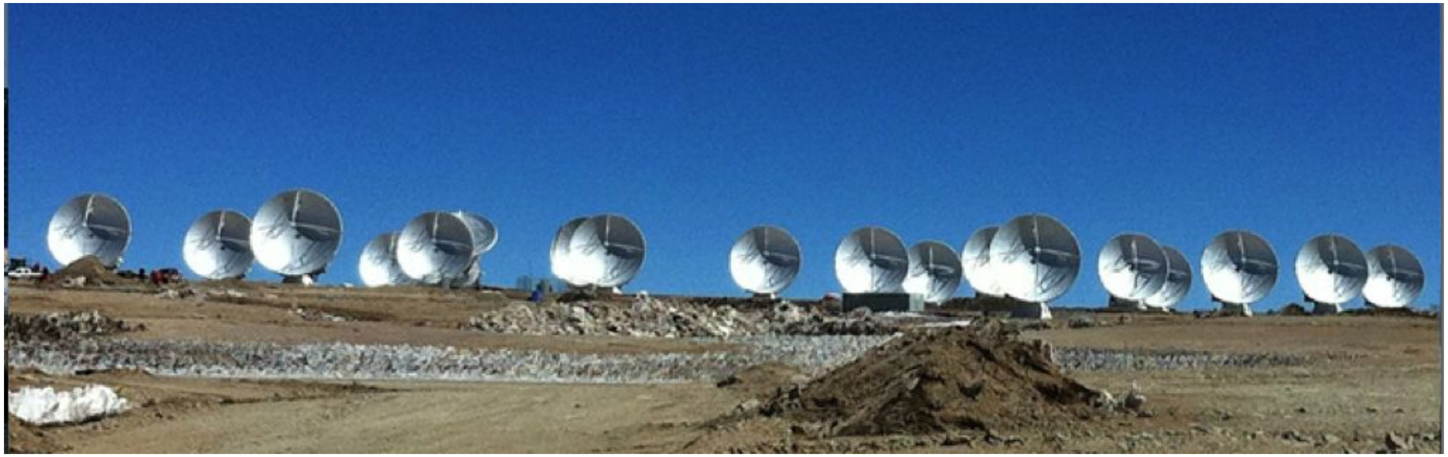
Introduction to Imaging in CASA



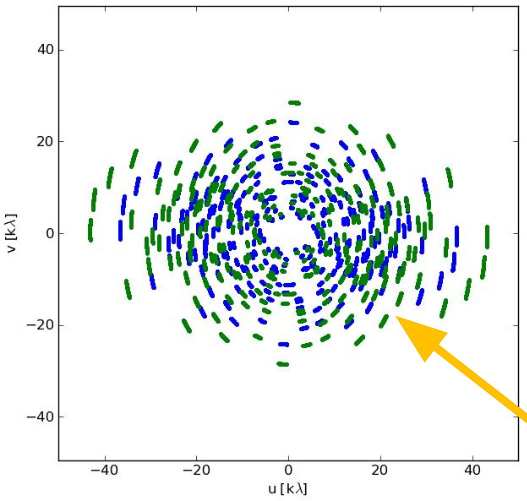
With contributions from Amanda Kepley, Crystal Brogan, David Wilner, Urvashi Rau, and others

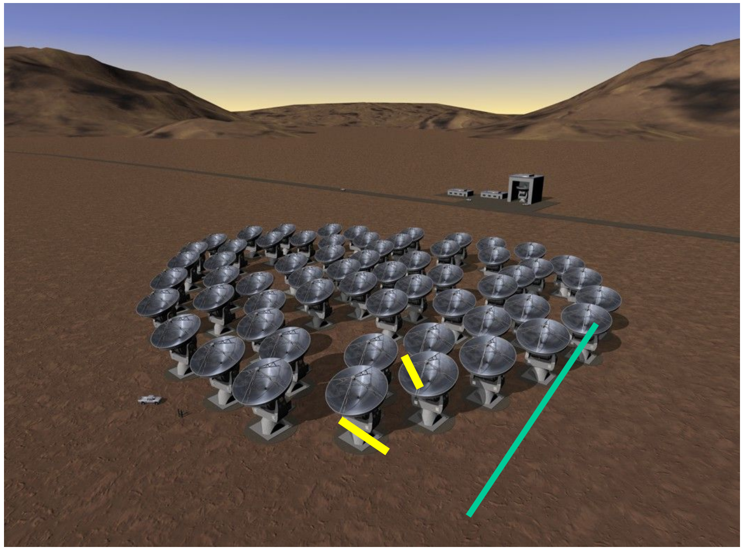
Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array

Goals of this talk

- Gain some intuition for interferometric imaging
- Delve into the theory underlying the imaging process.
- Tour of main deconvolution task in CASA: tclean

Interferometers discretely sample the uv-plane.



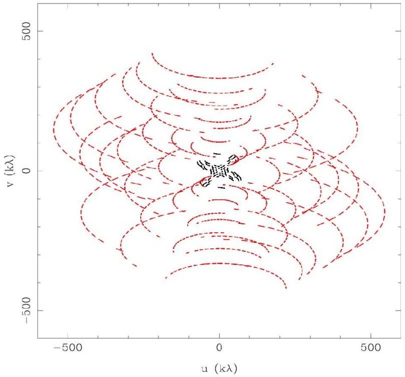


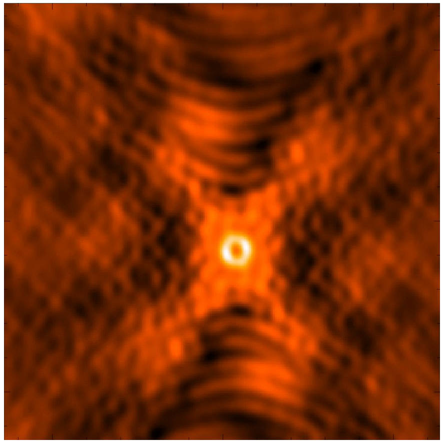
Missing short spacings

- 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)**

The observed (AKA dirty) image is the true image convolved with the PSF.

B(u,v)
(sampled visibilities)



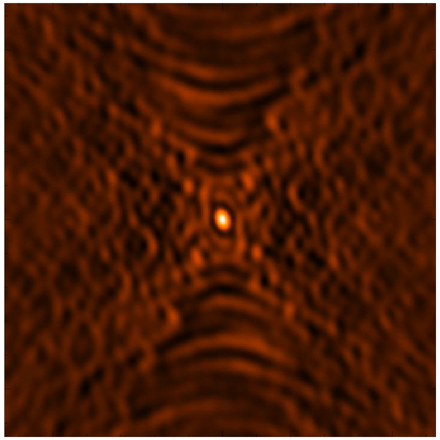


TD(x,y)
(dirty image)

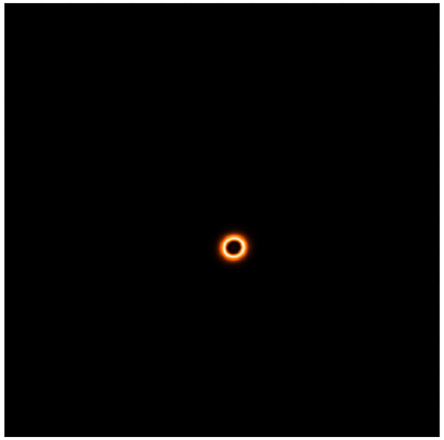
⇌ (Fourier Transform)

↑

b(x,y)
(dirty beam or psf)



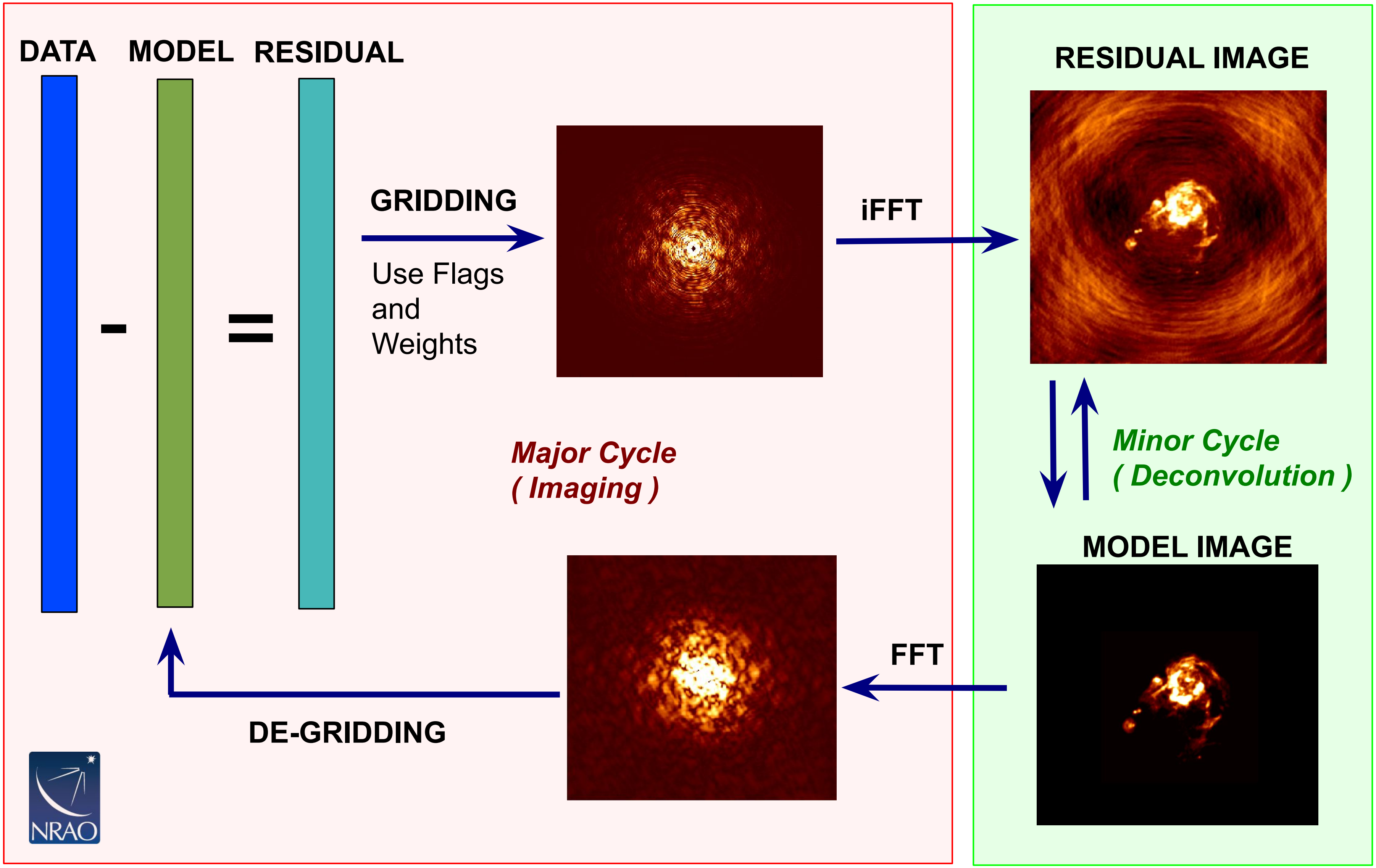
⊗
Convolve



T(x,y)
(True sky brightness)

- **Fourier transform of sampled visibilities yields the true sky brightness convolved with the point spread function (“dirty beam”).**
- **You need to deconvolve the PSF from the dirty image to reconstruct the source. A commonly used way to do this is called cleaning.**

This is a iterative process where the data is gridded, deconvolved, and de-gridded.



