Interactive Tutorial

ALMA Guides: a first look at imaging and at spectral line imaging

Emily Moravec

Slide authors: Holly Sheets and Dominic Ludovici, with contributions from Amanda Kepley, Urvashi Rau, and David Wilner

NSF AUI ALMA NAASC NORTH AMERICAN ALMA SCIENCE CENTER NRAO

Goals of this tutorial

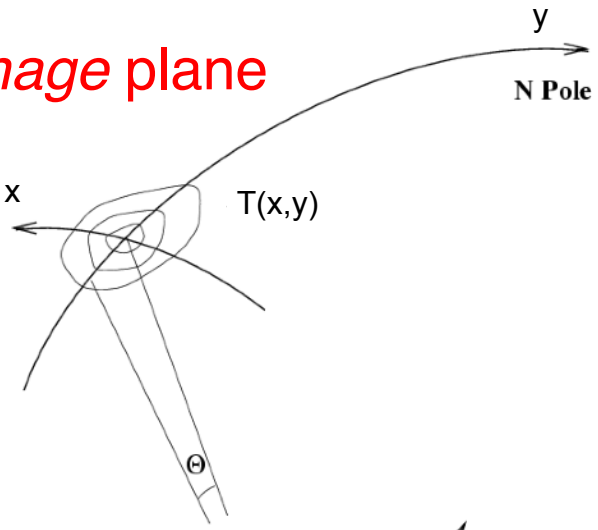
- Learn how to create continuum and line cubes in tclean
- Understand some key parameters in tclean

First look at imaging

From Sky Brightness to Visibility

1. An interferometer measures the interference pattern observed by pairs of apertures
2. The interference pattern is directly related to the source brightness. In particular, for small fields of view, the complex visibility, V(u,v), is the 2D Fourier transform of the brightness on the sky, T(x,y)

image plane



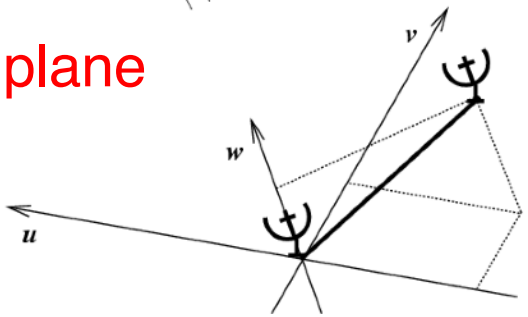
Fourier space/domain

$$V(u,v) = \int\int T(x,y) e^{2\pi i(ux+vy)} dxdy$$

Image space/domain

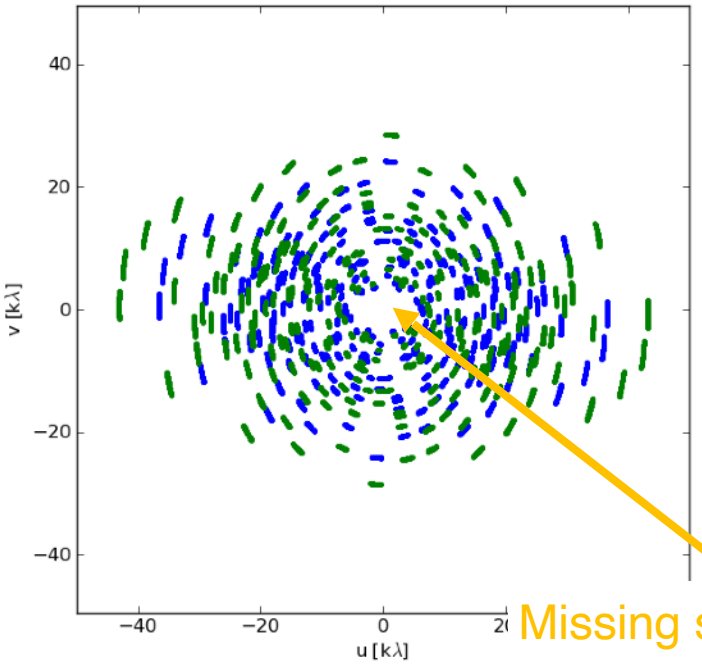
$$T(x,y) = \int\int V(u,v) e^{-2\pi i(ux+vy)} dudv$$

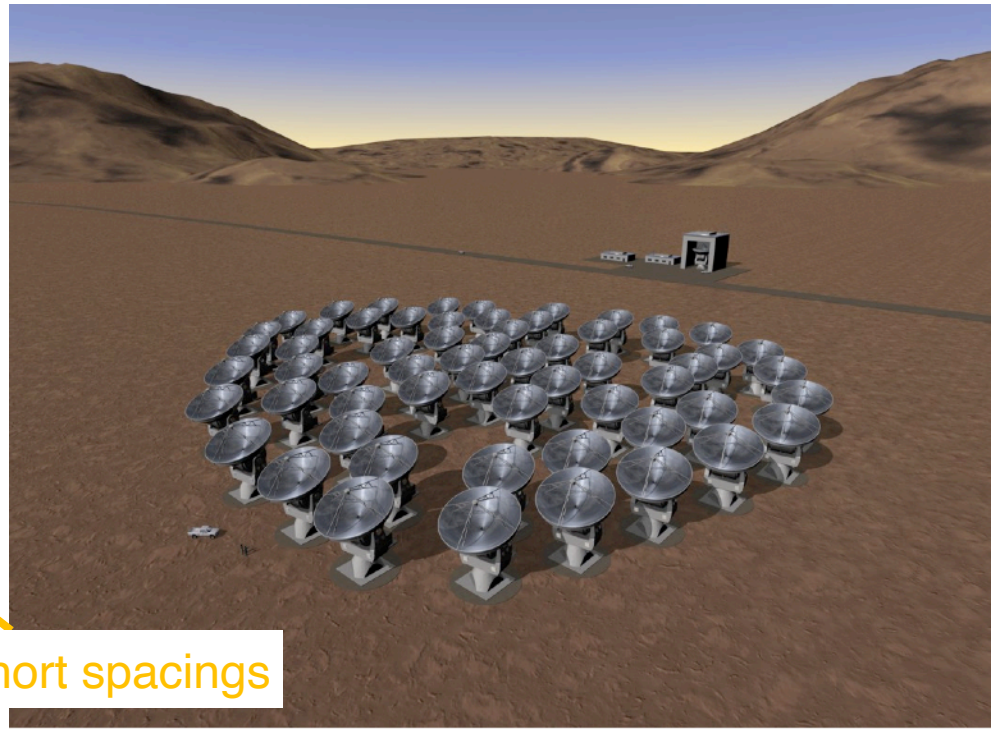
uv plane



Slide courtesy of Amanda Kepley

Interferometers discretely sample the uv-plane.





Missing short spacings

- Small uv-distance: **short baselines** (measures extended emission)
- Long uv-distance: **long baselines** (measures small scale emission)
- Orientation of baseline determines orientation in the uv-plane
- **Antennas can only physically be so close together leaving a hole in the center of the uv-plane (missing short spacings)**

