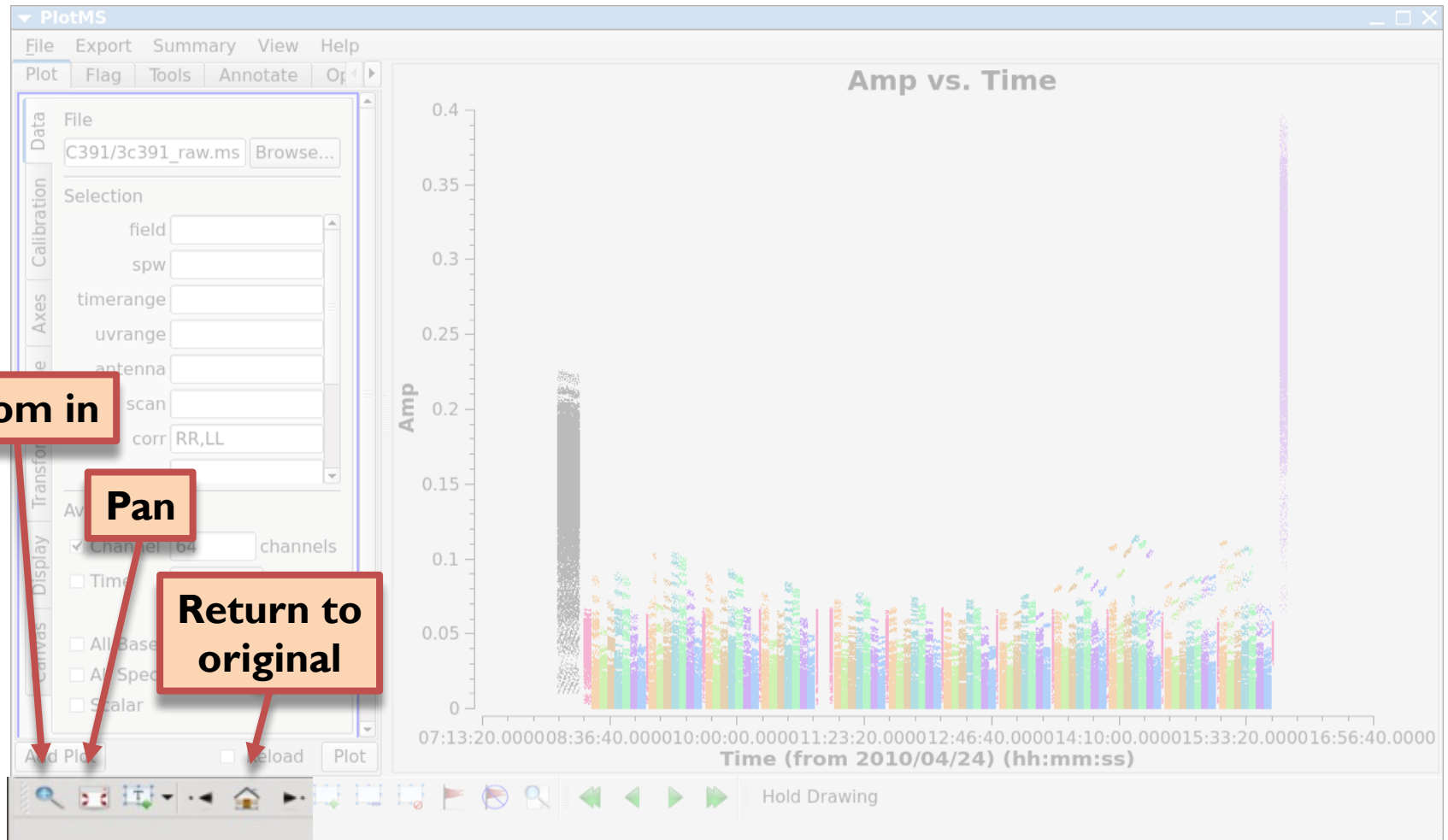
- `plotms` or `go`

CASA: *plotms*



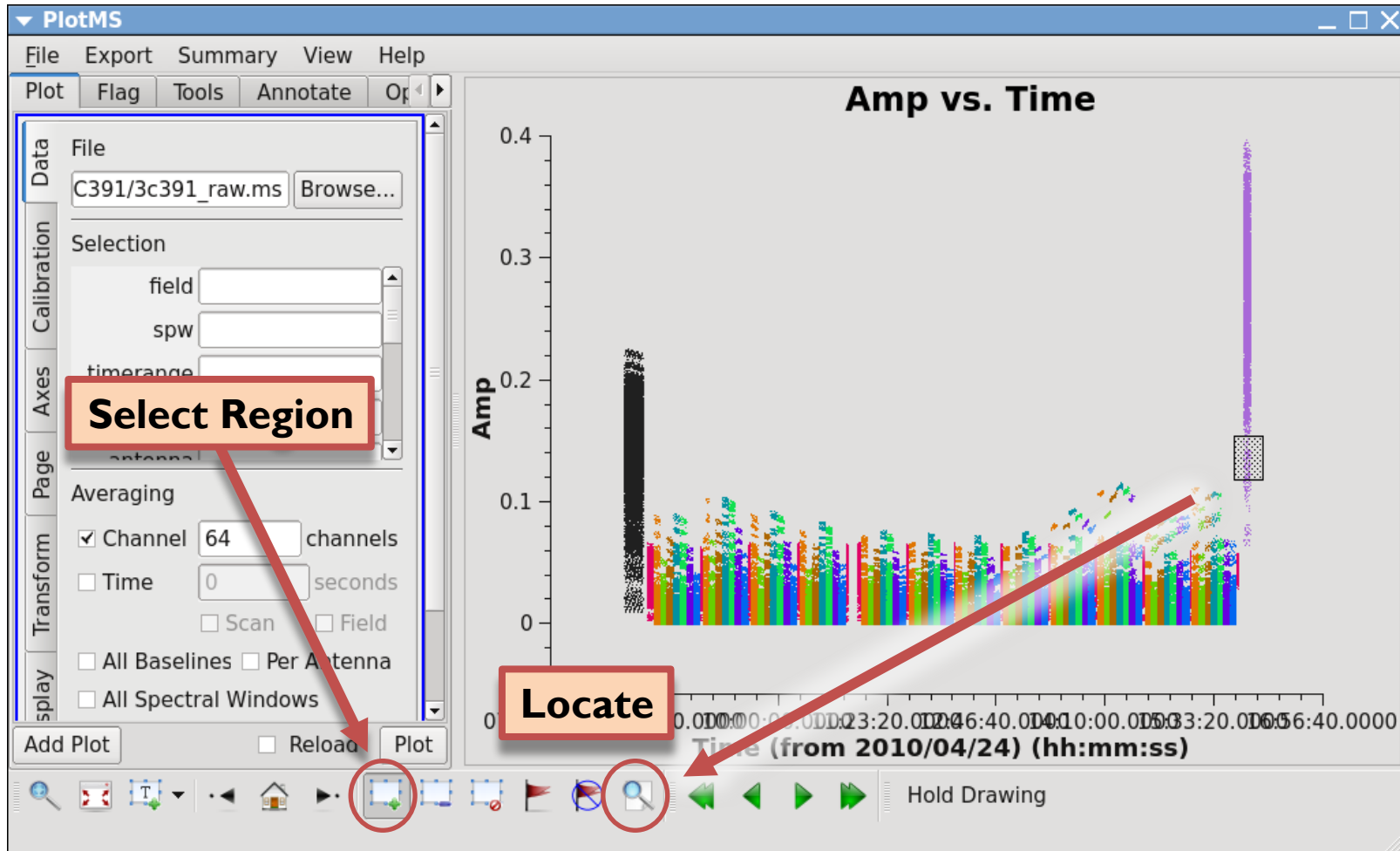
CASA: *plotms*

Navigate using the buttons at the bottom left of the window



CASA: *plotms*

Use the “Region” and “Locate” tools to identify data points

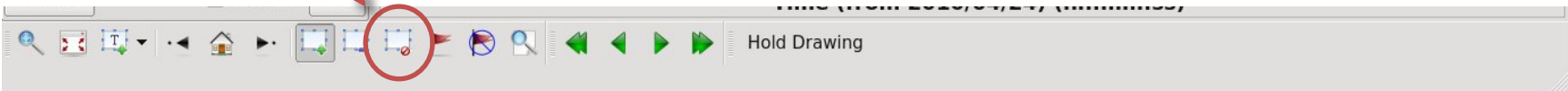


CASA: *plotms*

“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
```

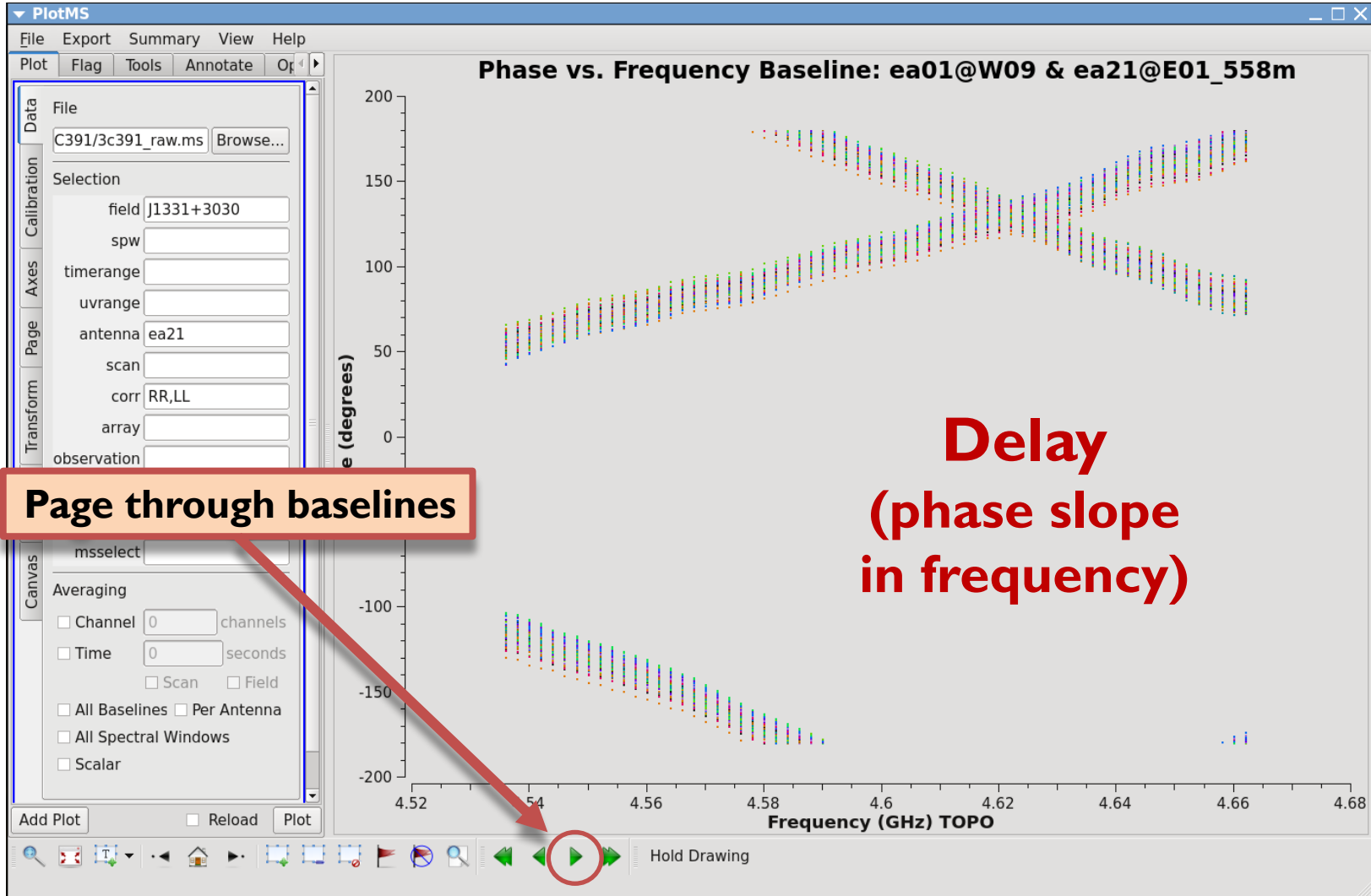
Clear regions in *plotms*:



- 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*



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: *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 [l=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 l = 7.66874, 7.59784, 7.53052 Jy @(4.535e+09,