DATA - MODEL = RESIDUAL

GRIDDING

Use Flags and Weights

iFFT

RESIDUAL IMAGE

Major Cycle (Imaging)

Minor Cycle (Deconvolution)

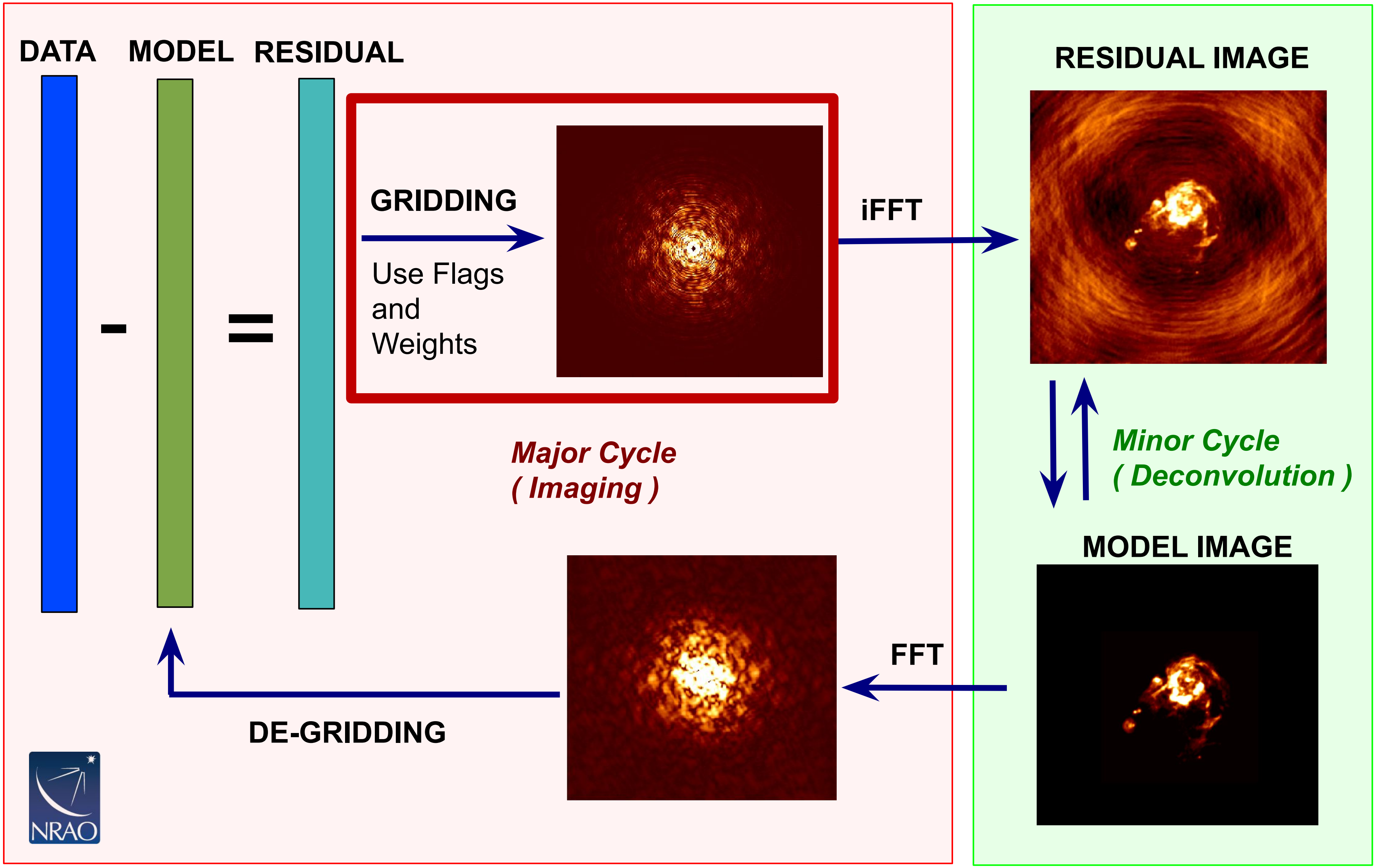
MODEL IMAGE

FFT

DE-GRIDDING

Slide courtesy Urvashi Rau

The gridding step requires pixel and image size as well as weighting scheme.



Slide courtesy Urvashi Rau

Gridding: Pixel and Image Size

- pixel size: satisfy sampling theorem for longest baselines

$$\Delta l < \frac{1}{2u_{max}} \qquad \Delta m < \frac{1}{2v_{max}}$$

  – in practice, 5 to 8 pixels across dirty beam main lobe to aid deconvolution

  – Beam size [arcsec] = 206265.0/(longest baseline in wavelengths)

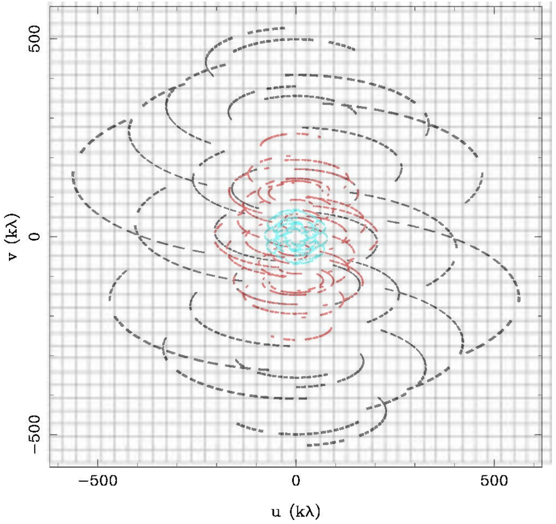
–image size: natural choice often full primary beam *A(l,m)*

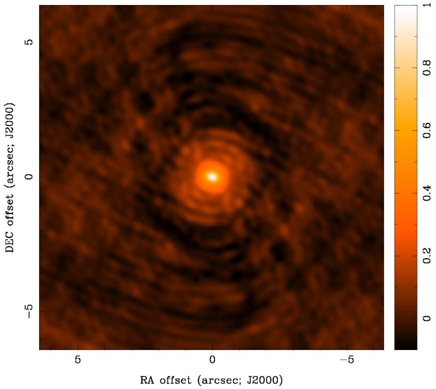
- For single fields:
  - 12m : FOV[arcsec] = 6300 / nu[GHz]
  - 7m: FOV[arcsec] = 10608 / nu[GHz]
  - nu[GHz] is the sky frequency.
- For mosaics:
  - You can get the imsize from the spatial tab of the OT. The parameters "p length" and "q length" to specify the dimensions of the mosaic. If you're imaging a mosaic, pad the imsize substantially to avoid artifacts.

Gridding: Visibility Weighting

- introduce weighting function *W(u,v)*
  - modifies sampling function
  - $S(u,v) \rightarrow S(u,v)W(u,v)$
  - changes *s(l,m)*, the dirty beam

- "natural" weighting
  - $W(u,v) = 1/\sigma^2$ in occupied cells, where σ^2 is the noise variance
  - maximizes point source sensitivity
  - lowest rms in image
  - generally gives more weight to short baselines, so the angular resolution is degraded

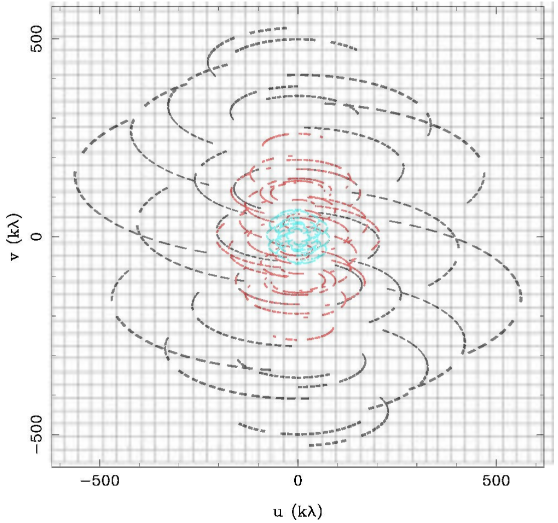


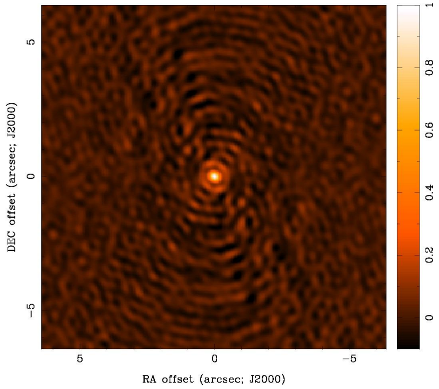


Slide courtesy David Wilner

Gridding: Visibility Weighting

- "uniform" weighting
  - *W(u,v)* inversely proportional to local density of *(u,v)* samples
  - weight for occupied cell = const
  - fills *(u,v)* plane more uniformly and dirty beam sidelobes are lower
  - gives more weight to long baselines, so angular resolution is enhanced
  - downweights some data, so point source sensitivity is degraded
  - n.b. can be trouble with sparse *(u,v)* coverage: cells with few samples have same weight as cells with many
  - rarely used in practice because of this.





Slide courtesy David Wilner

Gridding: Visibility Weighting

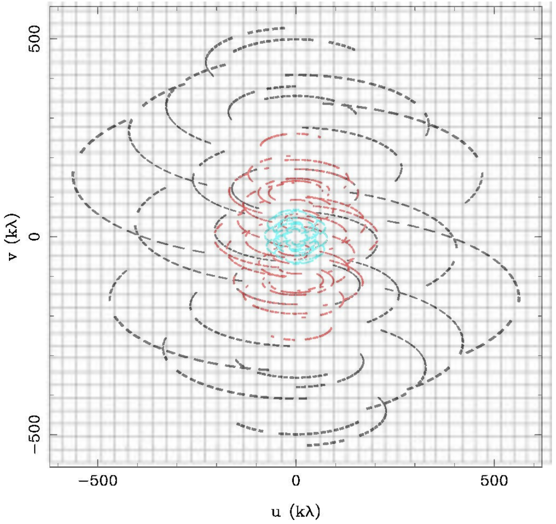
- “robust” (or “Briggs”) weighting
  - variant of uniform weighting that avoids giving too much weight to cells with low natural weight
  - software implementations differ
  - e.g. $W(u,v) = \dfrac{1}{\sqrt{1 + S_N^2/S_{thresh}^2}}$

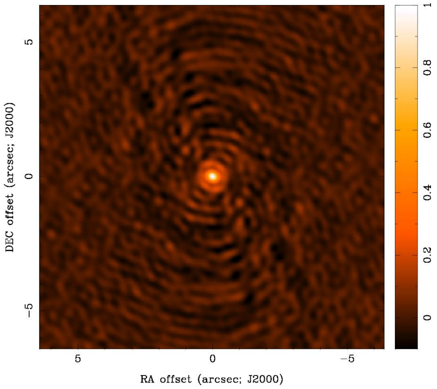
    S_N is cell natural weight

    S_{thresh} is a threshold

    high threshold → natural weight

    low threshold → uniform weight
- *an adjustable parameter allows for continuous variation between maximum point source sensitivity and resolution*
- **Use of robust < 0.0 not recommended.**