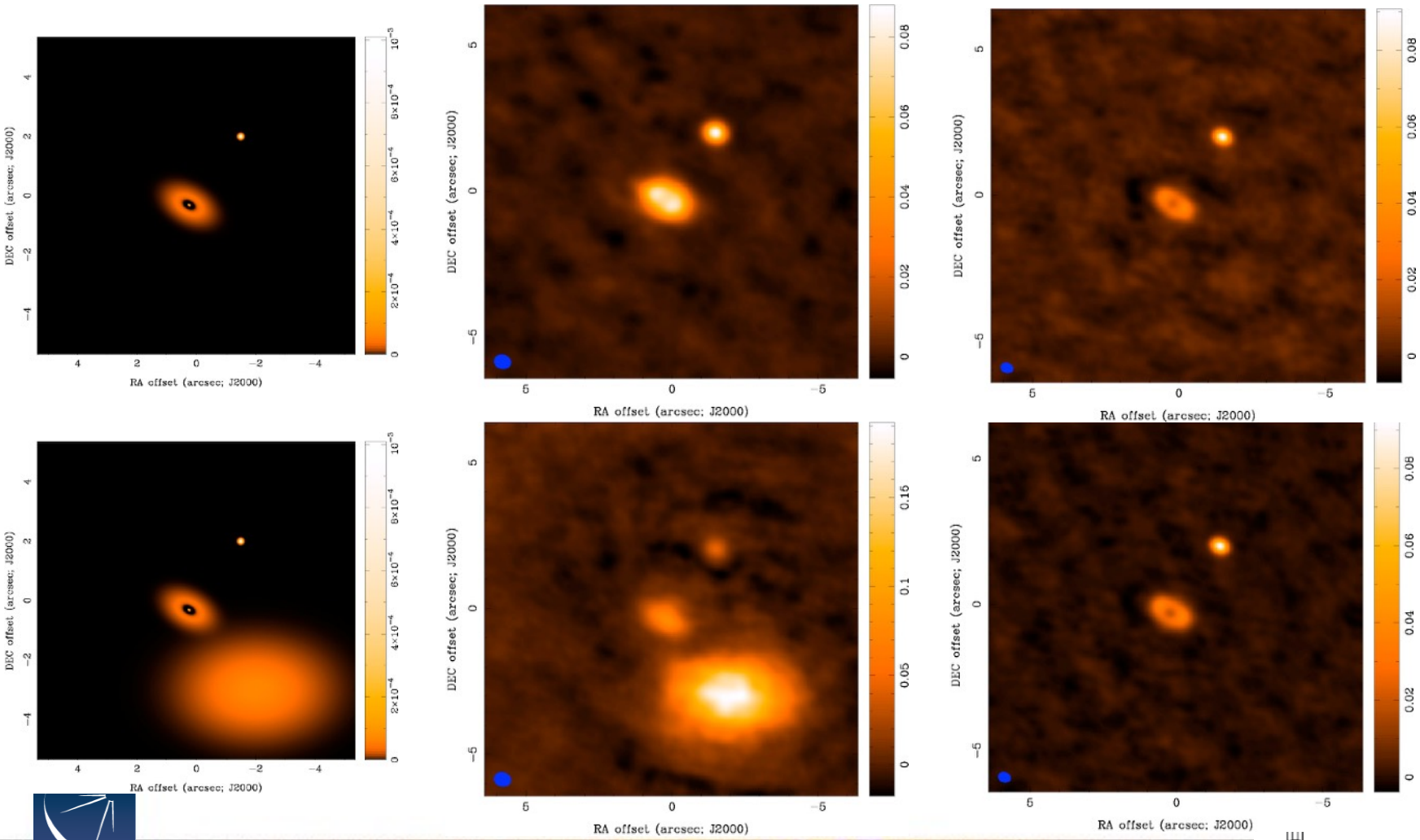
Slide courtesy of Amanda Kepley

Missing Short Spacings: Demonstration

Sky Model

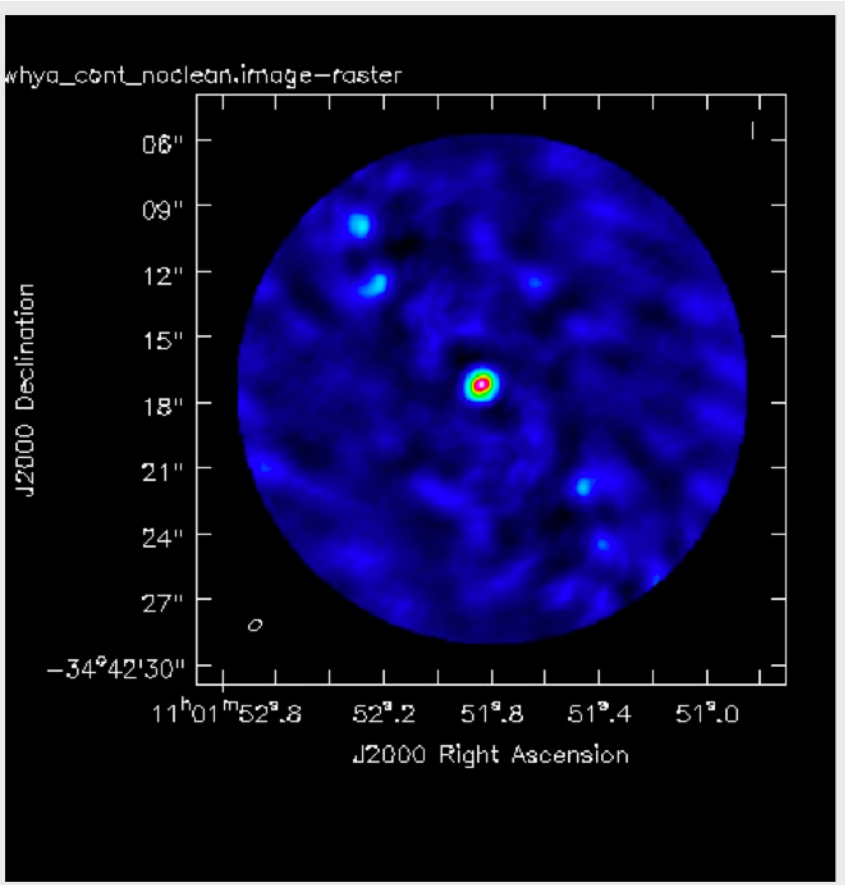
Full range of spatial scales

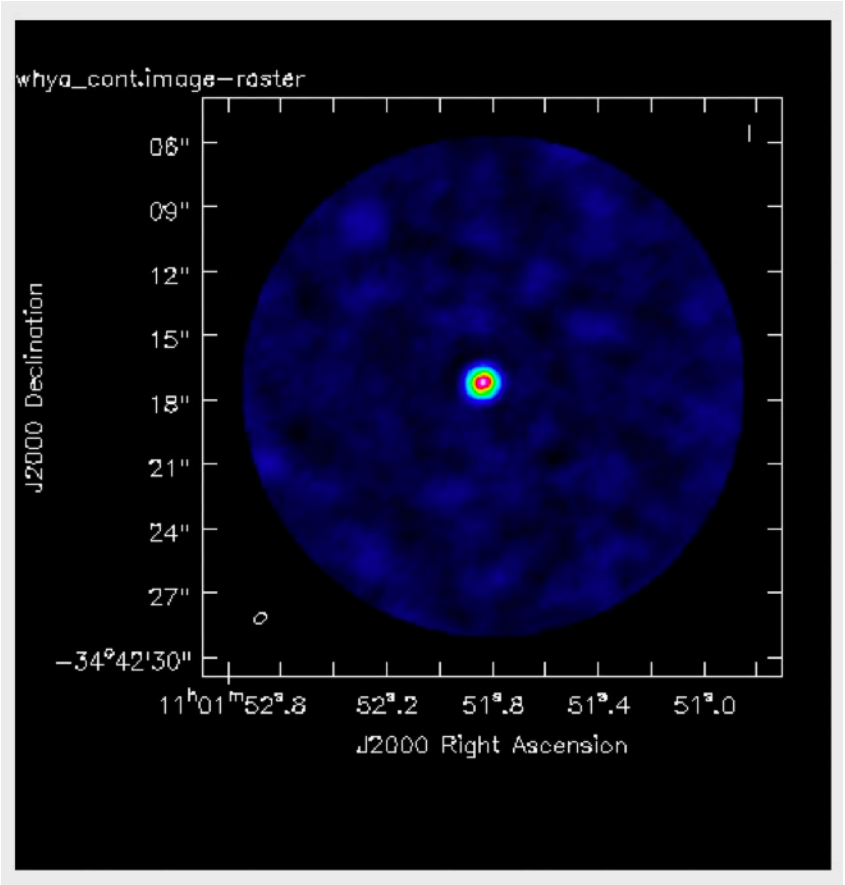
> 75 kλ i.e. cutting out a central hole



Courtesy David Wilner

Gaps in uv coverage: why we clean



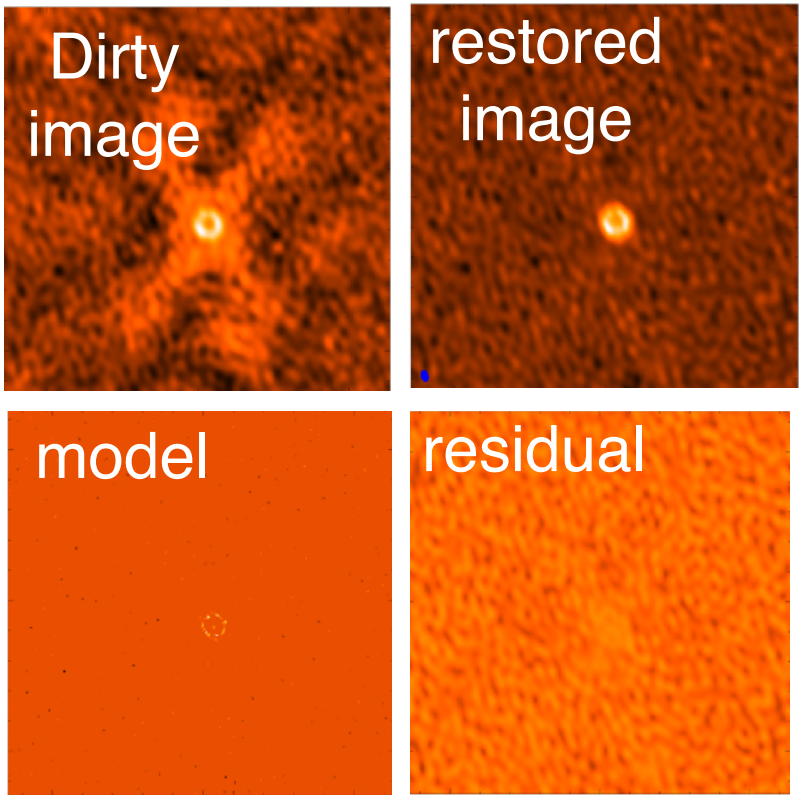


"Dirty" image of TW Hya vs. "Clean" image of TW Hya

Clean is the most common deconvolution algorithm.

Sky Model : List of delta-functions

(1) Construct the observed (dirty) image and PSF
(2) Search for the location of peak amplitude.
(3) Add a delta-function of this peak/location to the model
(4) Subtract the contribution of this component from the dirty image - a scaled/shifted copy of the PSF
Repeat steps (2), (3), (4) until a stopping criterion is reached.
(5) Restore : Smooth the model with a 'clean beam' and add residuals



Choices: what and how much PSF to subtract and when to stop

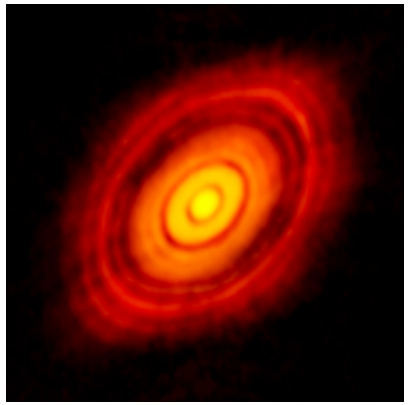
Slide courtesy of Amanda Kepley, adapted from slide by Urvashi Rau

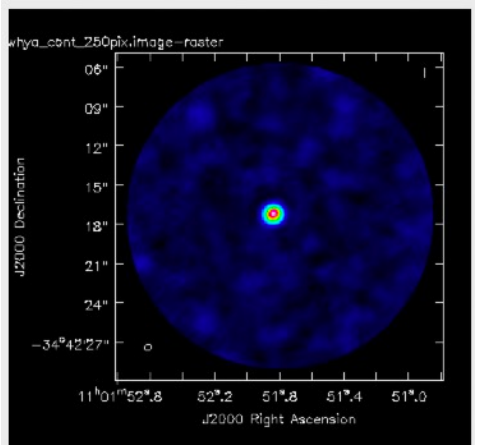
Time for Hands on Tutorial

First look at continuum imaging

Following ALMA CASA Guide “First Look at Imaging” : Continuum

- https://casaguides.nrao.edu/index.php?title=First_Look_at_Imaging_CASA_6.4





Cd to data directory and start-up CASA

$casa

Slides and commands (imaging_tutorial_commands.txt) are in https://astrocloud.nrao.edu/s/T7wzjL2tTP6Leg4

Using CASA tasks and getting oriented with the data

Bring up a list of the input parameters and enter them one by one:

inp listobs
vis='sis14_twhya_calibrated_flagged.ms'
go

(commands to input to CASA are highlighted in yellow)

Using CASA tasks and getting oriented with the data

Bring up a list of the input parameters and enter them one by one:

```
inp listobs
vis='sis14_twhya_calibrated_flagged.ms'
go
```

OR

All in one command (preferred!):

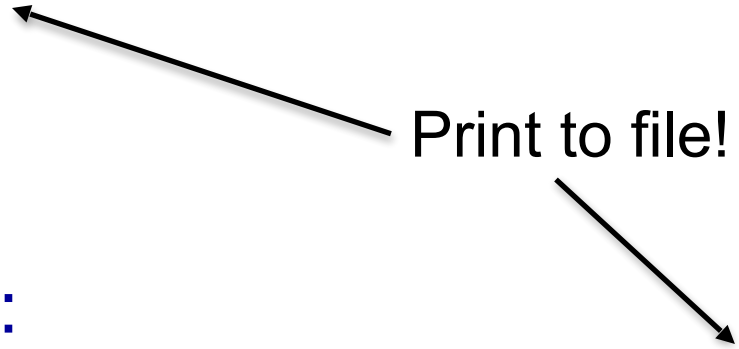
```
listobs(vis='sis14_twhya_calibrated_flagged.ms')
```

Using CASA tasks and getting oriented with the data

Bring up a list of the input parameters and enter them one by one:

inp listobs

vis='sis14_twhya_calibrated_flagged.ms'
listfile='twhya_listobs.txt'
go



OR

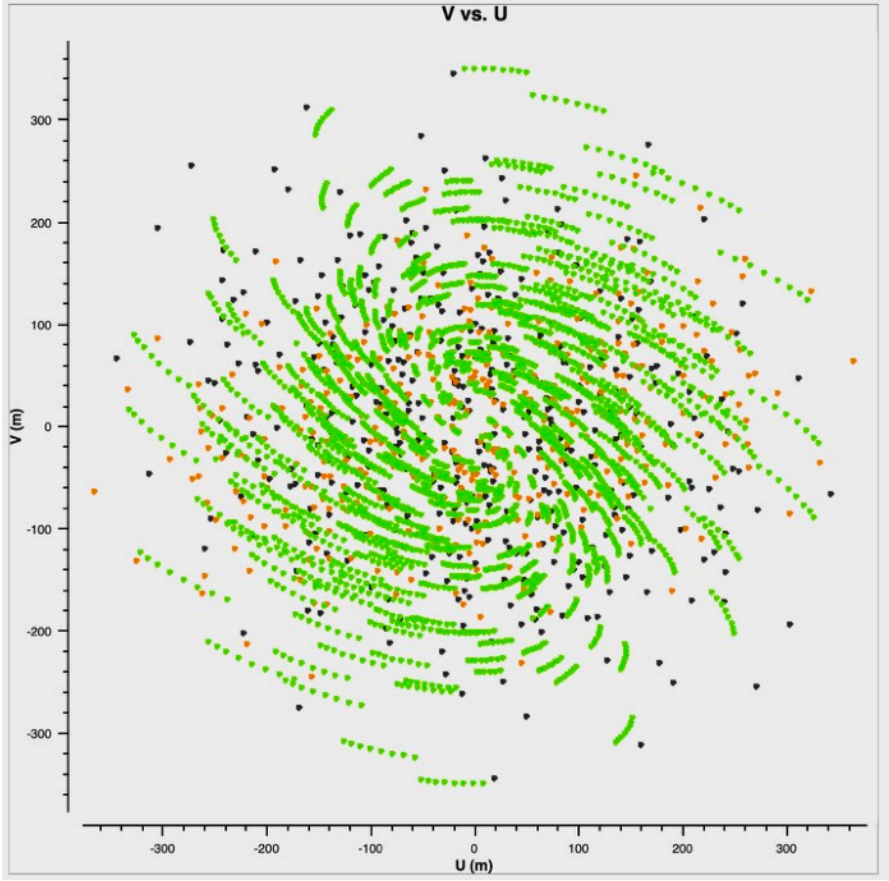
All in one command:

listobs(vis='sis14_twhya_calibrated_flagged.ms',listfile='twhya_listobs.txt')