4.601e+09, 4.665e+09)Hz ...

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*

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

`default plotcal`

`caltable = 'cal.G'`

`xaxis = 'time'`

`yaxis = 'phase'`

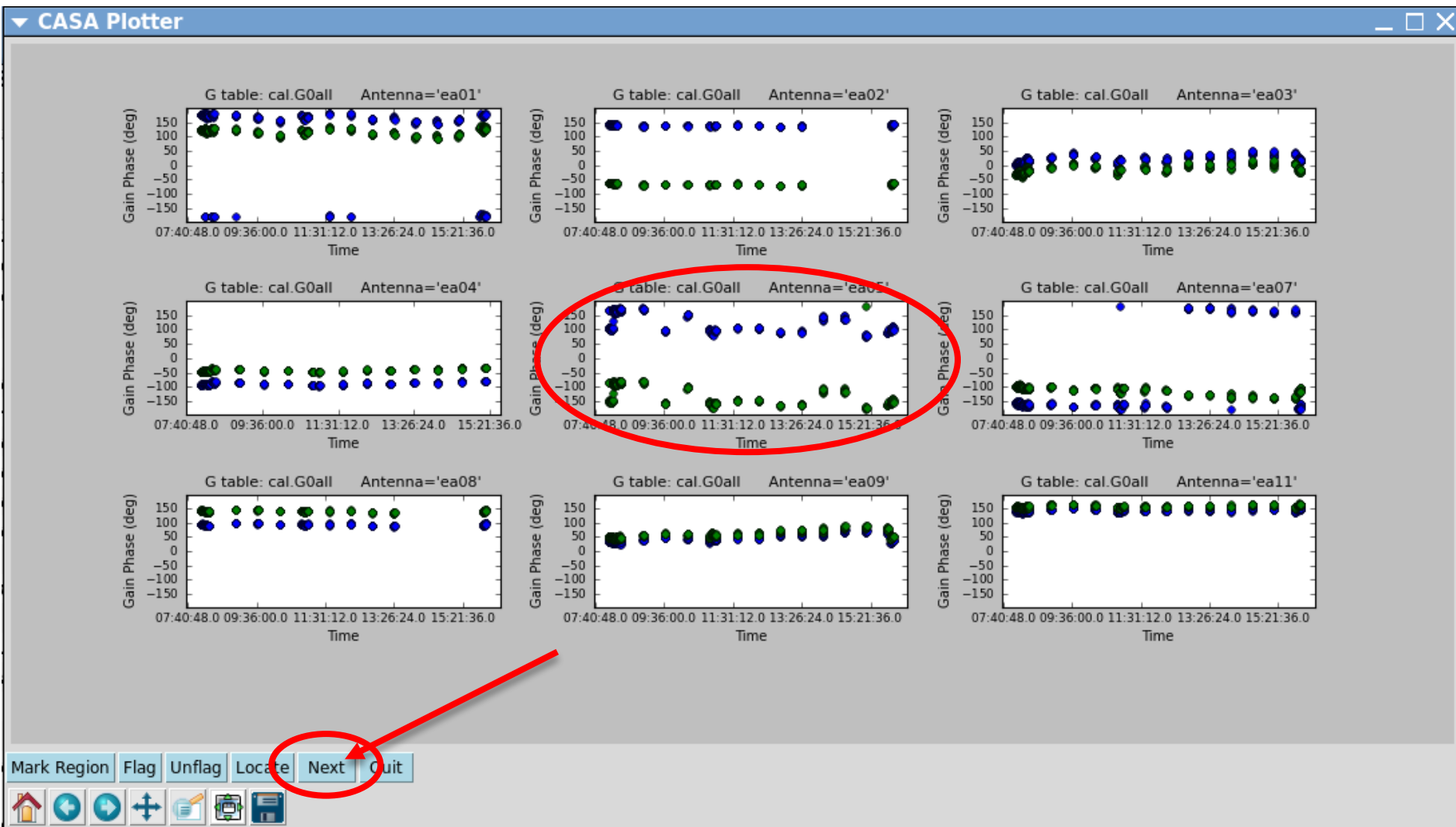
`subplot = 331` # display 3x3 plots per screen

`iteration = 'antenna'` # iterate through antennas

`plotrange = [-1,-1,-180,180]` # [xmin,xmax,ymin,ymax]

`plotcal` or `go`

CASA: *plotcal*



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'`

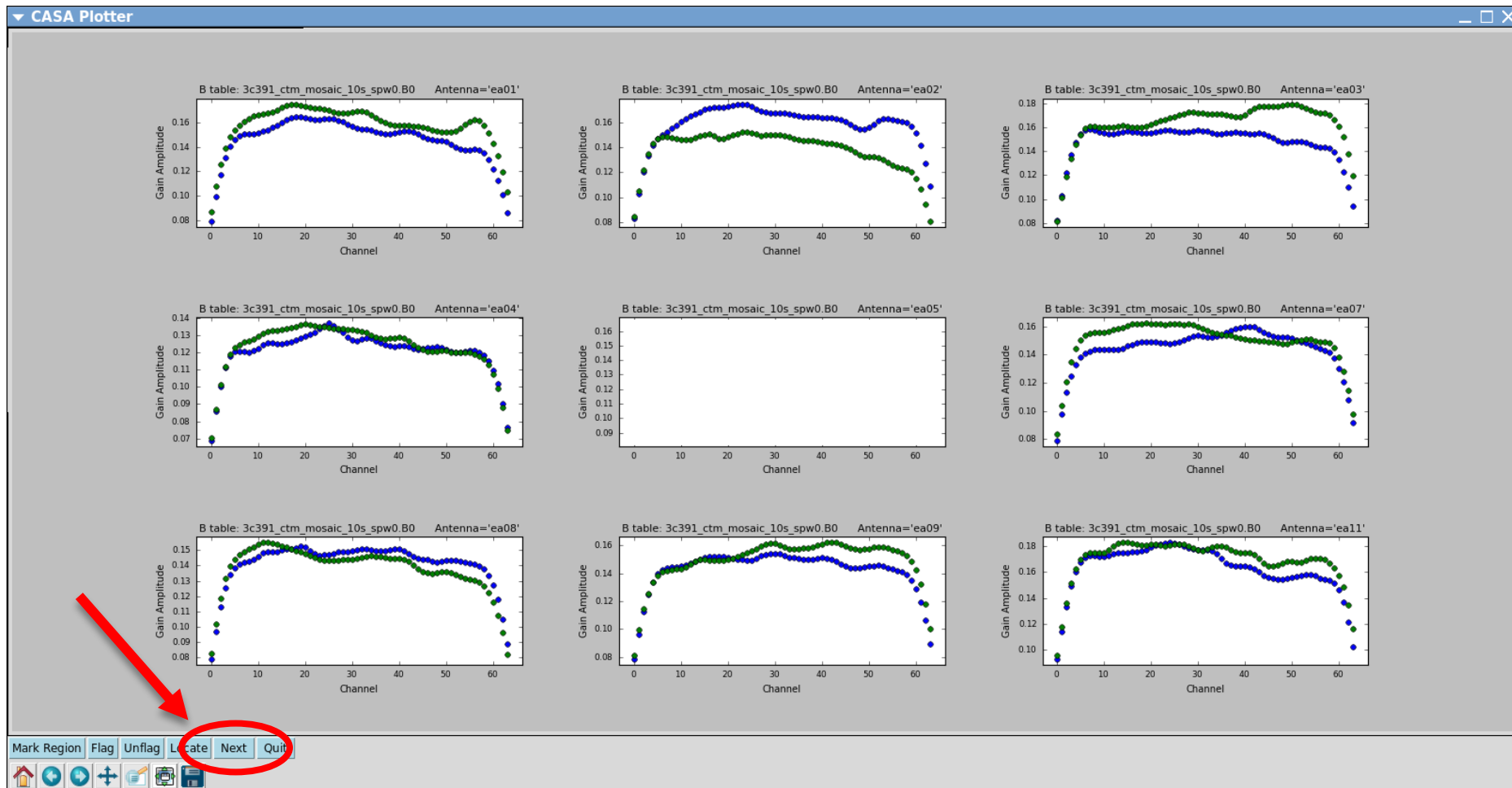
`yaxis = 'amp'`

`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
- 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.

Calibration strategy (polarization)

- Requirements for polarization calibration:
 - One observation of a position angle calibrator (3C 286)
 - Flux density model (*with info from previous set j y output*)
 - 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 ($\sim 60^\circ$)

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 properties 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 ...

$\alpha = \log(7.53052/7.6677) / \log(4665.0/4536.0)$

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!

setjy or go

Polarization: solve for cross-hand delays 15