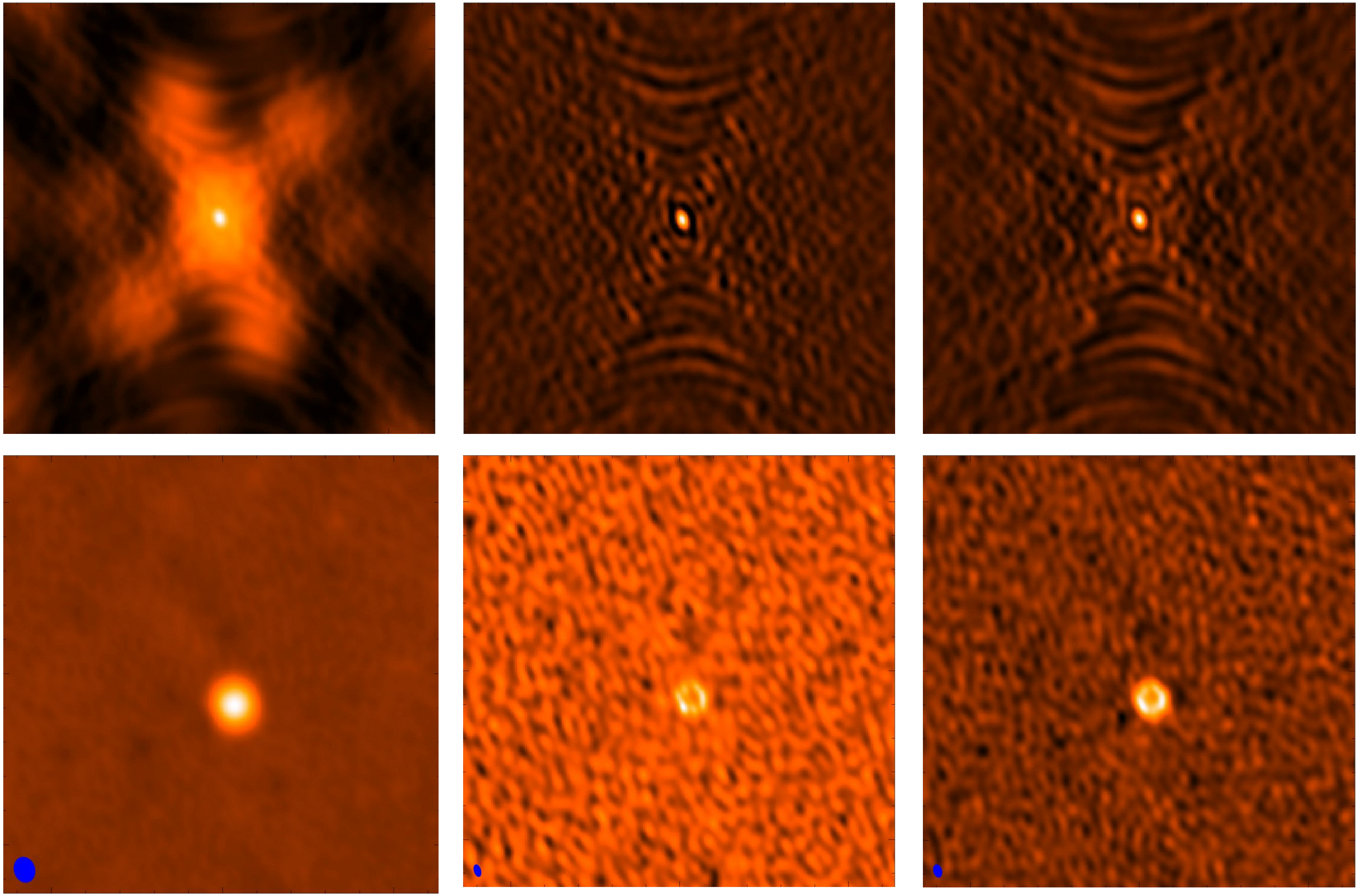


Slide courtesy David Wilner

Natural Uniform Robust=0

Beam

CLEAN image



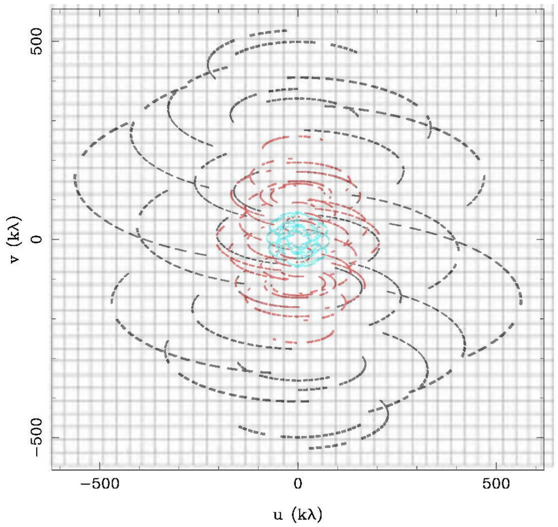
Gridding: Visibility Weighting

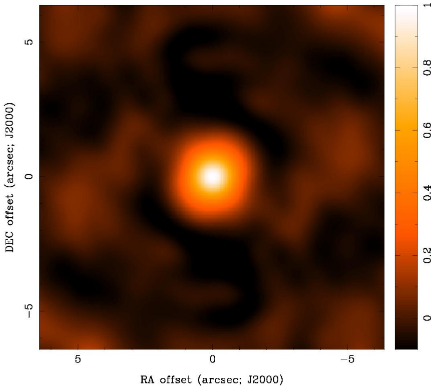
- uvtaper
  - apodize *(u,v)* sampling by a Gaussian

$$W(u,v) = \exp\left(-\frac{(u^2+v^2)}{t^2}\right)$$

t = adjustable tapering parameter

  - like convolving image by a Gaussian
  - gives more weight to short baselines, degrades angular resolution
  - downweights data at long baselines, so point source sensitivity degraded
  - may improve sensitivity to extended structure sampled by short baselines
  - Not a panacea





Slide courtesy David Wilner

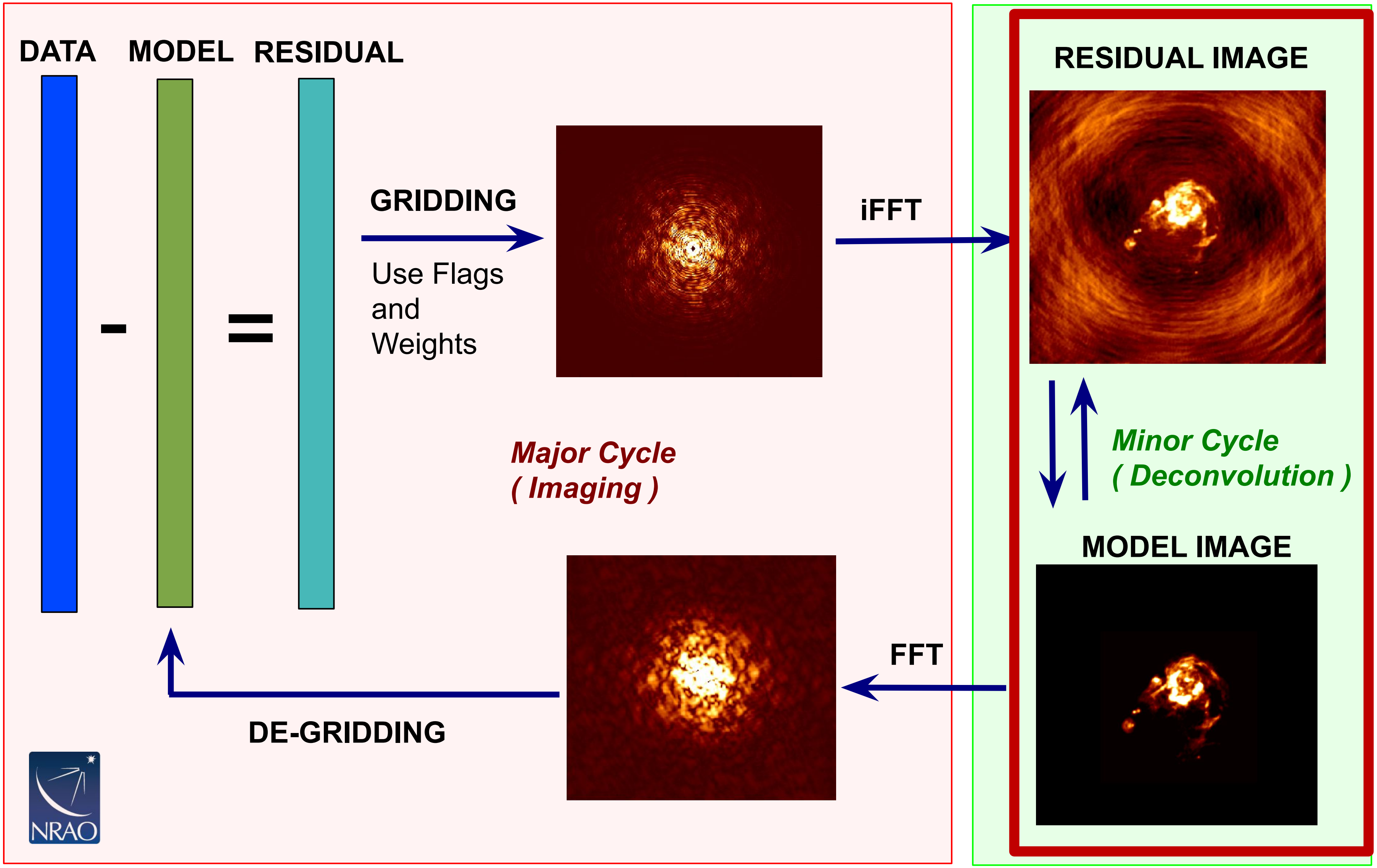
The weighting you choose depends on your science goals.

- Good first try is robust=0.5. It's a nice balance between resolution and noise.
- Detection experiment or weak extended source: try **natural** (maybe even with a taper)
- Finer detail of strong sources: try **robust**

	Robust/Uniform	Natural	Taper
resolution	higher	medium	lower
sidelobes	lower	higher	depends
point source sensitivity	lower	maximum	lower
extended source sensitivity	lower	medium	higher

Adapted from slide by David Wilner

Deconvolution requires specifying how you want to create and subtract the model.



Slide courtesy Urvashi Rau

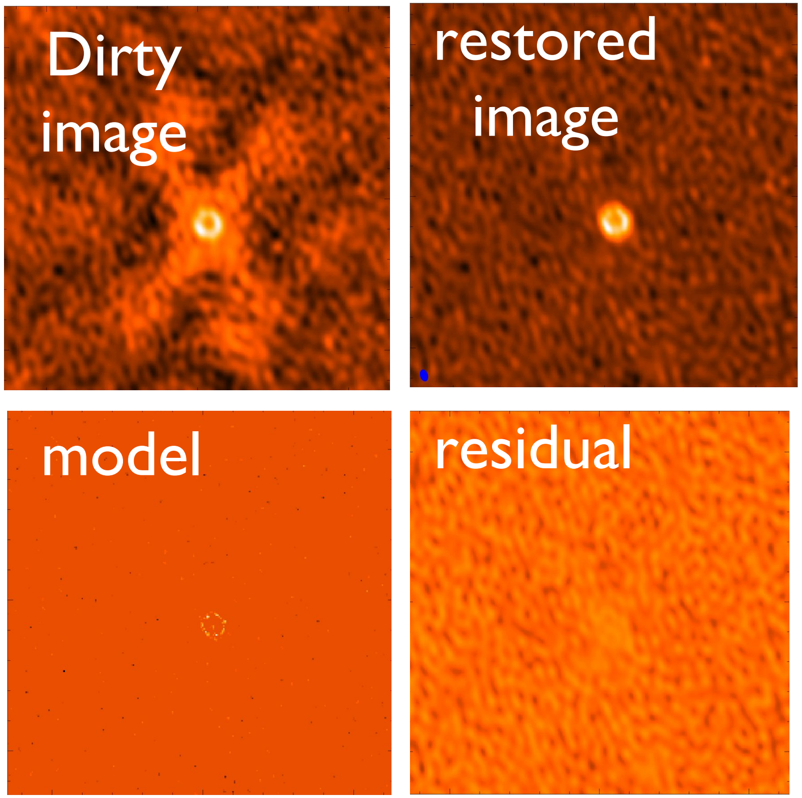
“Clean” is the most common deconvolution algorithm.