Inspecting your data:

Check the uv coverage:

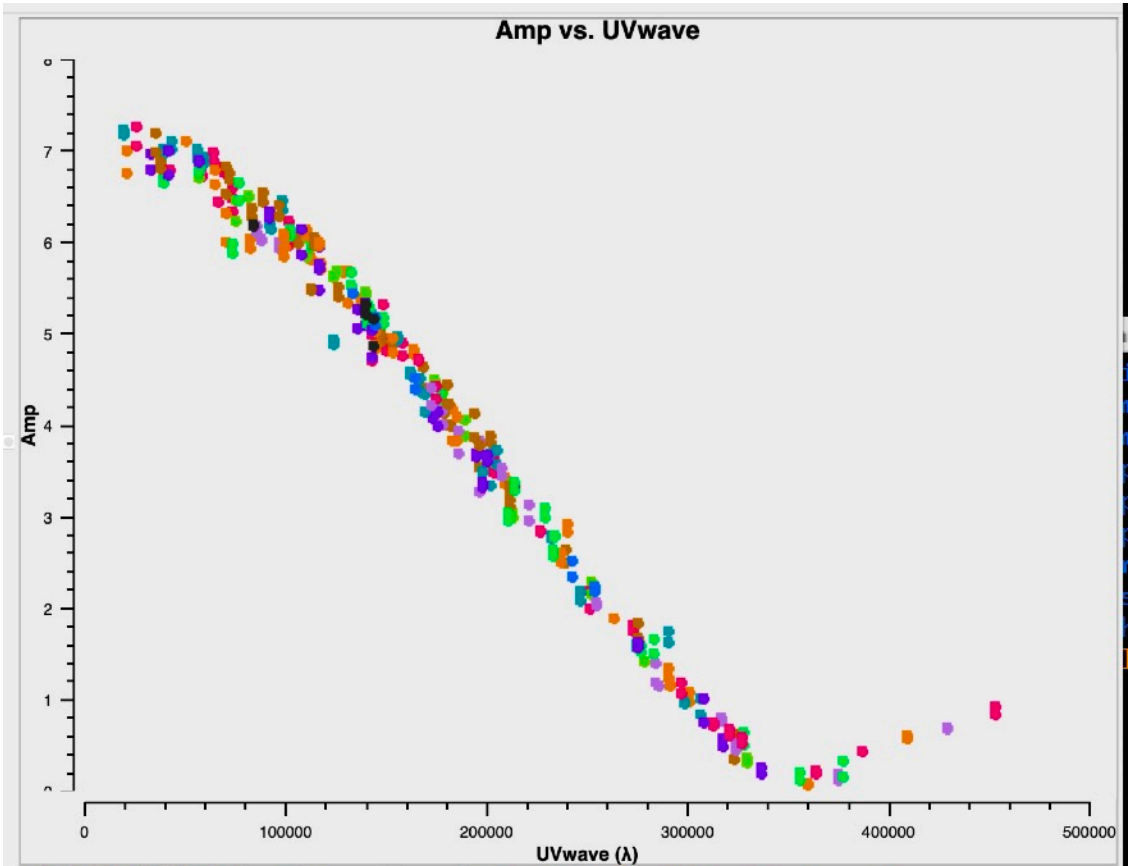
```
plotms(vis='sis14_twhya_calibrated_flagged.ms', xaxis='u', yaxis='v', avgchannel='10000', avgspw=False, avgtime='1e9', avgscan=False, coloraxis='field', showgui=True)
```



Inspecting your data:

Can use plotms to check your baseline coverage:

```
plotms(vis='sis14_twhya_calibrated_flagged.ms',
xaxis='UVwave', yaxis='Amp', avgchannel='10000',
avgspw=False, avgtime='1e9', avgscan=False,field='2',
coloraxis='antenna1', showgui=True)
```



First look at Imaging: the phase calibrator

We'll use phase_cal as the image name for our phase calibrator image.

First, remove any old files:

os.system('rm –rf phase_cal.*')

OR

rm –rf phase_cal.*

(not all unix commands work in CASA without a ! or os.system, but rm does)

First look at Imaging: the phase calibrator

Choosing tclean parameters:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

Look in the listobs output for the intent "CALIBRATE_PHASE#ON_SOURCE" to get the field number for our phase calibrator.

First look at Imaging: the phase calibrator

Choosing tclean parameters:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

Leave blank to use all spws

First look at Imaging: the phase calibrator

Choosing tclean parameters:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

For a continuum image, choose specmode = mfs (multifrequency synthesis)

First look at Imaging: the phase calibrator

Choosing tclean parameters:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom'
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

Since $\frac{\Delta \nu}{\nu}$ < 10%, choose hogbom

First look at Imaging: the phase calibrator

Choosing tclean parameters:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

We're only imaging a single pointing, with 12m only, so use the standard gridder.

First look at Imaging: the phase calibrator

Choosing tclean parameters:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

Want ~5 cells across minor axis of synthesized beam

Beam in arcseconds ~ 206265/(longest baseline in wavelengths)

Beam ~ 206265/429300 = 0.48"

First look at Imaging: the phase calibrator

Choosing tclean parameters:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

Image size = # of cells needed to roughly cover primary beam (larger if non-point source)

For single fields, primary beam in arcsec is:
~ 6300 / nu[GHz] for 12m,
~ 10608 / nu[GHz] for 7m,
where nu[GHz] is the sky frequency expressed in GHz.

First look at Imaging: the phase calibrator

Choosing tclean parameters:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

tclean will kindly tell you if your image size is inefficient, and make suggestions in the logger window!

First look at Imaging: the phase calibrator

Choosing tclean parameters:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

Weighting choice will depend on science goals.

First look at Imaging: the phase calibrator

Ways to get beam size and thus cell size:

- Look at alma-technical-handbook

	Band	3	4	5	6	7	8	9	10
	Frequency (GHz)	100	150	185	230	345	460	650	870
Configuration									
7-m	θ_{res} (arcsec)	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	θ_{MRS} (arcsec)	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
C43-1	θ_{res} (arcsec)	3.38	2.25	1.83	1.47	0.98	0.74	0.52	0.39
	θ_{MRS} (arcsec)	28.5	19.0	15.4	12.4	8.25	6.19	4.38	3.27
C43-2	θ_{res} (arcsec)	2.30	1.53	1.24	1.00	0.67	0.50	0.35	0.26
	θ_{MRS} (arcsec)	22.6	15.0	12.2	9.81	6.54	4.90	3.47	2.59
C43-3	θ_{res} (arcsec)	1.42	0.94	0.77	0.62	0.41	0.31	0.22	0.16
	θ_{MRS} (arcsec)	16.2	10.8	8.73	7.02	4.68	3.51	2.48	1.86
C43-4	θ_{res} (arcsec)	0.92	0.61	0.50	0.40	0.27	0.20	0.14	0.11
	θ_{MRS} (arcsec)	11.2	7.50	6.08	4.89	3.26	2.44	1.73	1.29
C43-5	θ_{res} (arcsec)	0.55	0.36	0.30	0.24	0.16	0.12	0.084	0.063
	θ_{MRS} (arcsec)	6.70	4.47	3.62	2.91	1.94	1.46	1.03	0.77
C43-6	θ_{res} (arcsec)	0.31	0.20	0.17	0.13	0.089	0.067	0.047	0.035
	θ_{MRS} (arcsec)	4.11	2.74	2.22	1.78	1.19	0.89	0.63	0.47
C43-7	θ_{res} (arcsec)	0.21	0.14	0.11	0.092	0.061	0.046	0.033	0.024
	θ_{MRS} (arcsec)	2.58	1.72	1.40	1.12	0.75	0.56	0.40	0.30
C43-8	θ_{res} (arcsec)	0.096	0.064	0.052	0.042	0.028	0.021	0.015	0.011
	θ_{MRS} (arcsec)	1.42	0.95	0.77	0.62	0.41	0.31	0.22	0.16
C43-9	θ_{res} (arcsec)	0.057	0.038	0.031	0.025	0.017	0.012	0.0088	-
	θ_{MRS} (arcsec)	0.81	0.54	0.44	0.35	0.24	0.18	0.13	-
C43-10	θ_{res} (arcsec)	0.042	0.028	0.023	0.018	0.012	0.0091	-	-
	θ_{MRS} (arcsec)	0.50	0.33	0.27	0.22	0.14	0.11	-	-

Table 7.1: Angular resolution (θ_{res}) and maximum recoverable scale (θ_{MRS}) values for different 7-m Array and 12-m Array configurations are shown for one representative frequency in each ALMA receiver band. The value of θ_{MRS} is computed using the 5th percentile baseline (L05) from Table 7.2 and Equation 7.6. The value of θ_{res} is the mean size of the interferometric beam obtained through simulations with CASA. Computations were done for a source at zenith; for sources transiting at lower elevations, the North-South angular measures will increase proportional to 1/sin(elevation). Calculations are based on the notional C43-X and 7m configurations with Briggs weighting and a robust parameter of 0.5.