```
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.G']
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'    # one solution over entire observing run
gaintable    = ['cal.antpos', 'cal.K', 'cal.BP',
                 'cal.G', 'cal.Kcross']
gainfield    = ['', '', '', '9', ''] # J0319+4130 field
```

```
polcal or go
```

Polarization: solve for R-L polarization angle

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default polcal

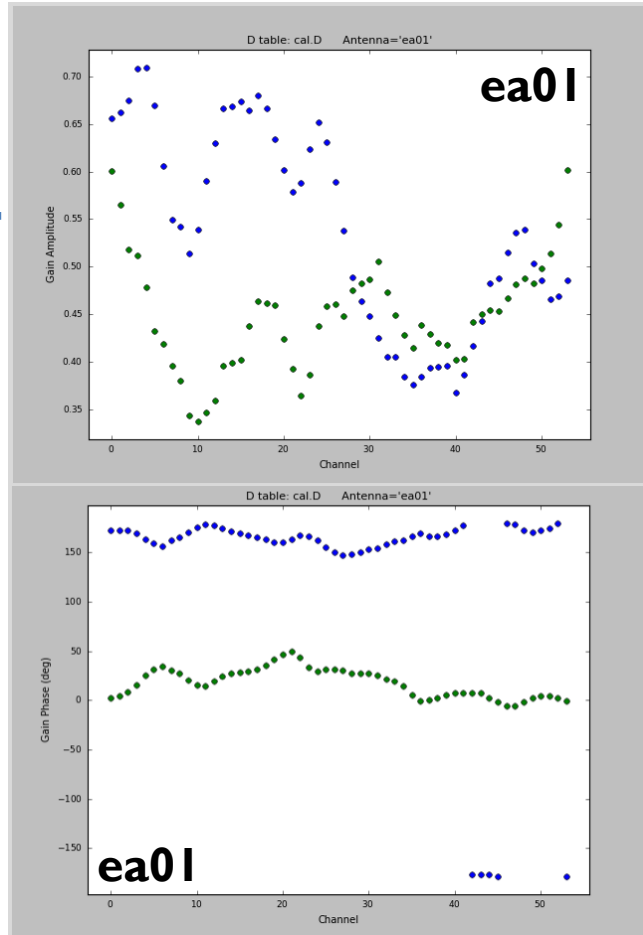
```
vis          = '3c391_raw.ms'
caltable     = 'cal.X'
field        = 'J1331+3030'
poltype      = 'Xf'          # angle (X) with frequency dependence (f)
combine      = 'scan'       # one solution for entire observing run
solint       = 'inf'        # one solution for entire observing run
gaintable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

polcal or go

Polarization calibration solutions: examples

Leakage solutions (cal.D)

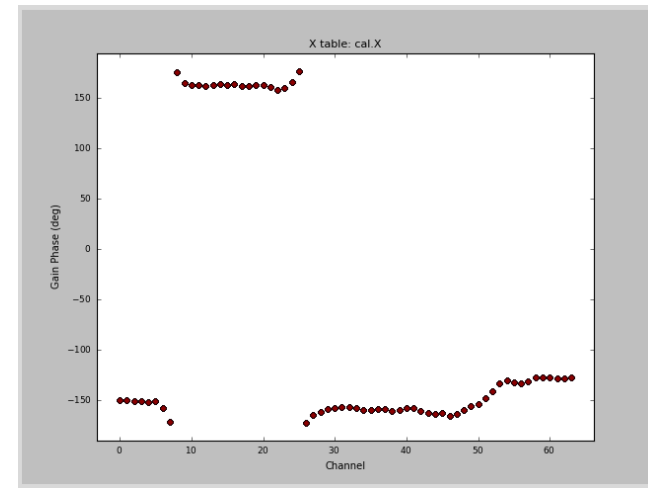
Gain Amplitude



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 `clean`
 - Rebuilt, improved version 'tclean' (test-clean) will replace `clean`
- 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` ($480 = 2^5 \times 3^1 \times 5$)

*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 *clean* uses one scale [0] --- assumes sky emission is made up of Dirac Delta functions
- Multi-scale algorithm 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)

```
vis = '3c391_calibrated.ms'
imasename = '3c391_I_multiscale'
field = ''
mode = 'mfs'
niter = 5000
threshold = '1.0mJy'
psfmode = 'clark'
imagermode = 'mosaic'
ftmachine = 'mosaic'
interactive = True
npercycle = 500 # default is 100 but use higher for a mosaic
imsize = [480,480]
cell = ['2.5arcsec', '2.5arcsec']
weighting = 'briggs'
robust = 0.5
multiscale = [0,6,18,54] # [0, 15, 45, 135] arcsec
smallscalebias = 0.9
```

CASA: clean

Interactive = True

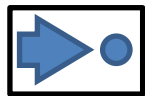
- Make a region
- Double-click inside to activate (green outline turns white)
- Start the clean:



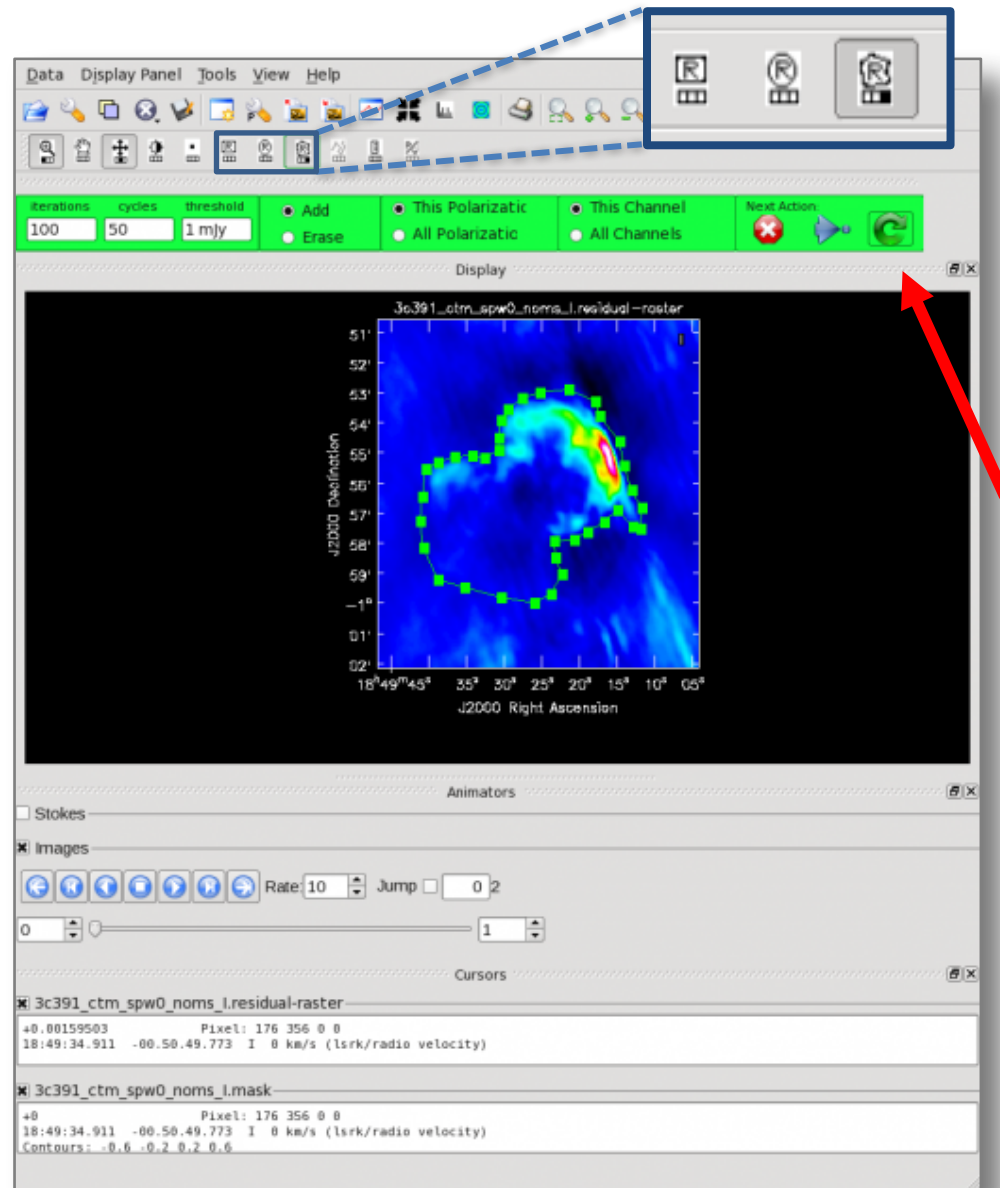
- Adjust regions and continue:



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



- To stop the clean:



CASA: viewer

View CASA images, fits files:
viewer

- Select your image:
'3c391_I_multiscale.image'