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



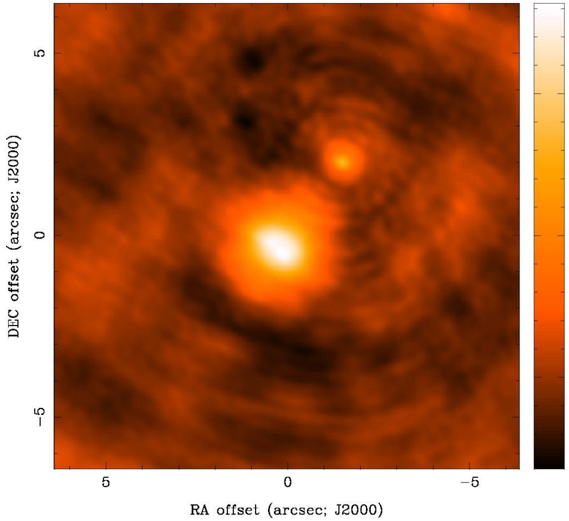
Choices: what and how much PSF to subtract and when to stop

Adapted from slide by Urvashi Rau

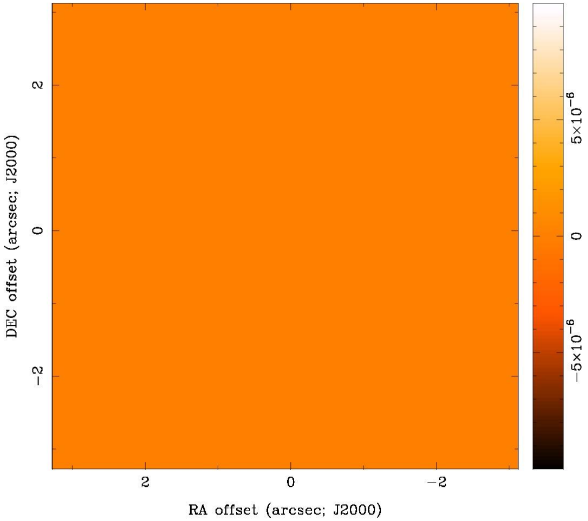
clean example

initialize

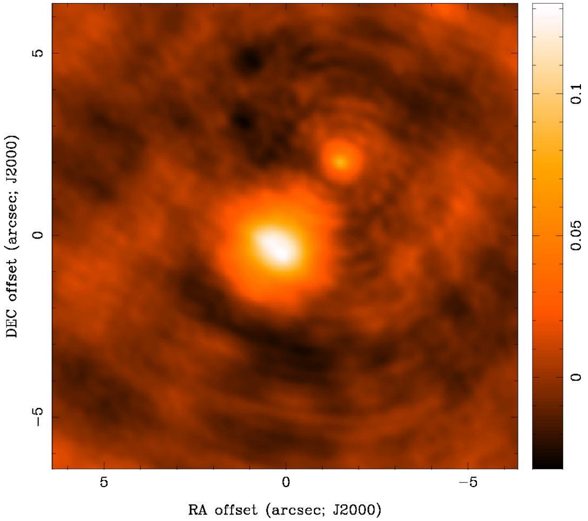
$T^D(l,m)$



0 clean components



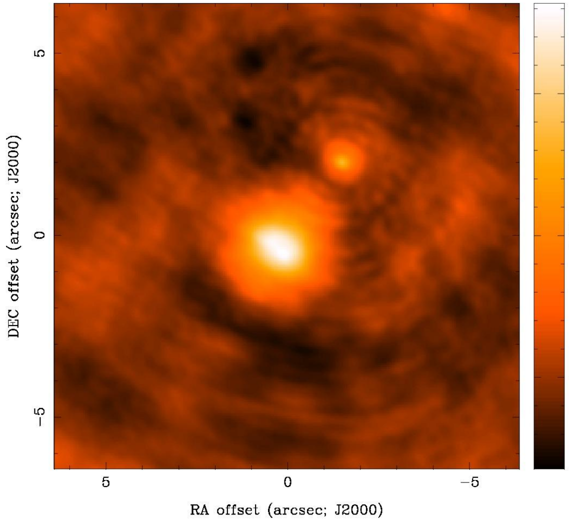
residual map



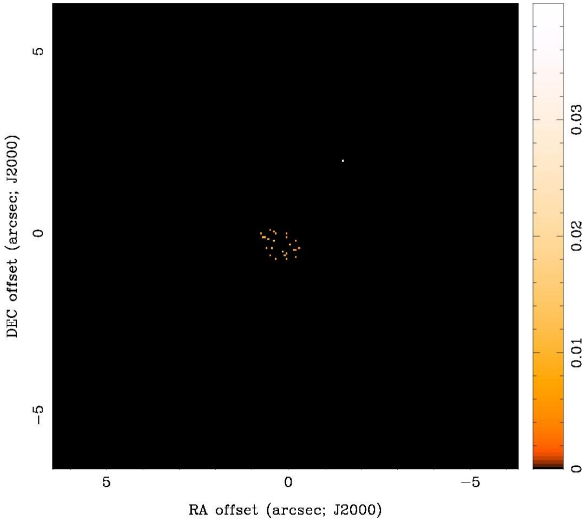
Slide courtesy David Wilner

clean example

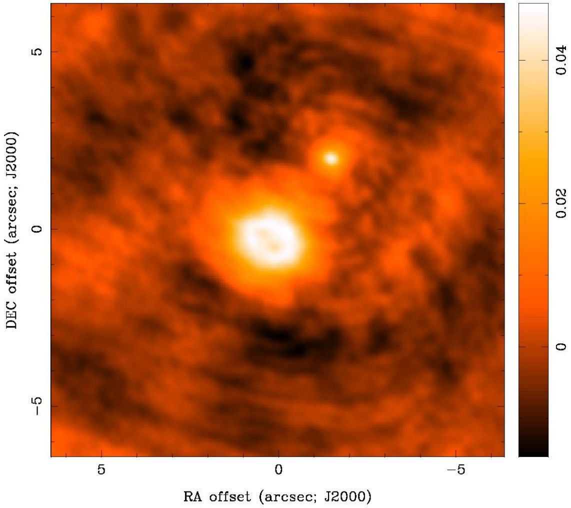
$T^D(l,m)$



30 clean components



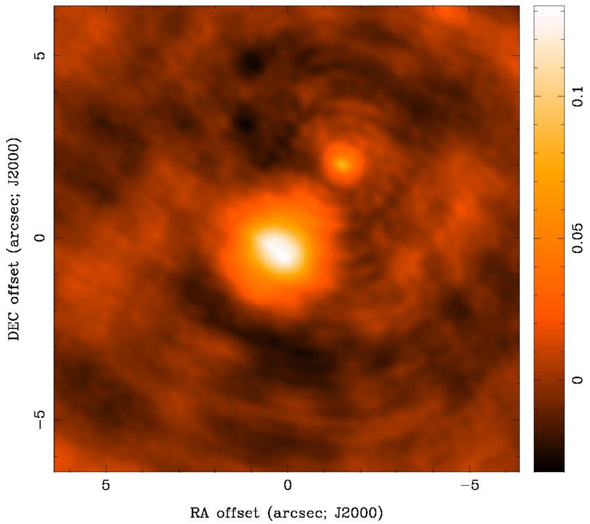
residual map



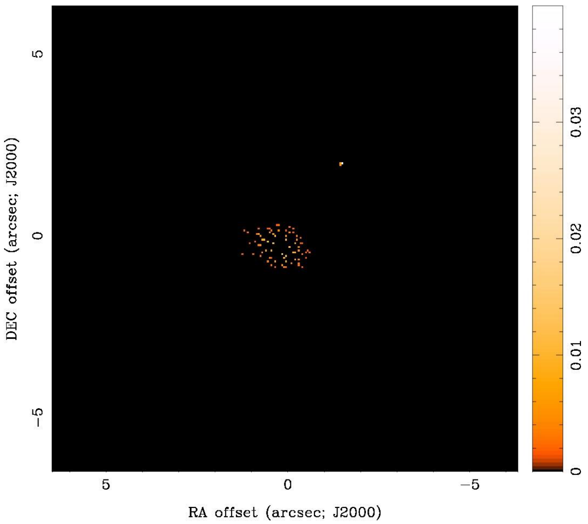
Slide courtesy David Wilner

clean example

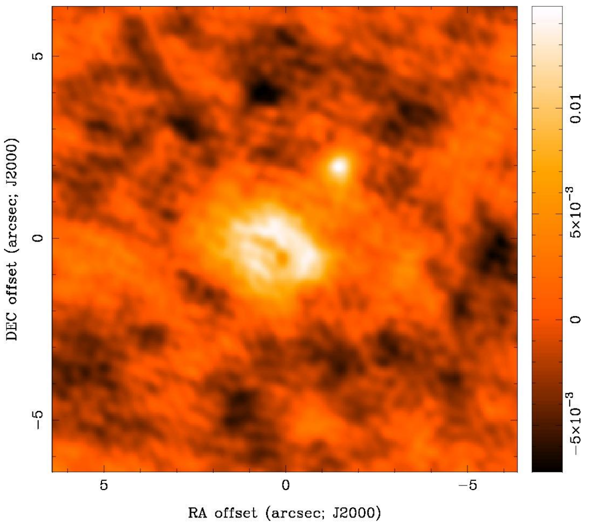
$T^D(l,m)$



100 clean components



residual map



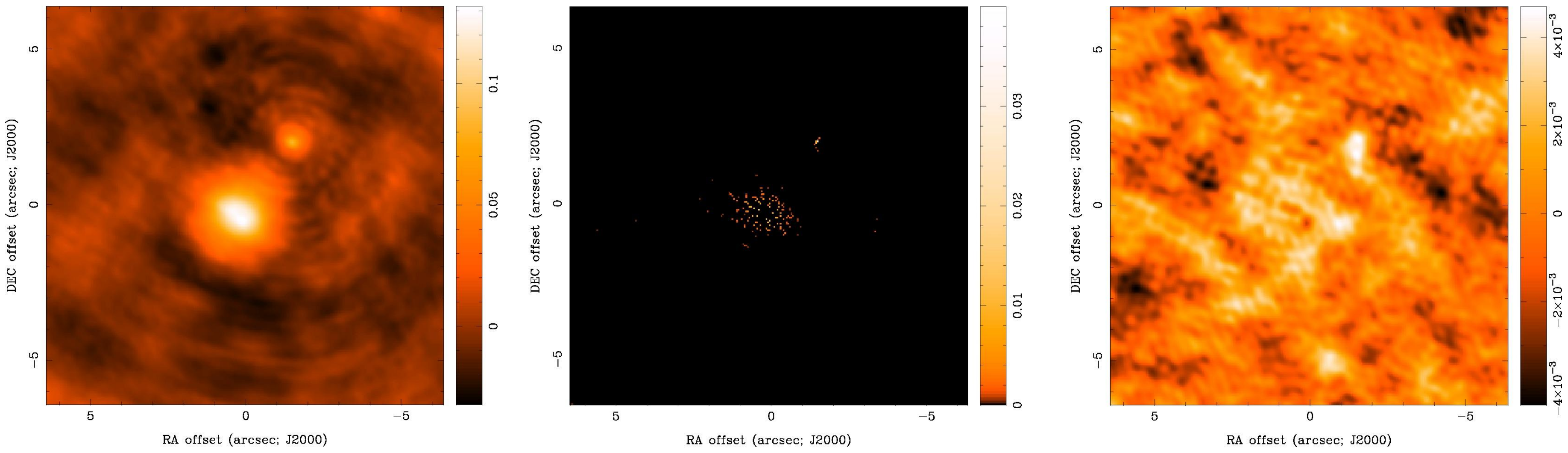
Slide courtesy David Wilner

clean example

$T^D(l,m)$

300 clean components

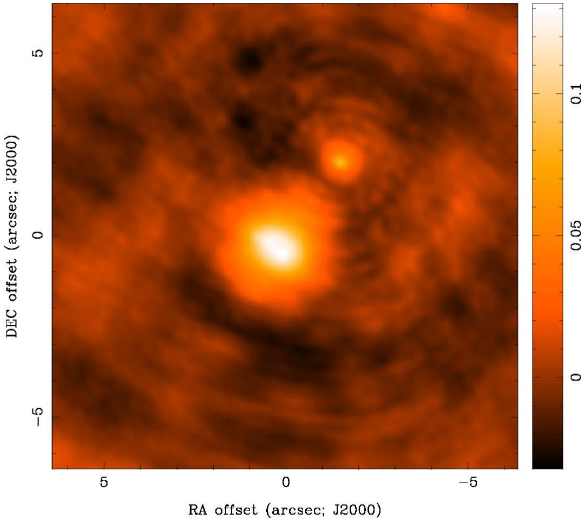
residual map



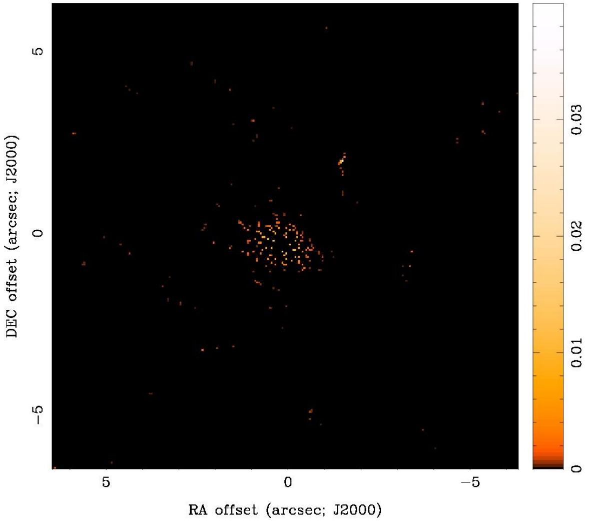
Slide courtesy David Wilner

clean example

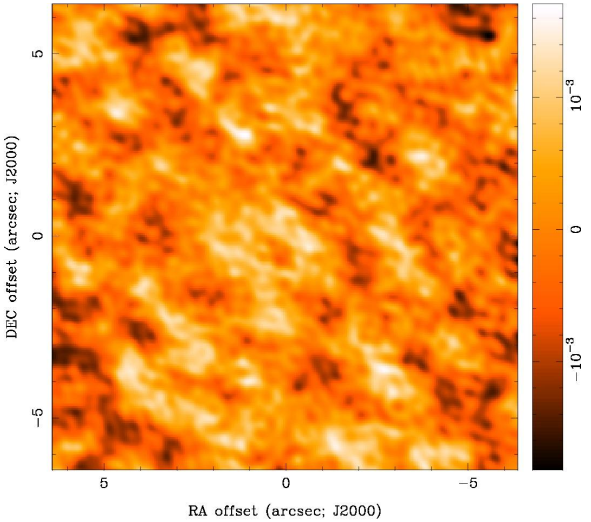
$T^D(l,m)$