Table 1: *Receiver Bands and Selected Properties*

Cycle 9 Receiver Bands					Most Compact			Most Extended		
Band	Frequency (GHz)	Wavelength (mm)	Primary Beam (FOV; ″)	Continuum Sensitivity (mJy/ beam)	Angular Resolution (″)	Approx. Maximum Scale (″) (see P.24)	Spectral Sens. ΔT_{line} (K)	Angular Resolution (mas)	Approx. Maximum Scale (″) (see P.24)	Spectral Sens. ΔT_{line} (K)
3	*84-116*	*3.6-2.6*	*69-50*	*0.082*	*4.0-2.9*	*34-25*	*0.084*	*50-36*	*0.59-0.43*	*537*
4	*125-163*	*2.4-1.8*	*46-36*	*0.089*	*2.7-2.1*	*23-18*	*0.085*	*34-26*	*0.40-0.31*	*540*
5	*158-211*	*1.9-1.4*	*37-28*	*0.12*	*2.1-1.6*	*18-14*	*0.11*	*27-20*	*0.32-0.24*	*706*
6	*211-275*	*1.4-1.1*	*28-21*	*0.12*	*1.6-1.2*	*14-10*	*0.11*	*20-15*	*0.24-0.18*	*744*
7	*275-373*	*1.1-0.8*	*21-16*	*0.22*	*1.23-0.91*	*10.4-7.7*	*0.2*	*15-11*	*0.18-0.13*	*1290*
8	*385-500*	*0.78-0.6*	*15-12*	*0.40*	*0.88-0.68*	*7.5-5.7*	*0.36*	*11-8.4*	*0.13-0.10*	*2410*
9	*602-720*	*0.5-0.42*	*9.7-8.1*	*1.4*	*0.56-0.47*	*4.7-4.0*	*1.7*	*9.5-7.9*	*0.14-0.11*	*6000*
10	*787-950*	*0.38-0.32*	*7.4-6.1*	*3.3*	*0.43-0.36*	*3.6-3.0*	*4.1*	*12-10*	*0.18-0.15*	*5100*

First look at Imaging: the phase calibrator

Ways to get beam size and thus cell size:

- Look at alma-technical-handbook
- Make dirty image (tclean with niter= 0 or 1) - log tells you beam size
- Use Analysis Utils (https://safe.nrao.edu/wiki/bin/view/Main/CasaExtensions)
    - pickCellSize

For a video overview of these concepts:

https://youtu.be/OC3IWpRRtEQ

https://youtu.be/EVY7000zAD4

- More videos available and under development!
- **Like and subscribe** to our Youtube channel **ALMA Primer** to get notified when new videos are uploaded.

First look at Imaging: the phase calibrator

Choosing tclean parameters:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

The threshold is one main stopping criterion for tclean. It will stop when the residuals fall below the threshold.

Setting the number of iterations, niter, is the other stopping criterion.

By default, niter=0, so running this command will do no cleaning. Try it!

First look at Imaging: the phase calibrator

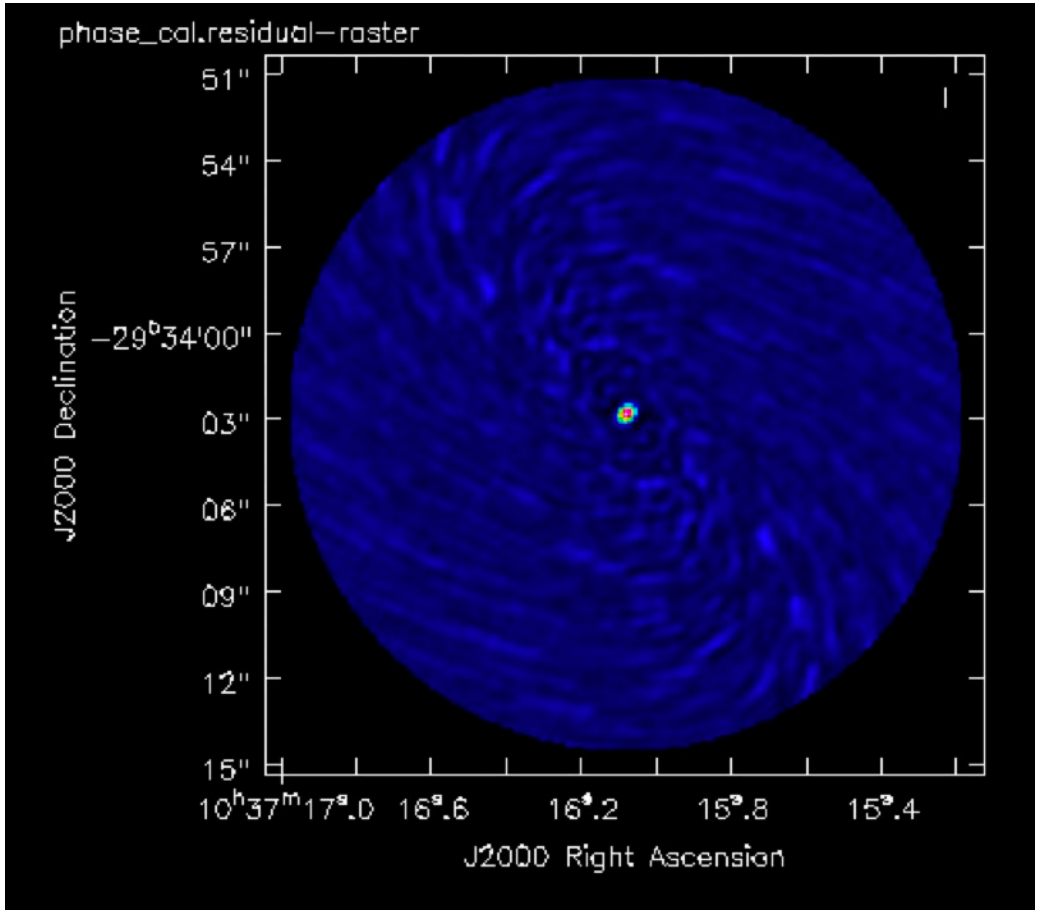
Run Tclean command:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_dirty', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
interactive=True)
```

First look at Imaging: the phase calibrator

Check the dirty image:

imview('phase_cal_dirty.image')



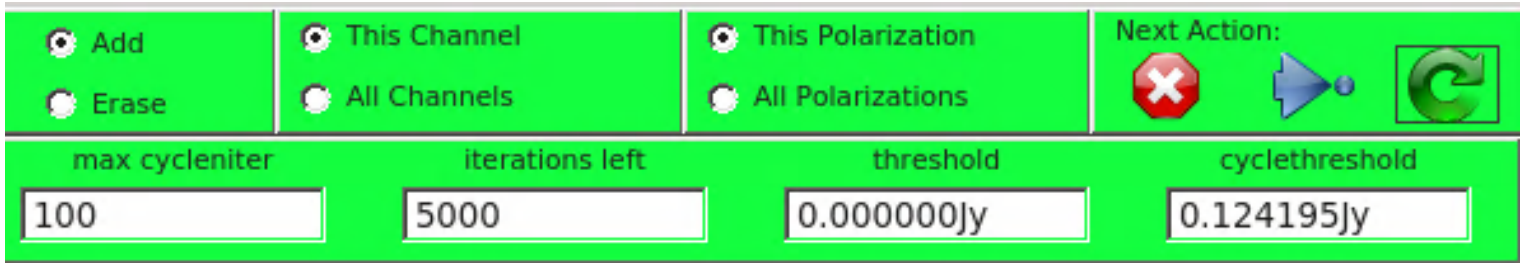
First look at Imaging: the phase calibrator

Now increase niter to some large number by adding it to the previous command:

```
tclean(vis='sis14_twhya_calibrated_flagged.ms',
imagename='phase_cal_clean', field='3',
spw='',
specmode='mfs',
deconvolver='hogbom',
gridder='standard',
imsize=[128,128],
cell=['0.1arcsec'],
weighting='briggs',
threshold='0.0mJy',
niter=5000,
interactive=True)
```

First look at Imaging: the phase calibrator

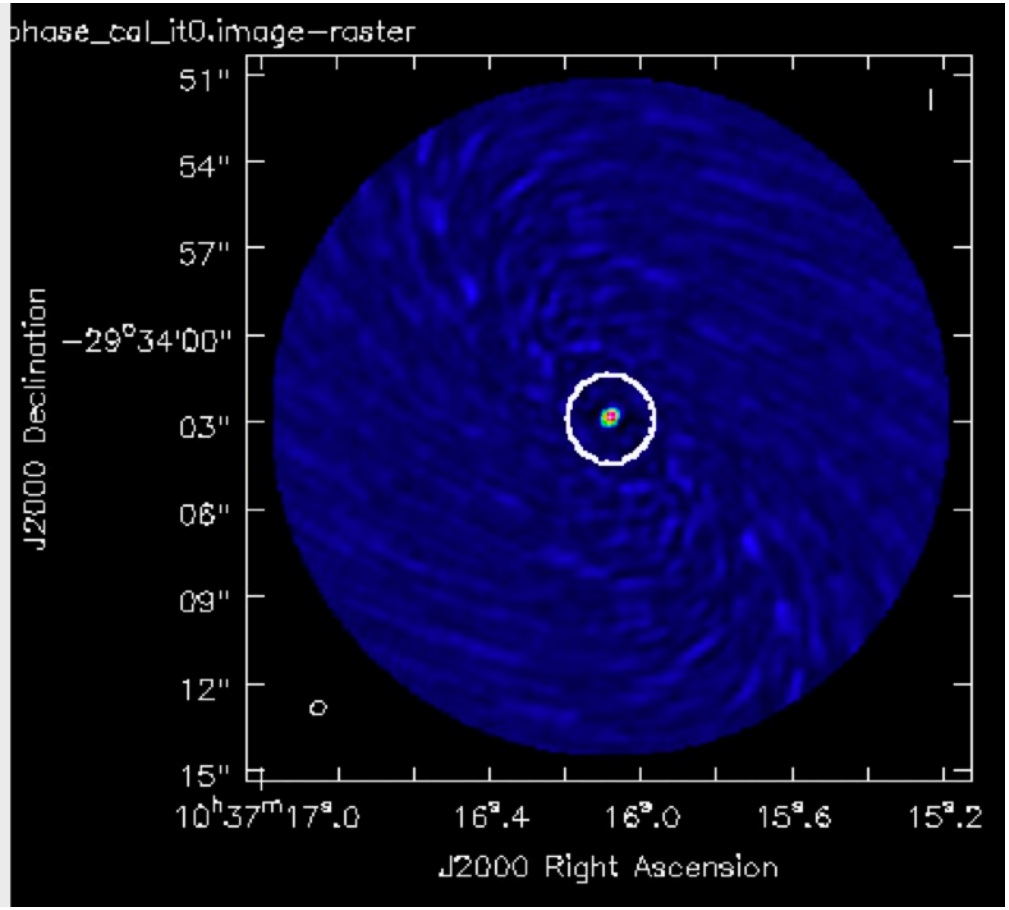
Creating a mask: select add, all channels



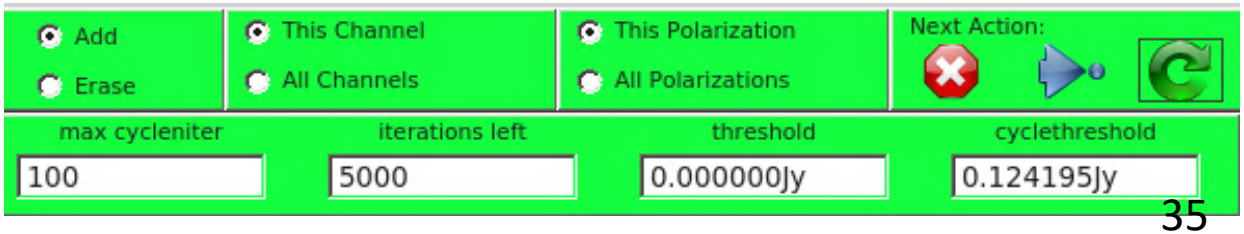
Click the oval with the R, to be able to draw an oval

First look at Imaging: the phase calibrator

Draw an oval around the source, and then double click to set the mask.

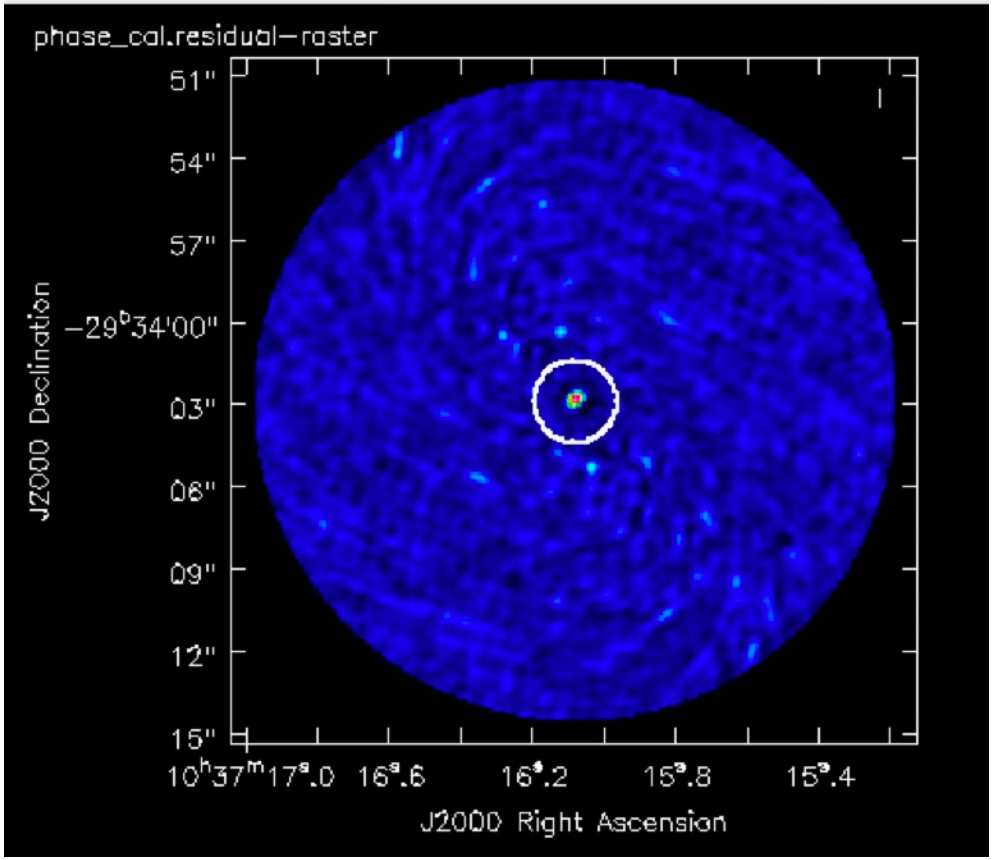


Then click the green circular arrow to run the first cycle.

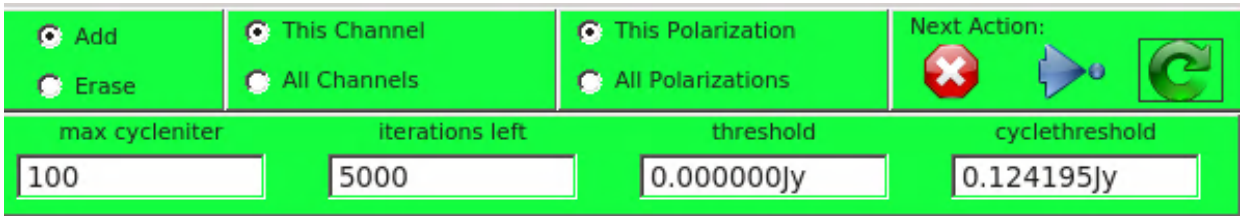


First look at Imaging: the phase calibrator

Now we see the noise looks a little brighter, relative to the source since we've removed some signal.



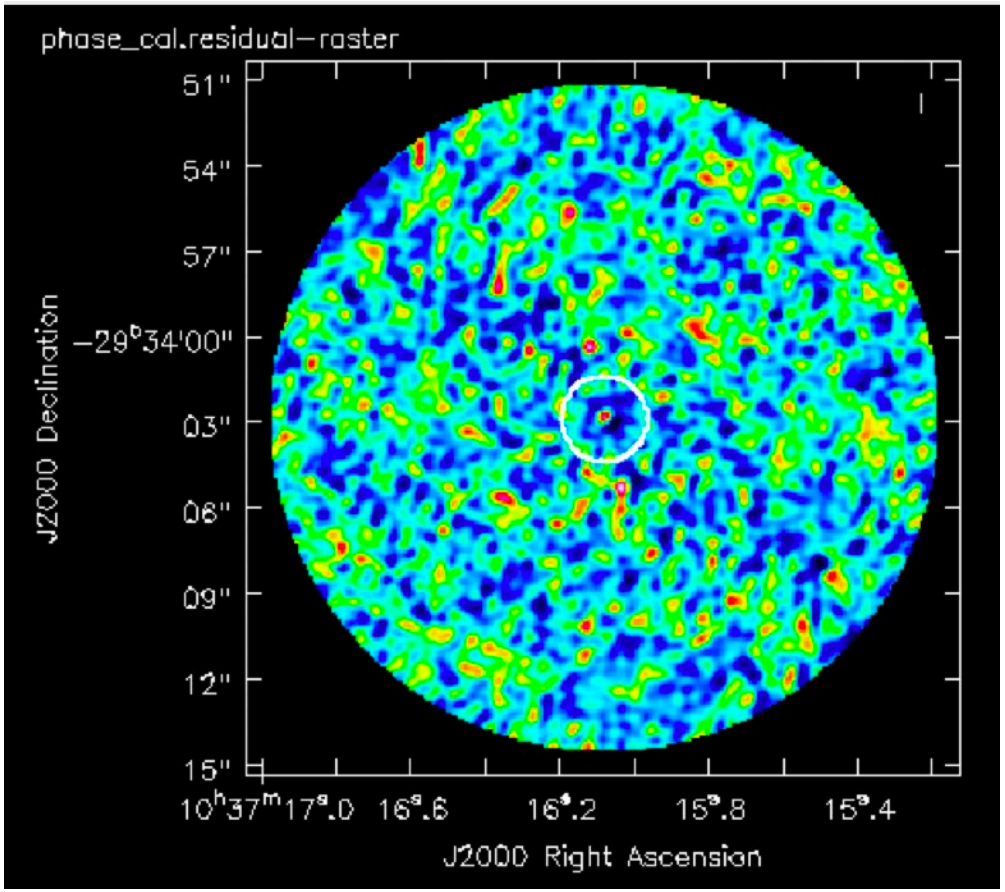
Click the green circular arrow again to run another cycle.



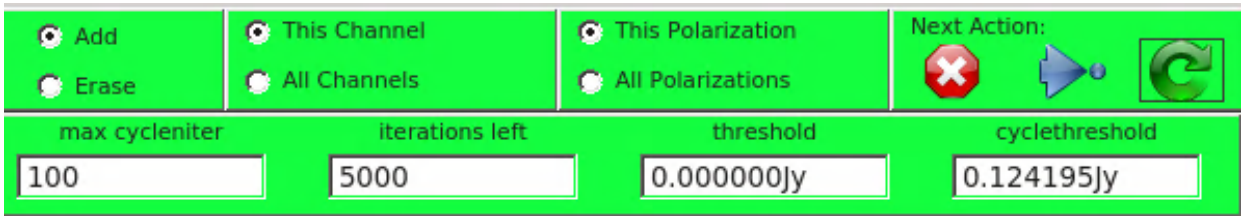
First look at Imaging: the phase calibrator

And we see the noise looks even brighter, relative to the source.

When the residuals for the source match the noise, stop!



Click the red stop sign to end the cleaning.



First look at Imaging: the science target

First split out only the science target data (field=5) and average over 8 channels (width=’8’) to reduce the size of the data set.

```
os.system('rm -rf twhya_smoothed.ms')
split(vis='sis14_twhya_calibrated_flagged.ms', field='5', width='8', outputvis='twhya_smoothed.ms', datacolumn='data’)
```

Try listobs on the new measurement set to verify. Note the field number has changed!

First look at Imaging: the science target

Now clean!

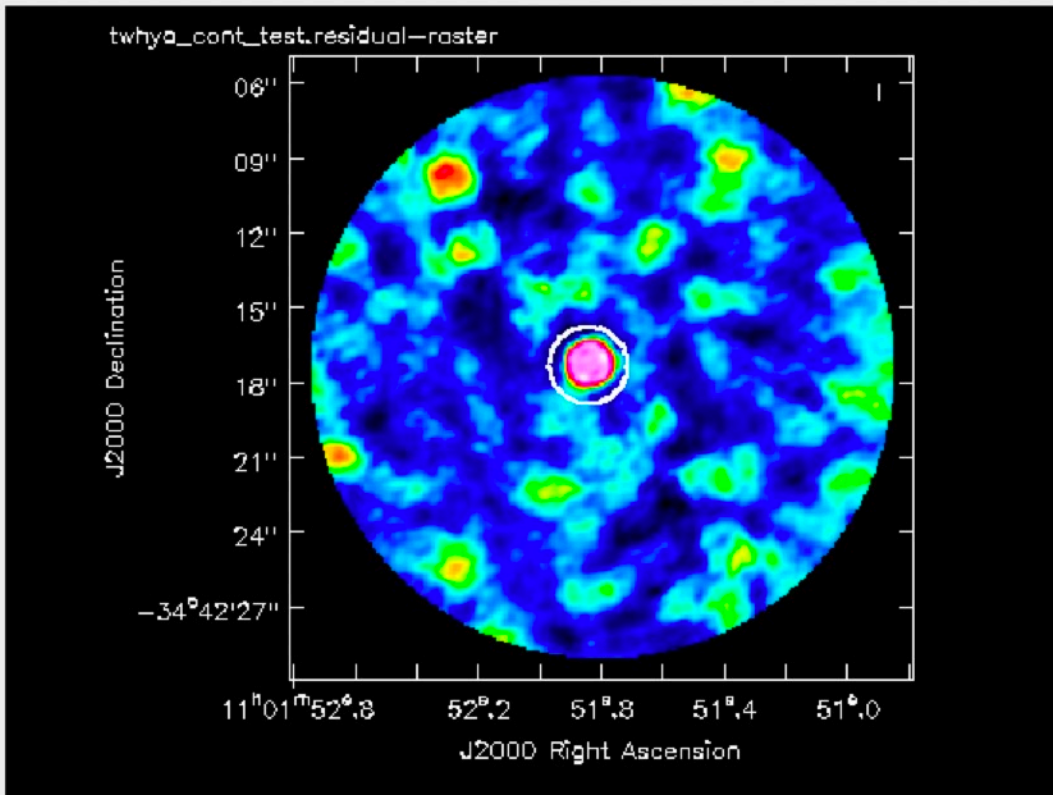
```
os.system('rm -rf twhya_cont.*')