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

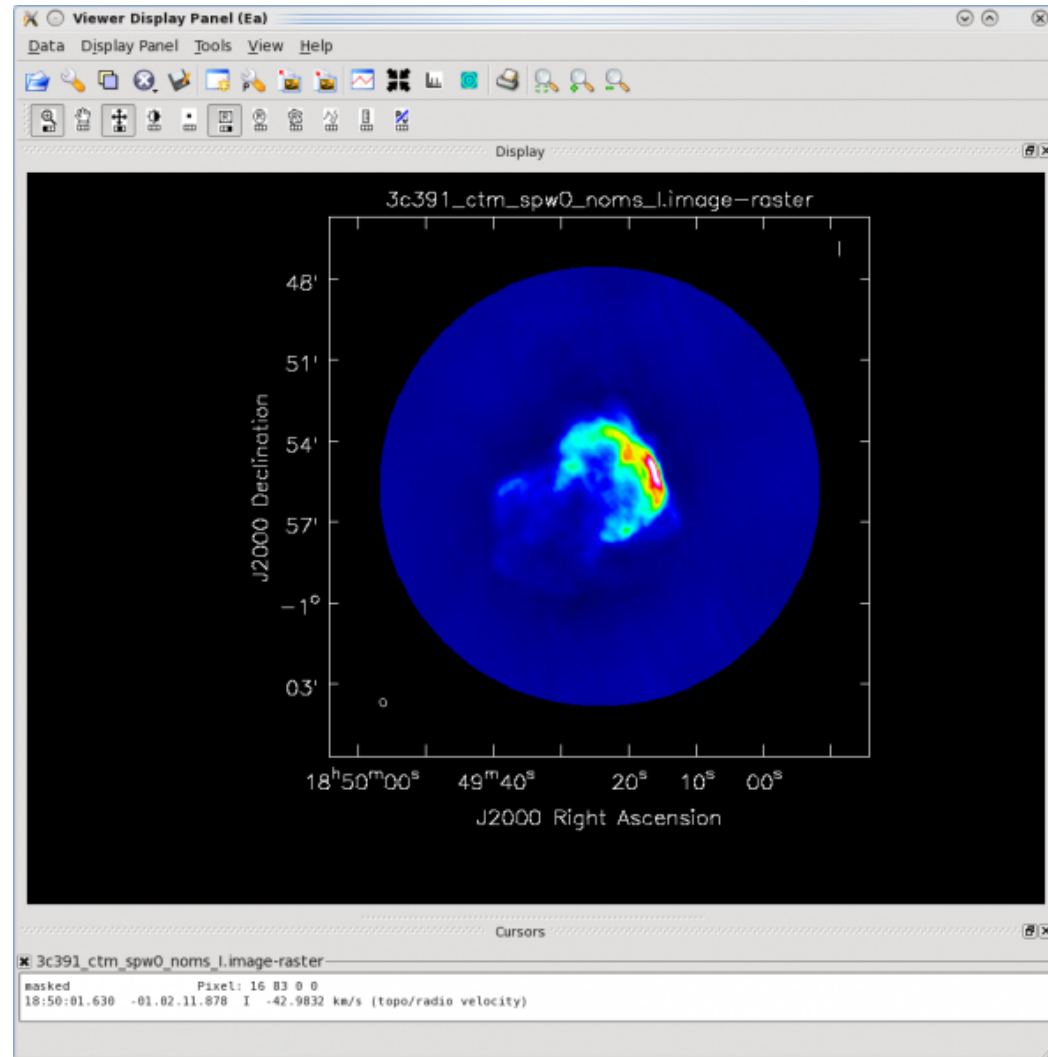


Image analysis: peak brightness, noise level

CASA command line

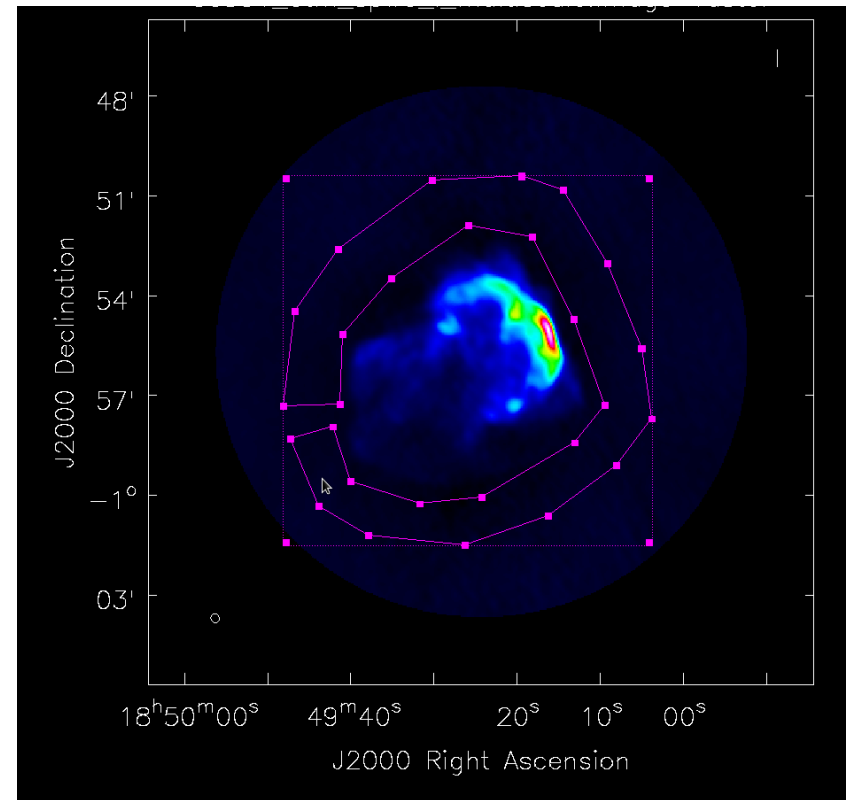
```
imstat(<image>)    or  
mystat = imstat(<image>)
```

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

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*)
 - `clean` 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 images made with wideband techniques (`nterms > 1`), use special CASA task `widebandpbcor`
(see online CASAGuide tutorial on VLA CASA imaging)
- Primary beam corrected images have increased noise at the edges, and at interstices of mosaic pointings

CASA: *clean* for Stokes IQUV image

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

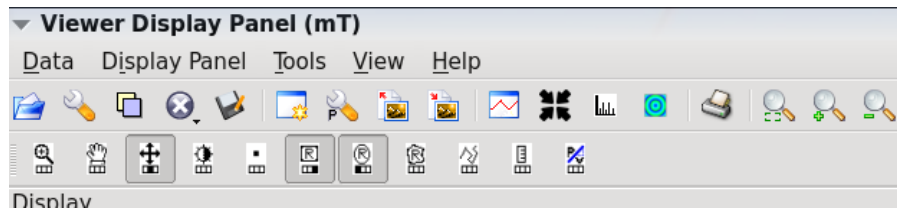
Select the “All Polarizations” button before making regions!



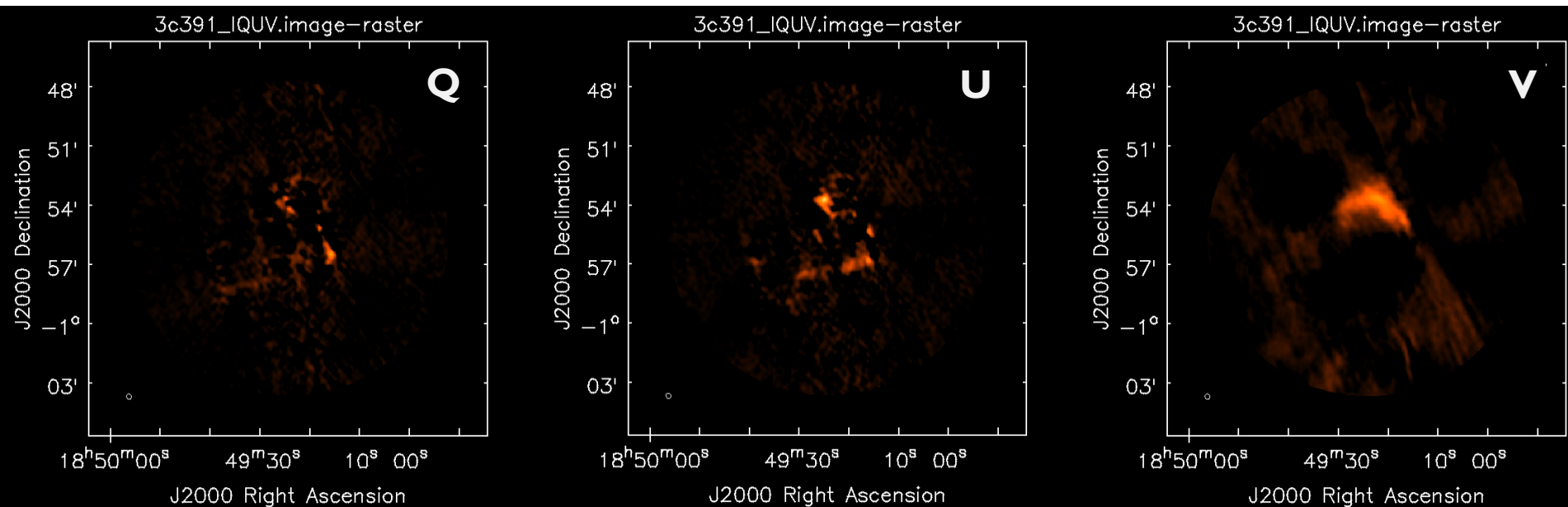
Polarized images (IQUV)

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

Change scaling through the
Data Display Options:



Iterate through the Stokes cube:



Polarization Intensity and Angle Images

- The CASAguide shows the use of task `immath` to calculate:

- Linear polarization image “P”

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

- Polarization position angle image “X”

$$\tan (2 X) = U / Q$$

- Example:

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

Polarization Intensity and Angle Images

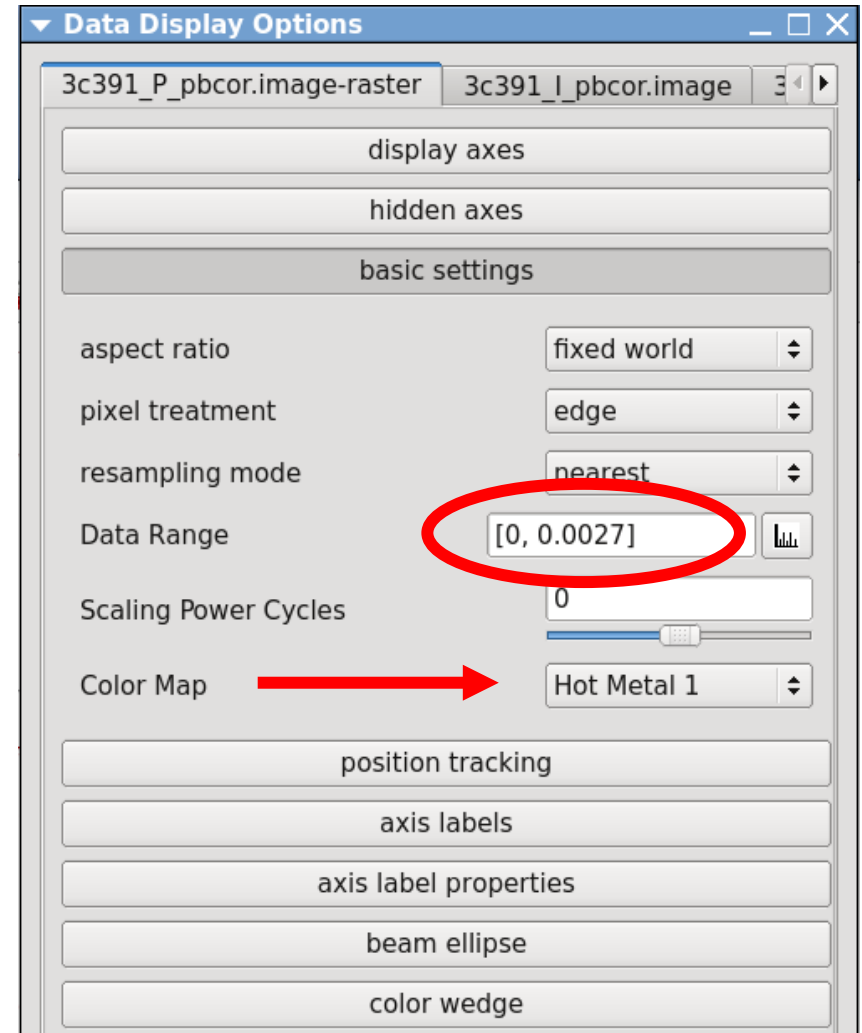
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- I. Load the linear polarization intensity image as a **raster**:

`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.



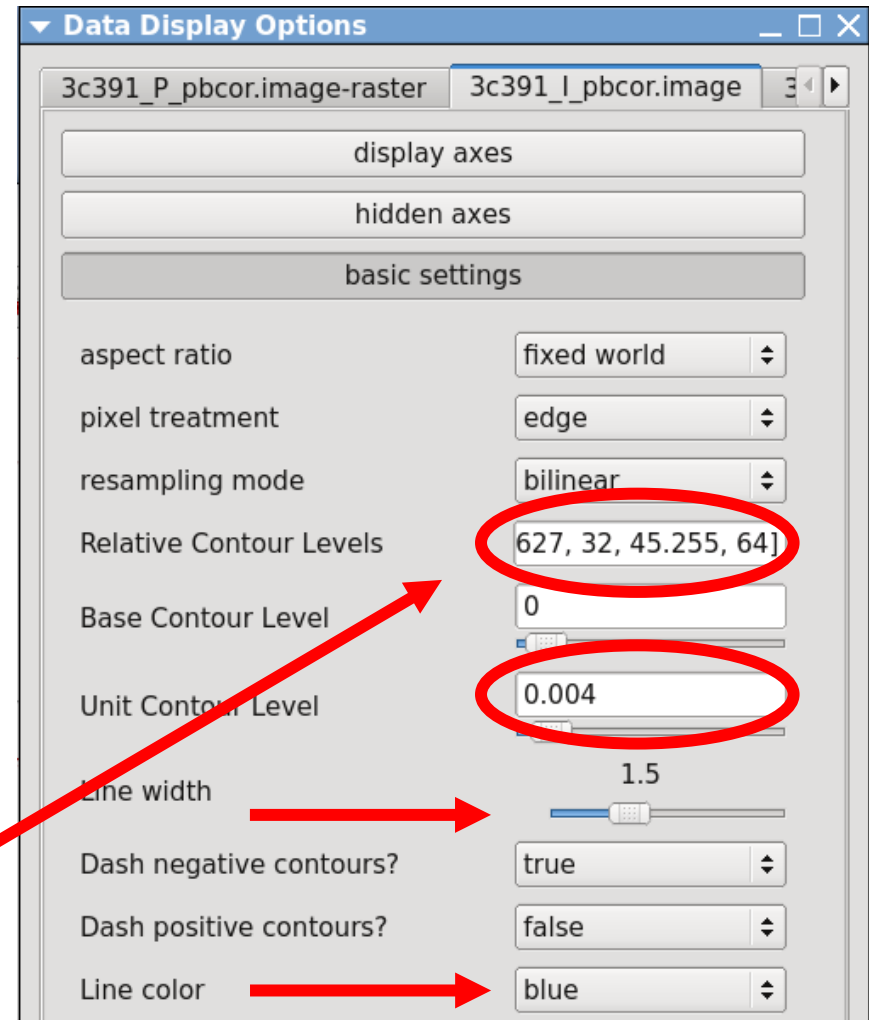
Polarization Intensity and Angle Images 20