583 clean components



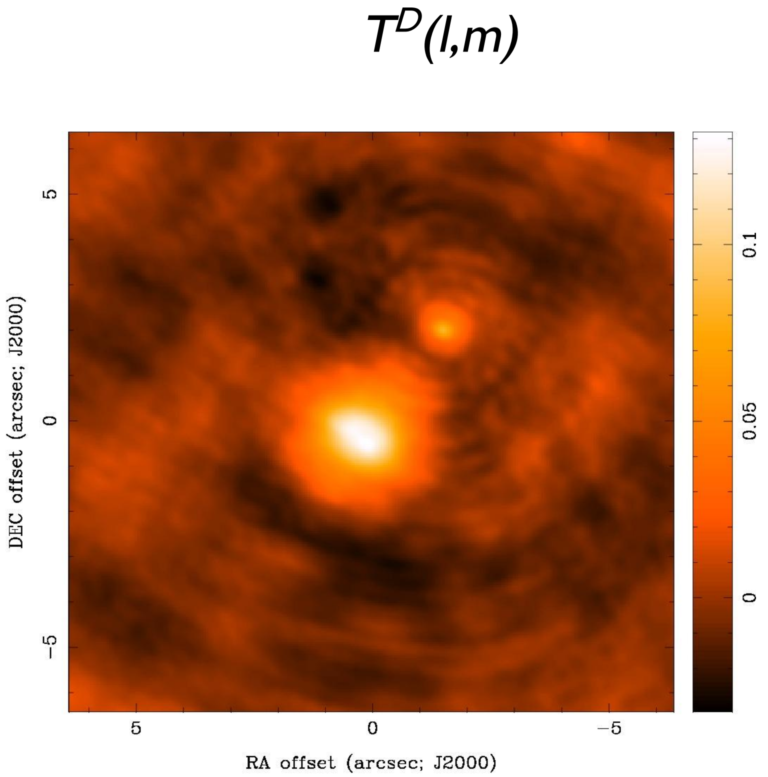
residual map

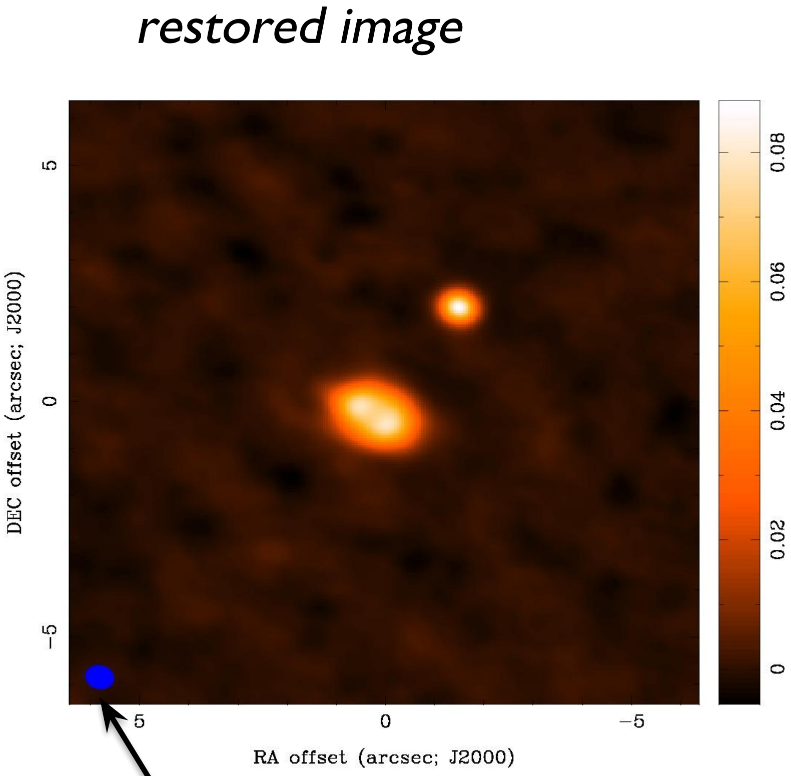


threshold reached

Slide courtesy David Wilner

clean example





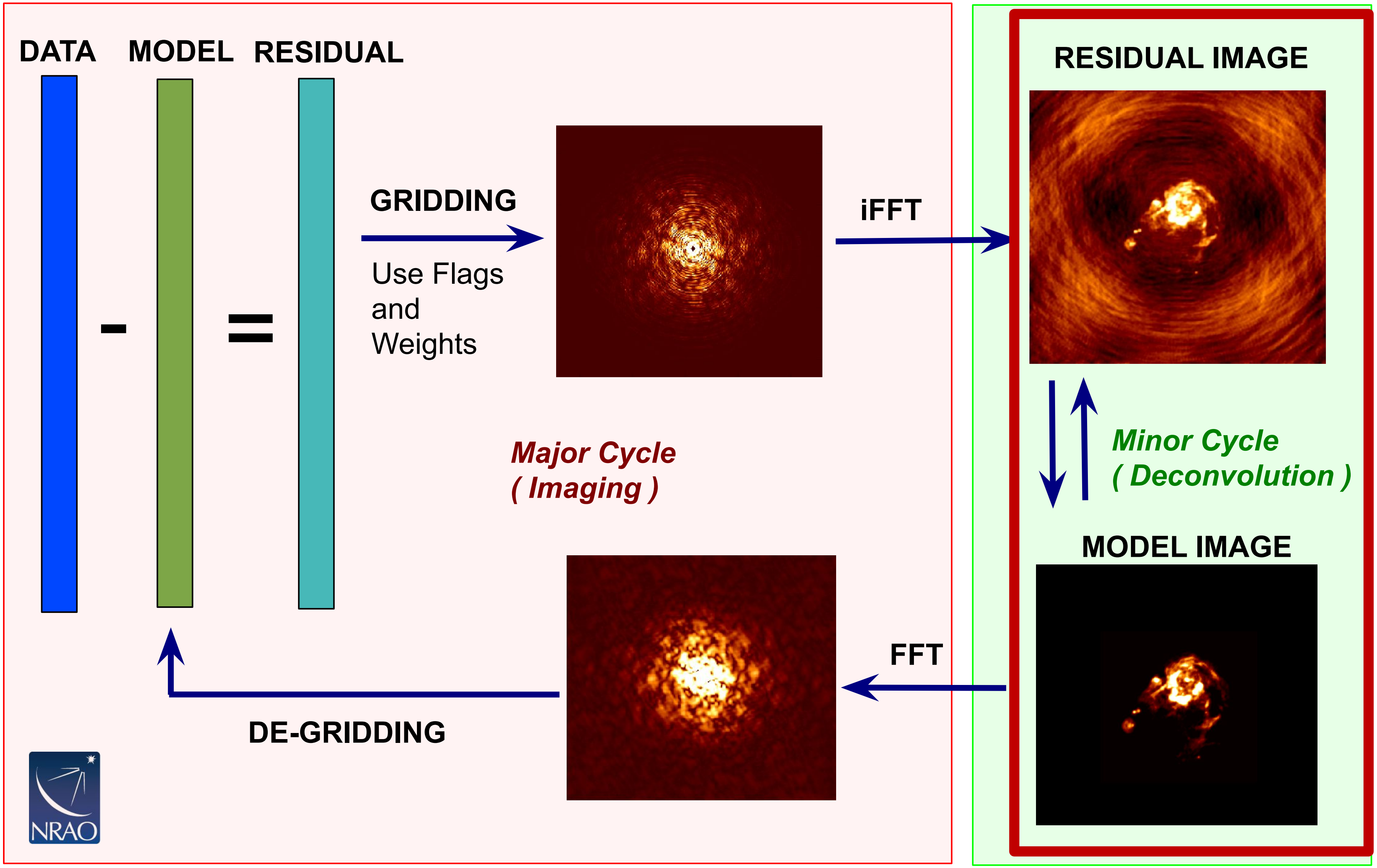
ellipse = clean beam fwhm

final image depends on

imaging parameters (pixel size, visibility weighting scheme, gridding) and deconvolution (algorithm, iterations, masks, stopping criteria)

Slide courtesy David Wilner

How do we do all this in practice?



Slide courtesy Urvashi Rau

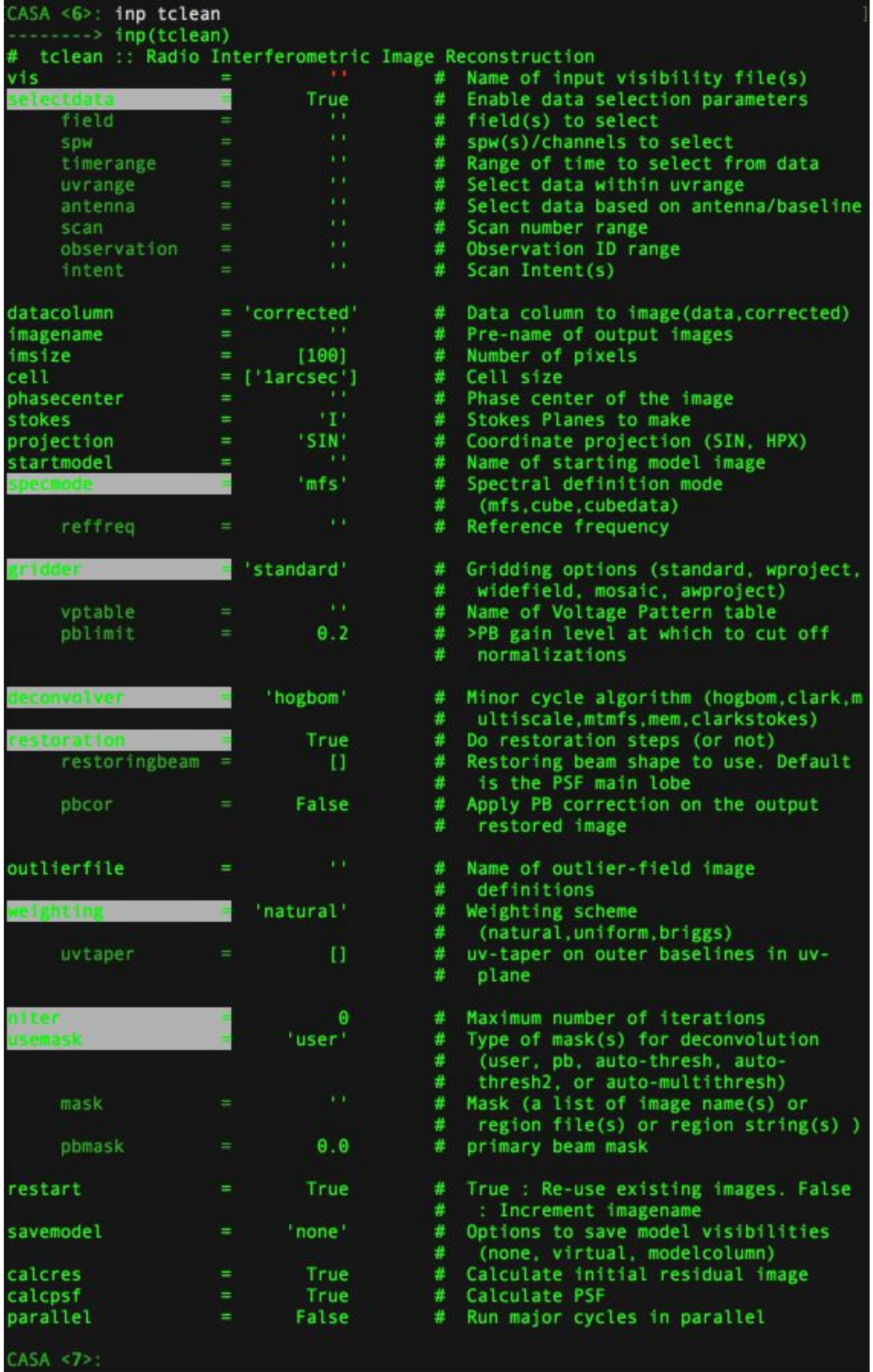
The main imaging task in CASA is tclean

- Tclean is a refactored version of the original clean task
  - *The original clean task is deprecated and SHOULD NOT BE USED.*
- Tclean task
  - takes the calibrated visibilities
  - grids them on the UV-plane
  - performs the FFT to a dirty image
  - deconvolves the image
  - restores the image from clean table and residual
- Major syntax and usage changes from clean to tclean are summarized here: https://casaguides.nrao.edu/index.php/TCLEAN_and_ALMA

TCLEAN in CASA:

There can be an intimidating number of parameters!