tclean(vis='twhya_smoothed.ms',
imagename='twhya_cont',
field='0', spw='', specmode='mfs',
gridder='standard',
deconvolver='hogbom',
imsize=[250,250],
cell=['0.1arcsec'],
weighting='briggs',
robust=0.5, threshold='0mJy',
niter=5000,
interactive=True)
```

Note the field is now '0'!.

First look at Imaging: the science target

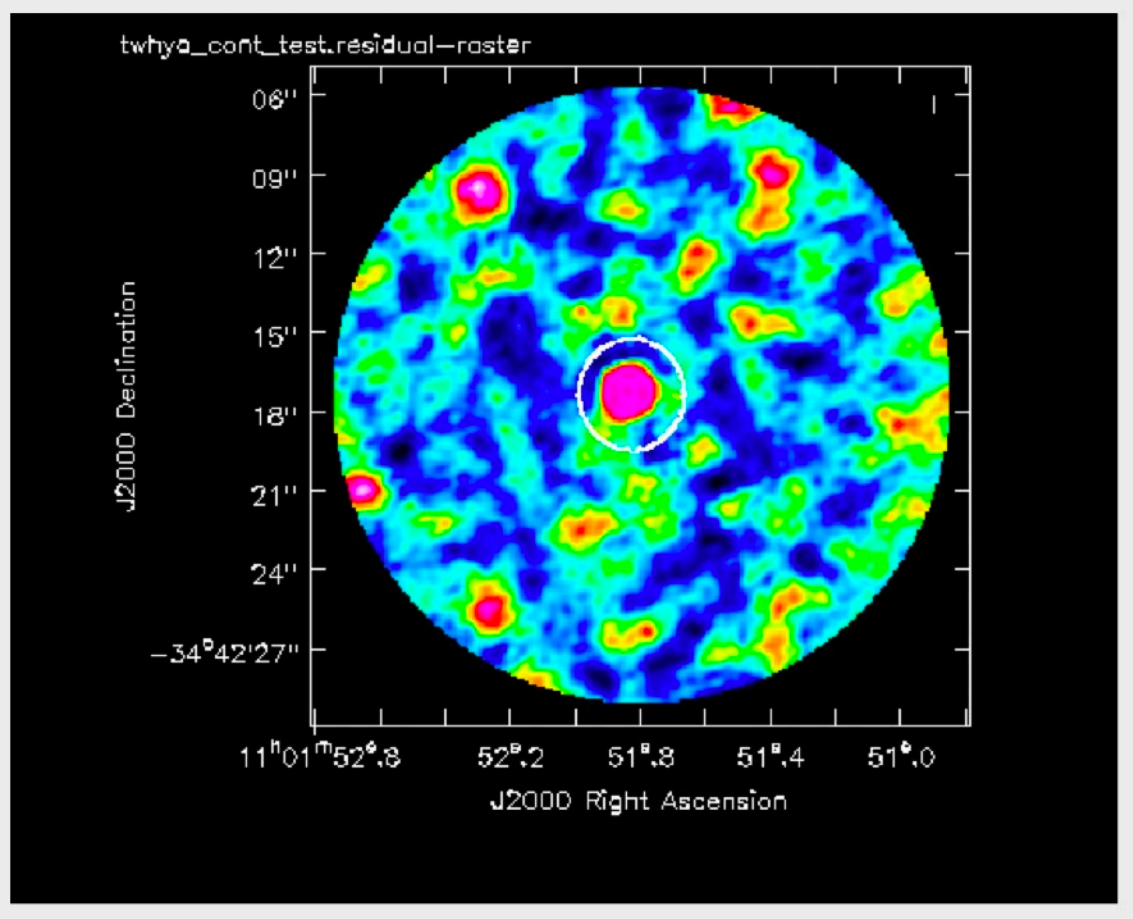
After ~68 iterations: we can see fainter parts of the disk now, so it looks bigger.



What if I want to adjust my mask? Change to erase, select an area surrounding the old mask, and double click to erase any mask inside.

First look at Imaging: the science target

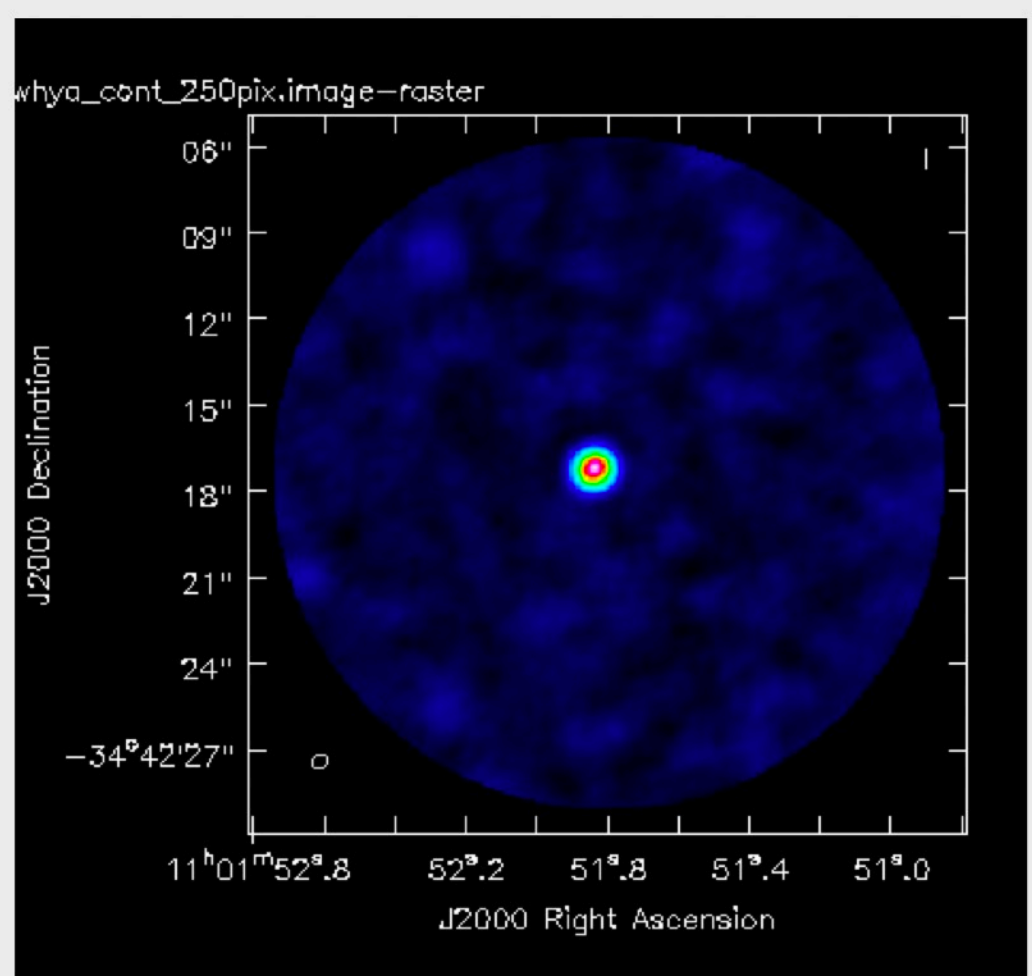
After 168 iterations: The brightest noise is the same color as the brightest source, so stop!



First look at Imaging: the science target

Use imview to inspect the tclean results:

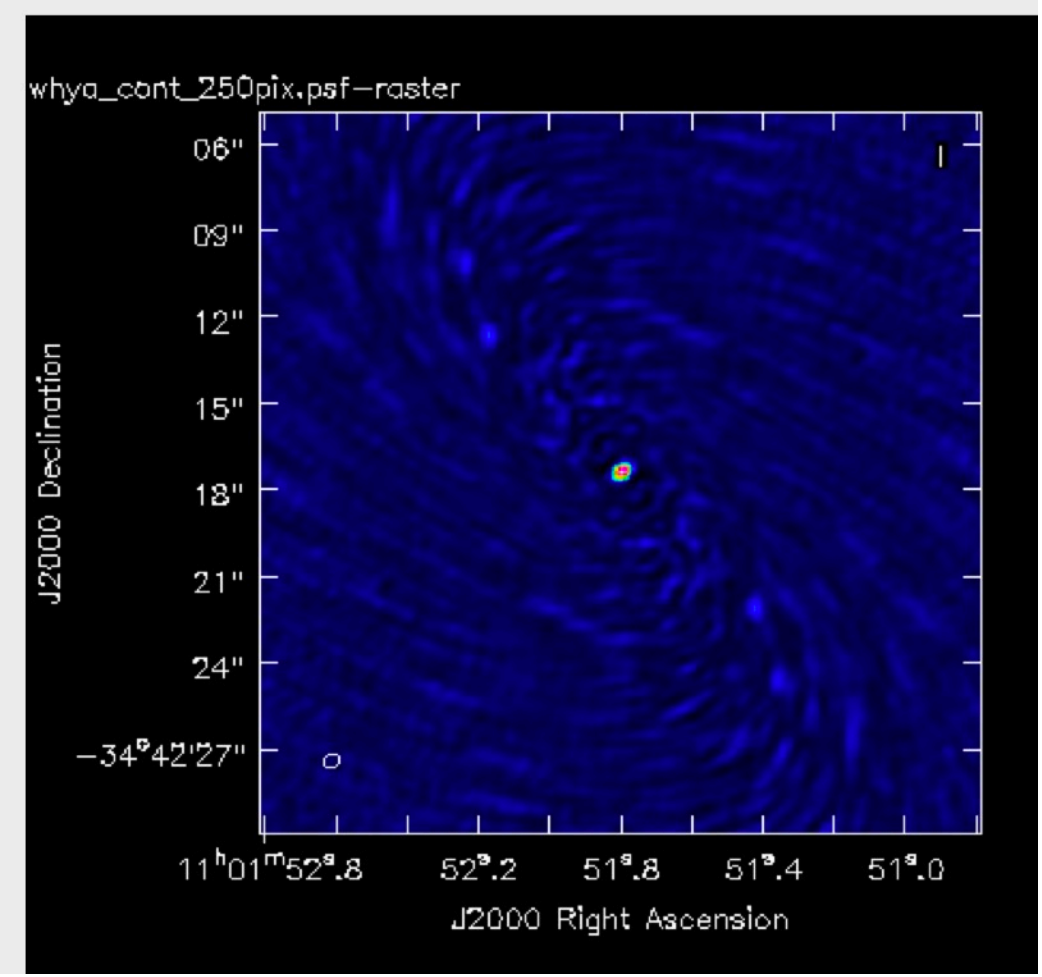
The Clean Image



First look at Imaging: the science target

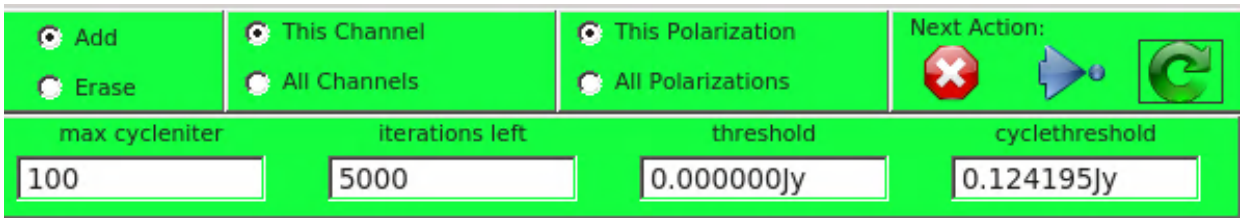
Use imview to inspect the tclean results:

The PSF



First look at Imaging: the science target

Hmm… but what about that blue arrow?



It auto-completes an interactive session!

Here you can also adjust iterations left and the threshold before auto-completing.

First look at Imaging: the science target

The last step for the continuum image: primary beam correction.