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

Modify Unit Contour Level:
 $\sim 5\sigma = 0.004 \text{ Jy/beam}$

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]`

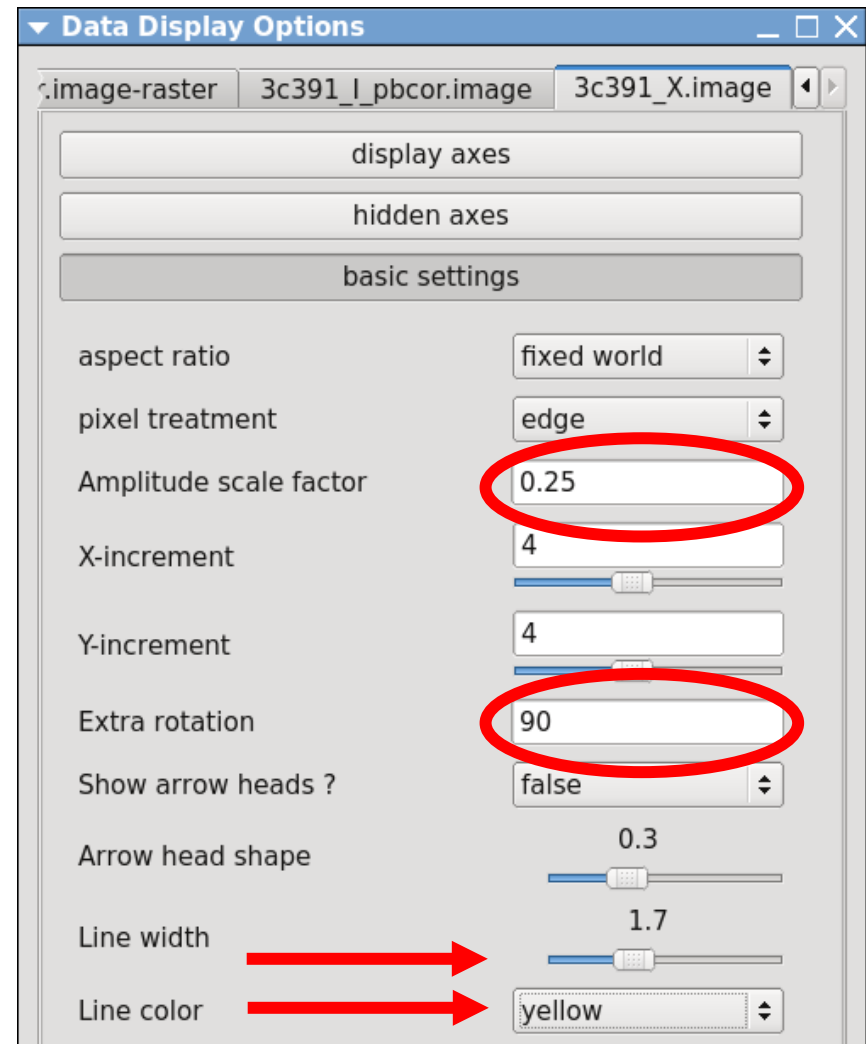


Polarization Intensity and Angle Images 21

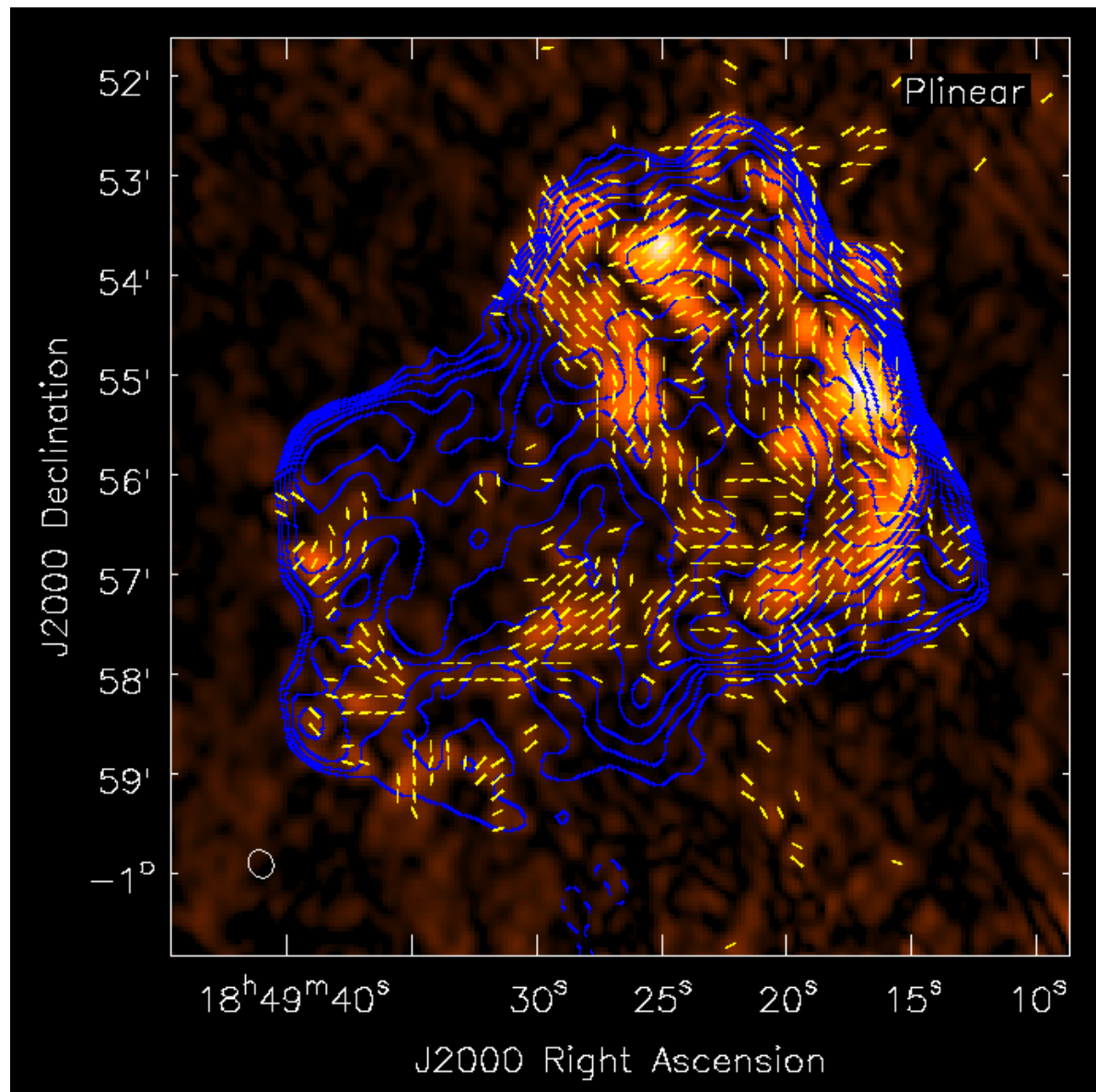
- Load the polarization position angle image as a **vector map**:
`3c391_X.image`

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!



Please fill out the **EXIT SURVEY!**

<http://go.nrao.edu/nrao-cdsurvey>

We strongly value your feedback. Thanks!



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