Start simple and make it more complicated as you need to.



```
CASA <6>: inp tclean
--------> inp(tclean)
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =         ''        #  Name of input visibility file(s)
selectdata          =       True        #  Enable data selection parameters
     field          =         ''        #  field(s) to select
     spw            =         ''        #  spw(s)/channels to select
     timerange      =         ''        #  Range of time to select from data
     uvrange        =         ''        #  Select data within uvrange
     antenna        =         ''        #  Select data based on antenna/baseline
     scan           =         ''        #  Scan number range
     observation    =         ''        #  Observation ID range
     intent         =         ''        #  Scan Intent(s)

datacolumn          = 'corrected'       #  Data column to image(data,corrected)
imagename           =         ''        #  Pre-name of output images
imsize              =      [100]        #  Number of pixels
cell                = ['1arcsec']       #  Cell size
phasecenter         =         ''        #  Phase center of the image
stokes              =        'I'        #  Stokes Planes to make
projection          =      'SIN'        #  Coordinate projection (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = 'standard'        #  Gridding options (standard, wproject,
                                        #   widefield, mosaic, awproject)
     vptable        =         ''        #  Name of Voltage Pattern table
     pblimit        =        0.2        #  >PB gain level at which to cut off
                                        #   normalizations

deconvolver         =   'hogbom'        #  Minor cycle algorithm (hogbom,clark,m
                                        #   ultiscale,mtmfs,mem,clarkstokes)
restoration         =       True        #  Do restoration steps (or not)
     restoringbeam  =         []        #  Restoring beam shape to use. Default
                                        #   is the PSF main lobe
     pbcor          =      False        #  Apply PB correction on the output
                                        #   restored image

outlierfile         =         ''        #  Name of outlier-field image
                                        #   definitions
weighting           =  'natural'        #  Weighting scheme
                                        #   (natural,uniform,briggs)
     uvtaper        =         []        #  uv-taper on outer baselines in uv-
                                        #   plane

niter               =          0        #  Maximum number of iterations
usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

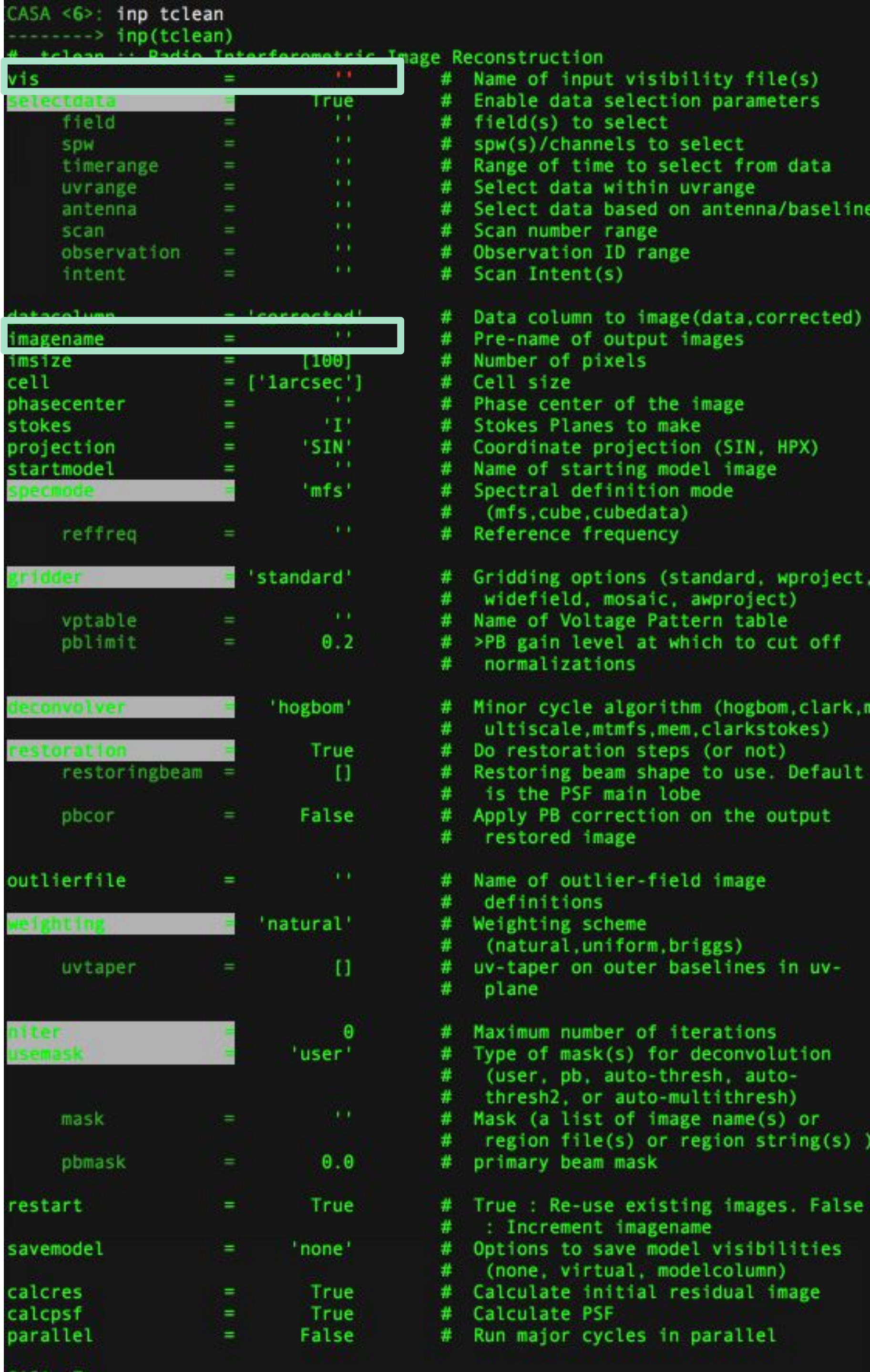
restart             =       True        #  True : Re-use existing images. False
                                        #   : Increment imagename
savemodel           =     'none'        #  Options to save model visibilities
                                        #   (none, virtual, modelcolumn)
calcres             =       True        #  Calculate initial residual image
calcpsf             =       True        #  Calculate PSF
parallel            =      False        #  Run major cycles in parallel

CASA <7>:
```

TCLEAN in CASA

vis = ms file (can be multiple ms'es)

imagename = whatever you want



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     spw            =         ''        #  spw(s)/channels to select
     timerange      =         ''        #  Range of time to select from data
     uvrange        =         ''        #  Select data within uvrange
     antenna        =         ''        #  Select data based on antenna/baseline
     scan           =         ''        #  Scan number range
     observation    =         ''        #  Observation ID range
     intent         =         ''        #  Scan Intent(s)

datacolumn          = 'corrected'       #  Data column to image(data,corrected)
imagename           =         ''        #  Pre-name of output images
imsize              =      [100]        #  Number of pixels
cell                = ['1arcsec']       #  Cell size
phasecenter         =         ''        #  Phase center of the image
stokes              =        'I'        #  Stokes Planes to make
projection          =      'SIN'        #  Coordinate projection (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = 'standard'        #  Gridding options (standard, wproject,
                                        #   widefield, mosaic, awproject)
     vptable        =         ''        #  Name of Voltage Pattern table
     pblimit        =        0.2        #  >PB gain level at which to cut off
                                        #   normalizations

deconvolver         =   'hogbom'        #  Minor cycle algorithm (hogbom,clark,m
                                        #   ultiscale,mtmfs,mem,clarkstokes)
restoration         =       True        #  Do restoration steps (or not)
     restoringbeam  =         []        #  Restoring beam shape to use. Default
                                        #   is the PSF main lobe
     pbcor          =      False        #  Apply PB correction on the output
                                        #   restored image

outlierfile         =         ''        #  Name of outlier-field image
                                        #   definitions
weighting           =  'natural'        #  Weighting scheme
                                        #   (natural,uniform,briggs)
     uvtaper        =         []        #  uv-taper on outer baselines in uv-
                                        #   plane

niter               =          0        #  Maximum number of iterations
usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

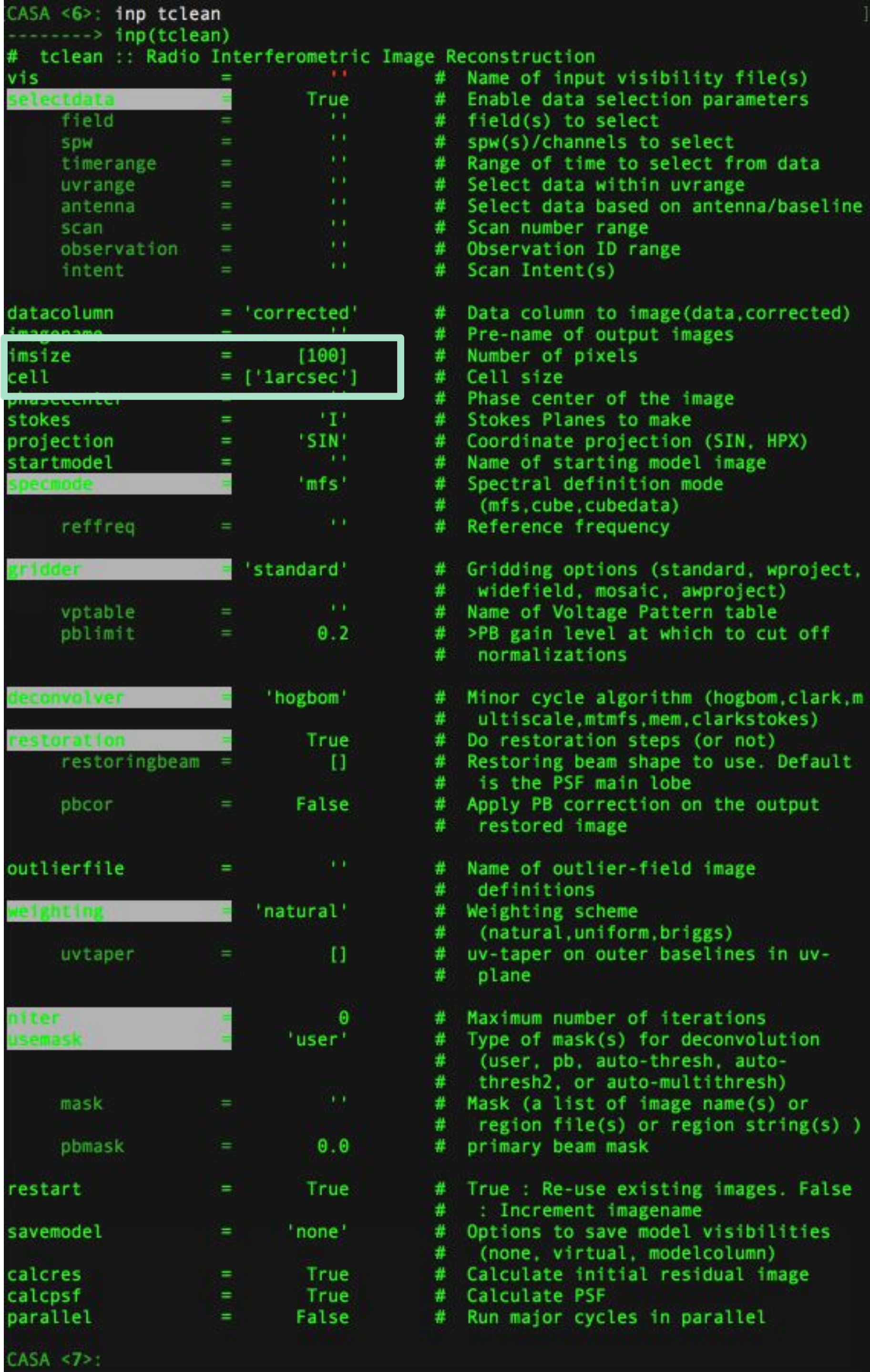
restart             =       True        #  True : Re-use existing images. False
                                        #   : Increment imagename
savemodel           =     'none'        #  Options to save model visibilities
                                        #   (none, virtual, modelcolumn)
calcres             =       True        #  Calculate initial residual image
calcpsf             =       True        #  Calculate PSF
parallel            =      False        #  Run major cycles in parallel
```

TCLEAN in CASA

imsize = size of image in pixels = typically primary beam (i.e., FOV)

cell = size of pixels in angular units = typically 5-8 pixels across synthesized beam (resolution)

See slide 7 for more details.