```
os.system('rm -rf twhya_cont.pbcor.image')

impbcor(imagename='twhya_cont.image',
pbimage='twhya_cont.pb',
outfile='twhya_cont.pbcor.image')
```

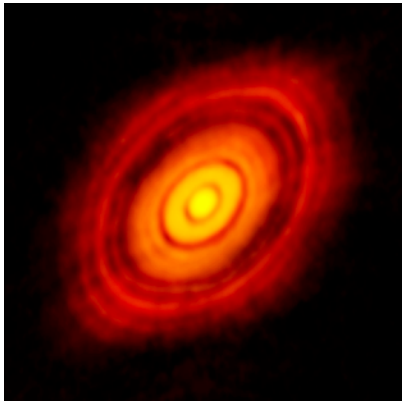
And inspect your image:

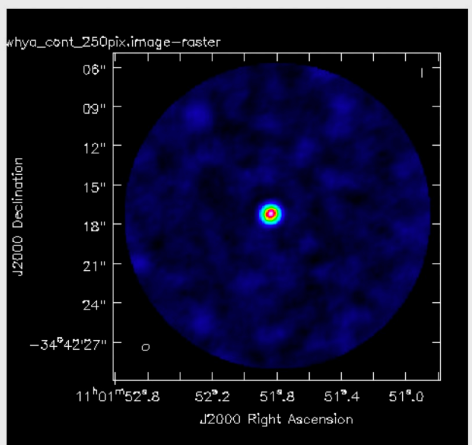
```
imview('twhya_cont.pbcor.image')
```

First look at spectral line imaging

Following ALMA CASA Guide “First Look at Line Imaging”

- https://casaguides.nrao.edu/index.php?title=First_Look_at_Line_Imaging_CASA_6.4

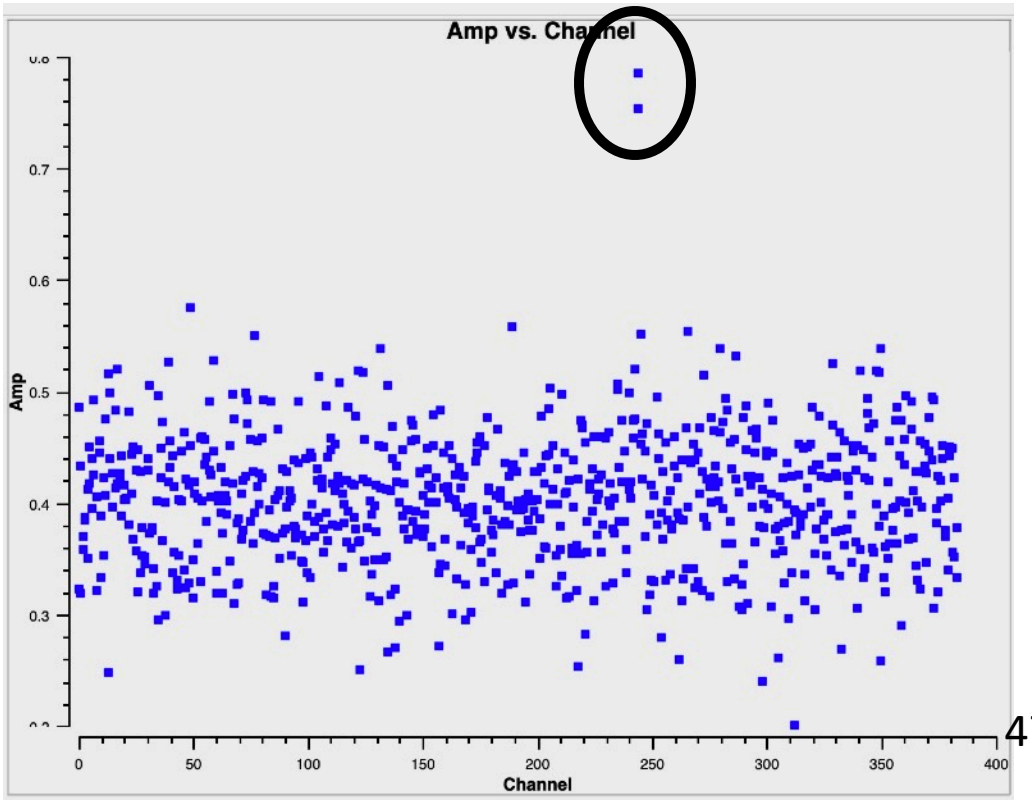




First look at Spectral Line Imaging: Removing the continuum

Need to remove any channels with notable emission before fitting continuum:

```
plotms(vis='sis14_twhya_selfcal.ms',
       xaxis='channel',
       yaxis='amp',
       field='5',
       avgspw=False,
       avgtime='1e9',
       avgscan=True,
       avgbaseline=True,
       showgui = True)
```



First look at Spectral Line Imaging: Removing the continuum

Fit and subtract the continuum:

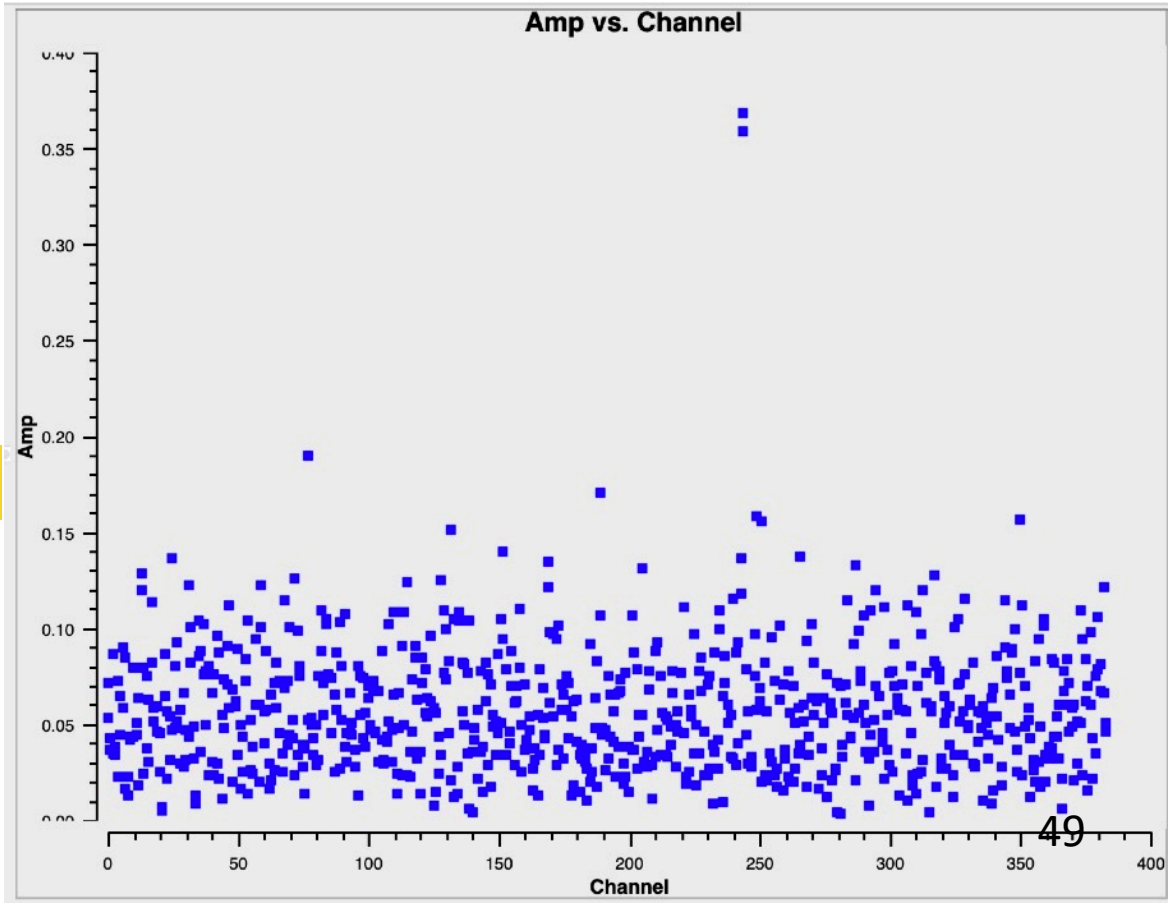
```
os.system('rm -rf sis14_twhya_selfcal.ms.contsub')
uvcontsub(vis = 'sis14_twhya_selfcal.ms',
          field = '5',
          fitspw = '0:0~239;281~383',
          excludechans = False,
          fitorder = 0,
          solint='int')
```

For large datasets this might take quite some time!

First look at Spectral Line Imaging: Removing the continuum

Use plotms to confirm:

```
plotms(vis='sis14_twhya_selfcal.ms.contsub',
       xaxis='channel',
       yaxis='amp',
       field='0',
       avgspw=False,
       avgtime='1e9',
       avgscan=True,
       avgbaseline=True,
       showgui = True)
```



First look at Spectral Line Imaging: Specmode=cube now

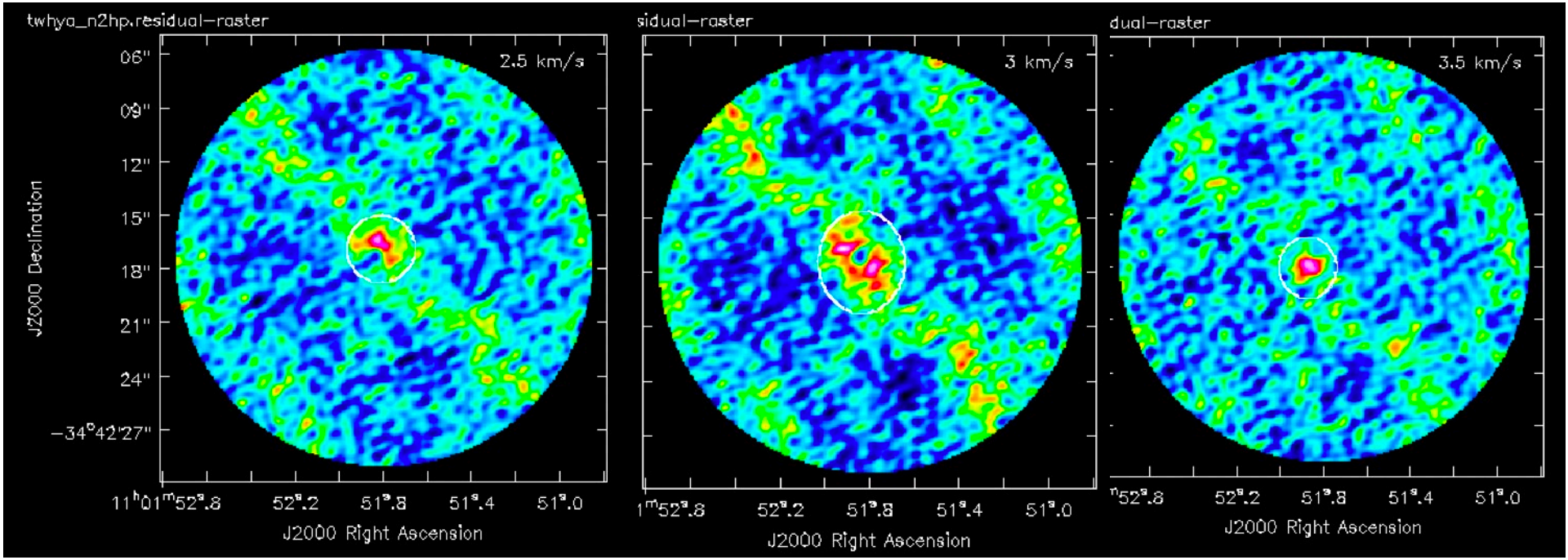
```
restfreq = '372.67249GHz'