```
CASA <6>: inp tclean
--------> inp(tclean)
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =          ''        #  Name of input visibility file(s)
selectdata          =        True        #  Enable data selection parameters
     field          =          ''        #  field(s) to select
     spw            =          ''        #  spw(s)/channels to select
     timerange      =          ''        #  Range of time to select from data
     uvrange        =          ''        #  Select data within uvrange
     antenna        =          ''        #  Select data based on antenna/baseline
     scan           =          ''        #  Scan number range
     observation    =          ''        #  Observation ID range
     intent         =          ''        #  Scan Intent(s)

datacolumn          = 'corrected'        #  Data column to image(data,corrected)
imagename           =          ''        #  Pre-name of output images
imsize              =       [100]        #  Number of pixels
cell                = ['1arcsec']        #  Cell size
phasecenter         =          ''        #  Phase center of the image
stokes              =         'I'        #  Stokes Planes to make
projection          =       'SIN'        #  Coordinate projection (SIN, HPX)
startmodel          =          ''        #  Name of starting model image
specmode            =       'mfs'        #  Spectral definition mode
                                         #   (mfs,cube,cubedata)
     reffreq        =          ''        #  Reference frequency

gridder             =  'standard'        #  Gridding options (standard, wproject,
                                         #   widefield, mosaic, awproject)
     vptable        =          ''        #  Name of Voltage Pattern table
     pblimit        =         0.2        #  >PB gain level at which to cut off
                                         #   normalizations

deconvolver         =    'hogbom'        #  Minor cycle algorithm (hogbom,clark,m
                                         #   ultiscale,mtmfs,mem,clarkstokes)
restoration         =        True        #  Do restoration steps (or not)
     restoringbeam  =          []        #  Restoring beam shape to use. Default
                                         #   is the PSF main lobe
     pbcor          =       False        #  Apply PB correction on the output
                                         #   restored image

outlierfile         =          ''        #  Name of outlier-field image
                                         #   definitions
weighting           =   'natural'        #  Weighting scheme
                                         #   (natural,uniform,briggs)
     uvtaper        =          []        #  uv-taper on outer baselines in uv-
                                         #   plane

niter               =           0        #  Maximum number of iterations
usemask             =      'user'        #  Type of mask(s) for deconvolution
                                         #   (user, pb, auto-thresh, auto-
                                         #   thresh2, or auto-multithresh)
     mask           =          ''        #  Mask (a list of image name(s) or
                                         #   region file(s) or region string(s) )
     pbmask         =         0.0        #  primary beam mask

restart             =        True        #  True : Re-use existing images. False
                                         #   : Increment imagename
savemodel           =      'none'        #  Options to save model visibilities
                                         #   (none, virtual, modelcolumn)
calcres             =        True        #  Calculate initial residual image
calcpsf             =        True        #  Calculate PSF
parallel            =       False        #  Run major cycles in parallel

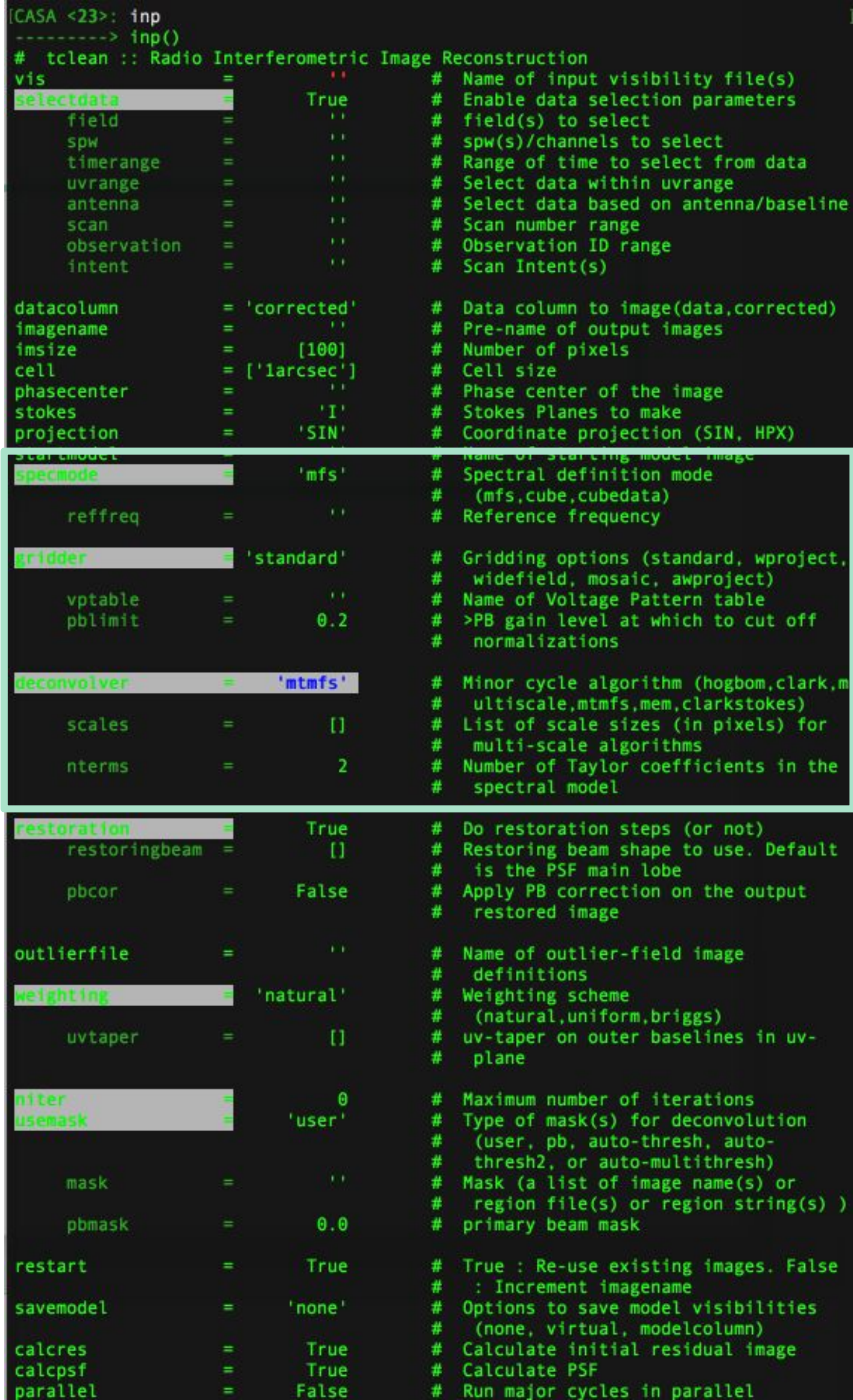
CASA <7>:
```

Key tclean parameters

The **specmode** parameter controls whether you image the continuum (mfs) or line emission (cube).

The **gridder** option is used to specify what sort of gridding you will be doing (standard, mosaic, widefield, wproject, or awproject). The first two are most common with ALMA. The rest more common with the VLA.

The **deconvolver** options gives you access to different deconvolution options (hogbom, clark, mtmfs, multiscale, clarkstokes)



```
CASA <23>: inp
---------> inp()
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =          ''       #  Name of input visibility file(s)
selectdata          =        True       #  Enable data selection parameters
     field          =          ''       #  field(s) to select
     spw            =          ''       #  spw(s)/channels to select
     timerange      =          ''       #  Range of time to select from data
     uvrange        =          ''       #  Select data within uvrange
     antenna        =          ''       #  Select data based on antenna/baseline
     scan           =          ''       #  Scan number range
     observation    =          ''       #  Observation ID range
     intent         =          ''       #  Scan Intent(s)

datacolumn          = 'corrected'       #  Data column to image(data,corrected)
imagename           =          ''       #  Pre-name of output images
imsize              =       [100]       #  Number of pixels
cell                = ['1arcsec']       #  Cell size
phasecenter         =          ''       #  Phase center of the image
stokes              =         'I'       #  Stokes Planes to make
projection          =       'SIN'       #  Coordinate projection (SIN, HPX)
startmodel          =          ''       #  Name of starting model image
specmode            =       'mfs'       #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =          ''       #  Reference frequency

gridder             =  'standard'       #  Gridding options (standard, wproject,
                                        #   widefield, mosaic, awproject)
     vptable        =          ''       #  Name of Voltage Pattern table
     pblimit        =         0.2       #  >PB gain level at which to cut off
                                        #   normalizations

deconvolver         =     'mtmfs'       #  Minor cycle algorithm (hogbom,clark,m
                                        #   ultiscale,mtmfs,mem,clarkstokes)
     scales         =          []       #  List of scale sizes (in pixels) for
                                        #   multi-scale algorithms
     nterms         =           2       #  Number of Taylor coefficients in the
                                        #   spectral model

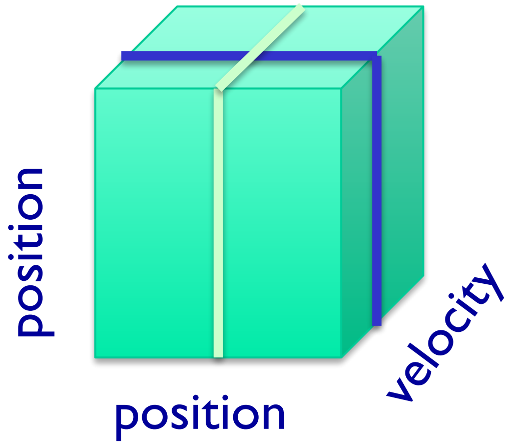
restoration         =        True       #  Do restoration steps (or not)
     restoringbeam  =          []       #  Restoring beam shape to use. Default
                                        #   is the PSF main lobe
     pbcor          =       False       #  Apply PB correction on the output
                                        #   restored image

outlierfile         =          ''       #  Name of outlier-field image
                                        #   definitions
weighting           =   'natural'       #  Weighting scheme
                                        #   (natural,uniform,briggs)
     uvtaper        =          []       #  uv-taper on outer baselines in uv-
                                        #   plane