os.system('rm -rf twhya_n2hp.*')
tclean(vis = 'sis14_twhya_selfcal.ms.contsub', imagename =
'twhya_n2hp',field = '0',spw = '0',specmode =
'cube',perchanweightdensity=True, nchan = 15,start = '0.0km/s',width =
'0.5km/s',outframe = 'LSRK', restfreq = restfreq,deconvolver=
'hogbom',gridder = 'standard',imsize = [250, 250],cell =
'0.1arcsec',phasecenter = 0,weighting = 'briggsbwtaper',robust =
0.5,restoringbeam='common',interactive = True,niter=5000)
```

(note: no threshold set, so defaults to 0.0)

First look at Spectral Line Imaging: Masking options

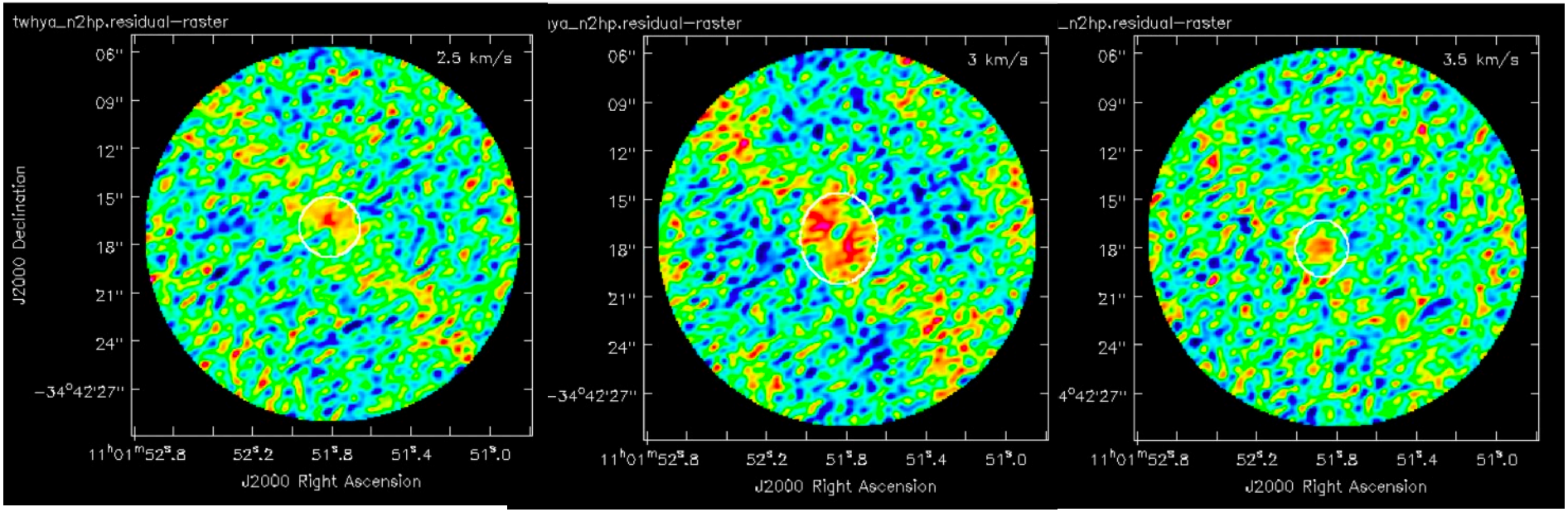
Can do channel by channel mask, or select “all channels” and do single mask for all channels: here ch 5,6,7.



Dirty images with masks.

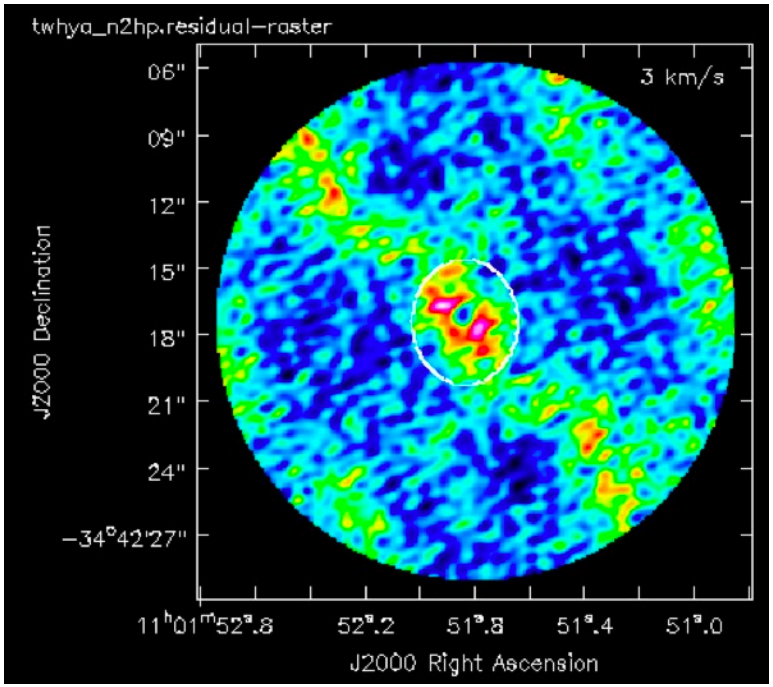
First look at Spectral Line Imaging: specmode = cube

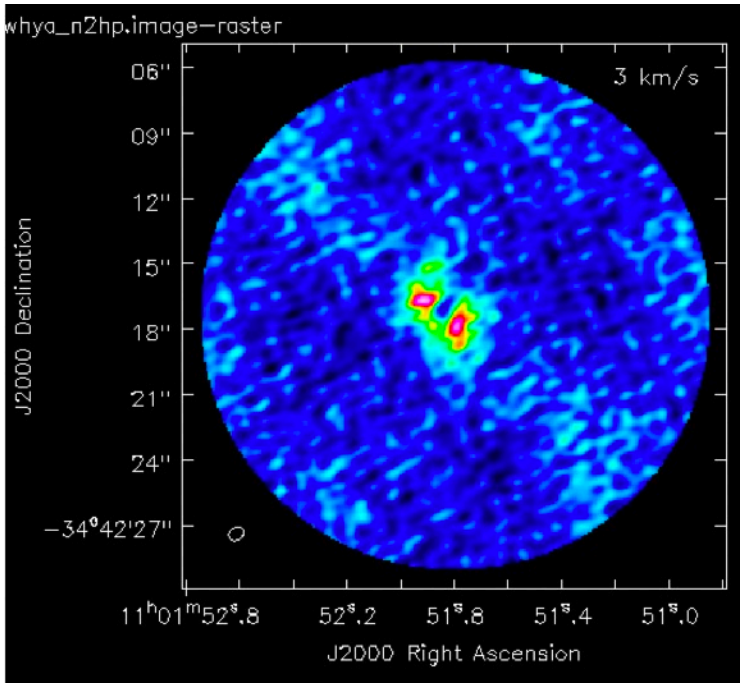
Residuals for channels 5,6,7 after 2 major cycles:



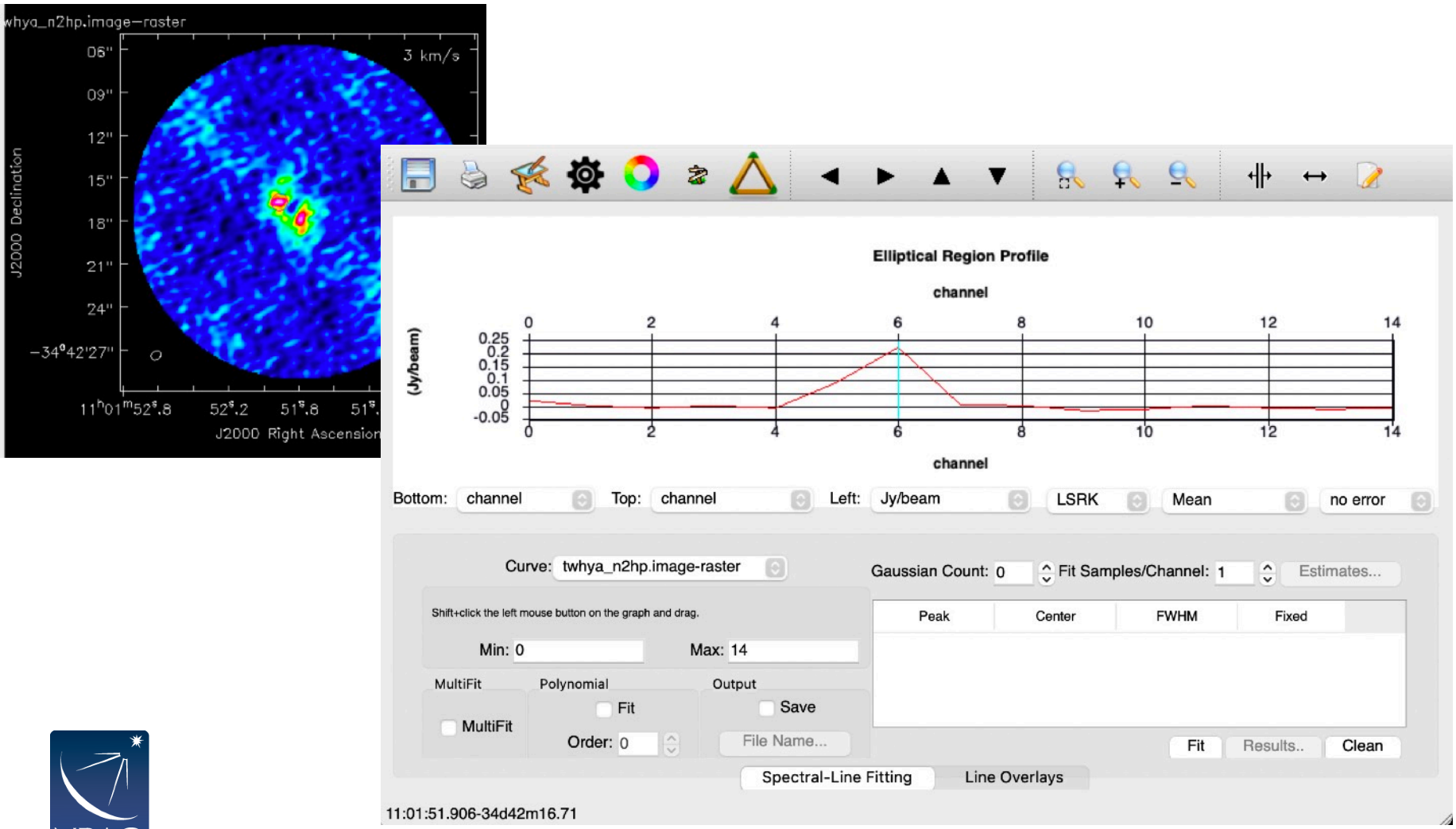
First look at Spectral Line Imaging: specmode = cube

Channel 6: Dirty vs Clean





First look at Spectral Line Imaging: spectral profile tool



First look at Spectral Line Imaging: primary beam correction

```
os.system('rm -rf twhya_n2hp.pbcor.image')

impbcor(imagename='twhya_n2hp.image',
pbimage='twhya_n2hp.pb',
outfile='twhya_n2hp.pbcor.image')
```

Image Analysis: Moment Maps

https://casaguides.nrao.edu/index.php?title=First_Look_at_Image_Analysis_CASA_6.4

immoments(*imagename, moments=[0], axis='spectral', region='', box='', chans='', stokes='', mask='', includepix=- 1, excludepix=- 1, outfile='', stretch=False*)

- moments = -1 - mean value of the spectrum
- moments = 0 - integrated value of the spectrum
- moments = 1 - intensity weighted coordinate; traditionally used to get "velocity fields"
- moments = 2 - intensity weighted dispersion of the coordinate; traditionally used to get "velocity dispersion"
- moments = 3 - median value of the spectrum
- moments = 4 - median coordinate
- moments = 5 - standard deviation about the mean of the spectrum
- moments = 6 - root mean square of the spectrum
- moments = 7 - absolute mean deviation of the spectrum
- moments = 8 - maximum value of the spectrum
- moments = 9 - coordinate of the maximum value of the spectrum
- moments = 10 - minimum value of the spectrum
- moments = 11 - coordinate of the minimum value of the spectrum