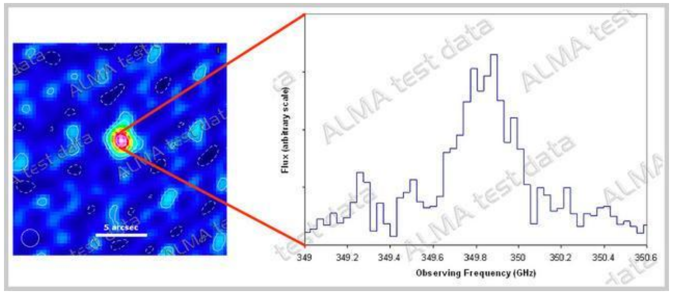
niter               =           0       #  Maximum number of iterations
usemask             =      'user'       #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =          ''       #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =         0.0       #  primary beam mask

restart             =        True       #  True : Re-use existing images. False
                                        #   : Increment imagename
savemodel           =      'none'       #  Options to save model visibilities
                                        #   (none, virtual, modelcolumn)
calcres             =        True       #  Calculate initial residual image
calcpsf             =        True       #  Calculate PSF
parallel            =       False       #  Run major cycles in parallel
```

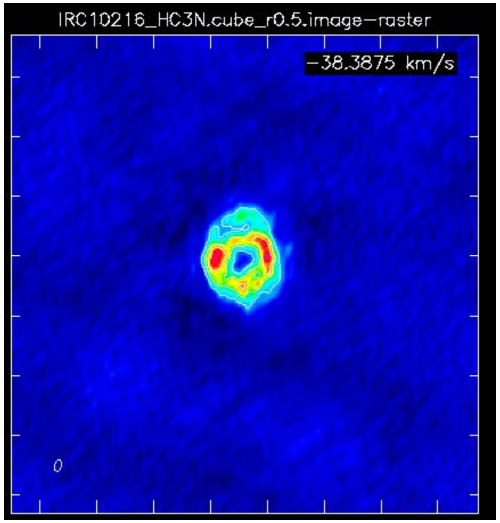
Specmode options: Imaging spectral lines



Spectrum

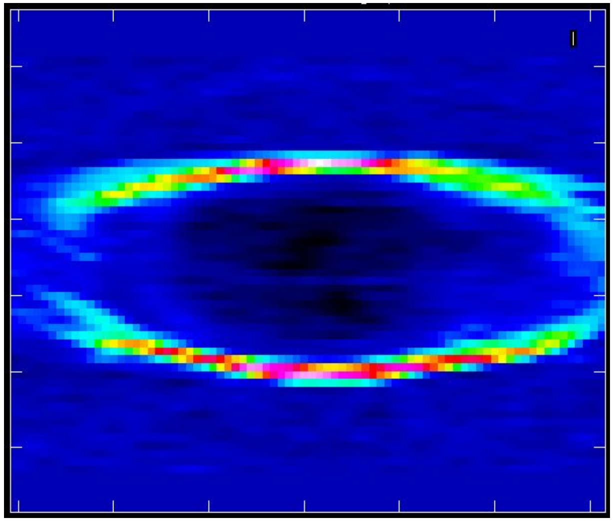


Channel map



Fixed velocity, polarization, etc.

Position-velocity map



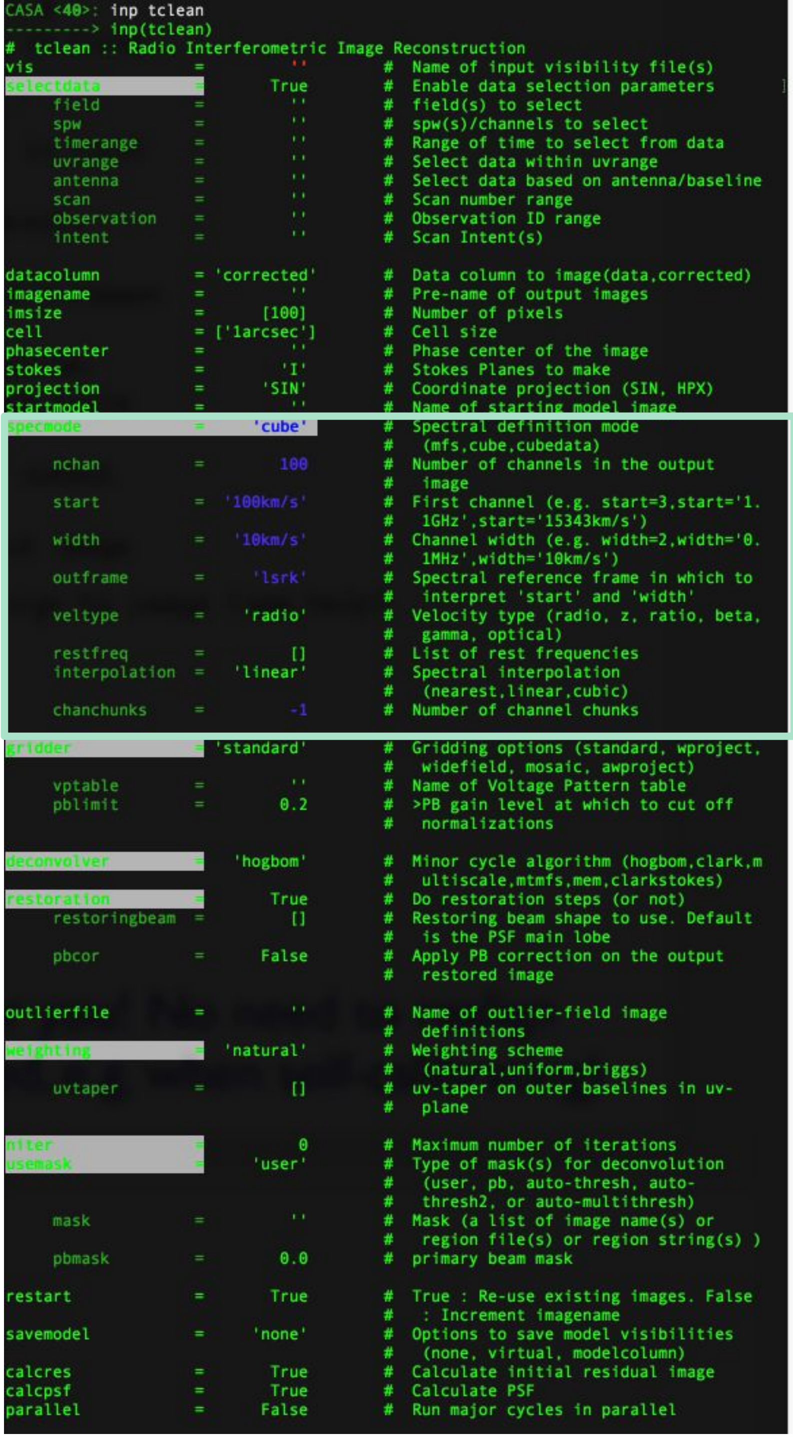
One fixed position, polarization, etc.

Specmode options: Imaging spectral lines

specmode=‘cube’

- Set the dimensions of the cube
- Set Rest frequency
- Set Velocity Frame (LSRK, BARY, …)
- Set Doppler definition (optical/radio)
- If imaging large cubes, set chanchunks=-1. Default (1) tries to put entire cube in memory, which can fail for large cubes.
- You may want to consider setting perchanweightdensity=True. This option calculates the weights per channel instead over the whole cube. This will give a flat noise spectrum at the expense of a slightly larger beam. The ALMA Cycle 7 pipeline sets perchanweightdensity=False.

tclean will calculate the Doppler corrections for you! No need to realign beforehand. If needed, **cvel2** will do it for you, e.g. when self-calibrating.



```
CASA <40>: inp tclean
---------> inp(tclean)
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =          ''        #  Name of input visibility file(s)
selectdata          =        True        #  Enable data selection parameters
     field          =          ''        #  field(s) to select
     spw            =          ''        #  spw(s)/channels to select
     timerange      =          ''        #  Range of time to select from data
     uvrange        =          ''        #  Select data within uvrange
     antenna        =          ''        #  Select data based on antenna/baseline
     scan           =          ''        #  Scan number range
     observation    =          ''        #  Observation ID range
     intent         =          ''        #  Scan Intent(s)

datacolumn          = 'corrected'        #  Data column to image(data,corrected)
imagename           =          ''        #  Pre-name of output images
imsize              =       [100]        #  Number of pixels
cell                = ['1arcsec']        #  Cell size
phasecenter         =          ''        #  Phase center of the image
stokes              =         'I'        #  Stokes Planes to make
projection          =       'SIN'        #  Coordinate projection (SIN, HPX)
startmodel          =          ''        #  Name of starting model image
specmode            =      'cube'        #  Spectral definition mode
                                         #   (mfs,cube,cubedata)
     nchan          =         100        #  Number of channels in the output
                                         #   image
     start          =  '100km/s'         #  First channel (e.g. start=3,start='1.
                                         #   1GHz',start='15343km/s')
     width          =   '10km/s'         #  Channel width (e.g. width=2,width='0.
                                         #   1MHz',width='10km/s')
     outframe       =      'lsrk'        #  Spectral reference frame in which to
                                         #   interpret 'start' and 'width'
     veltype        =     'radio'        #  Velocity type (radio, z, ratio, beta,
                                         #   gamma, optical)
     restfreq       =          []        #  List of rest frequencies
     interpolation  =    'linear'        #  Spectral interpolation
                                         #   (nearest,linear,cubic)
     chanchunks     =          -1        #  Number of channel chunks

gridder             =  'standard'        #  Gridding options (standard, wproject,
                                         #   widefield, mosaic, awproject)
     vptable        =          ''        #  Name of Voltage Pattern table
     pblimit        =         0.2        #  >PB gain level at which to cut off
                                         #   normalizations

deconvolver         =    'hogbom'        #  Minor cycle algorithm (hogbom,clark,m
                                         #   ultiscale,mtmfs,mem,clarkstokes)
restoration         =        True        #  Do restoration steps (or not)
     restoringbeam  =          []        #  Restoring beam shape to use. Default
                                         #   is the PSF main lobe
     pbcor          =       False        #  Apply PB correction on the output
                                         #   restored image

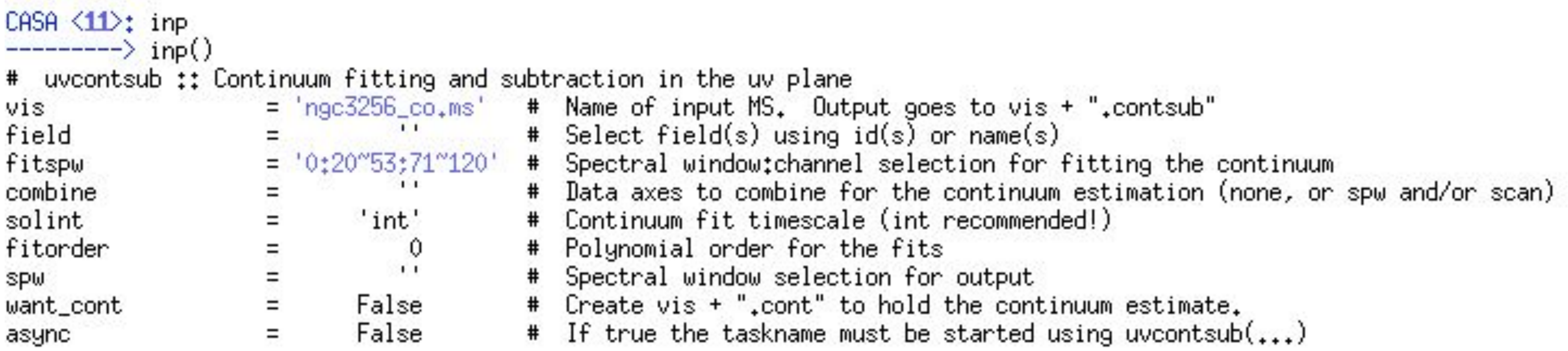
outlierfile         =          ''        #  Name of outlier-field image
                                         #   definitions
weighting           =   'natural'        #  Weighting scheme
                                         #   (natural,uniform,briggs)
     uvtaper        =          []        #  uv-taper on outer baselines in uv-
                                         #   plane

niter               =           0        #  Maximum number of iterations
usemask             =      'user'        #  Type of mask(s) for deconvolution
                                         #   (user, pb, auto-thresh, auto-
                                         #   thresh2, or auto-multithresh)
     mask           =          ''        #  Mask (a list of image name(s) or
                                         #   region file(s) or region string(s) )
     pbmask         =         0.0        #  primary beam mask

restart             =        True        #  True : Re-use existing images. False
                                         #   : Increment imagename
savemodel           =      'none'        #  Options to save model visibilities
                                         #   (none, virtual, modelcolumn)
calcres             =        True        #  Calculate initial residual image
calcpsf             =        True        #  Calculate PSF
parallel            =       False        #  Run major cycles in parallel
```

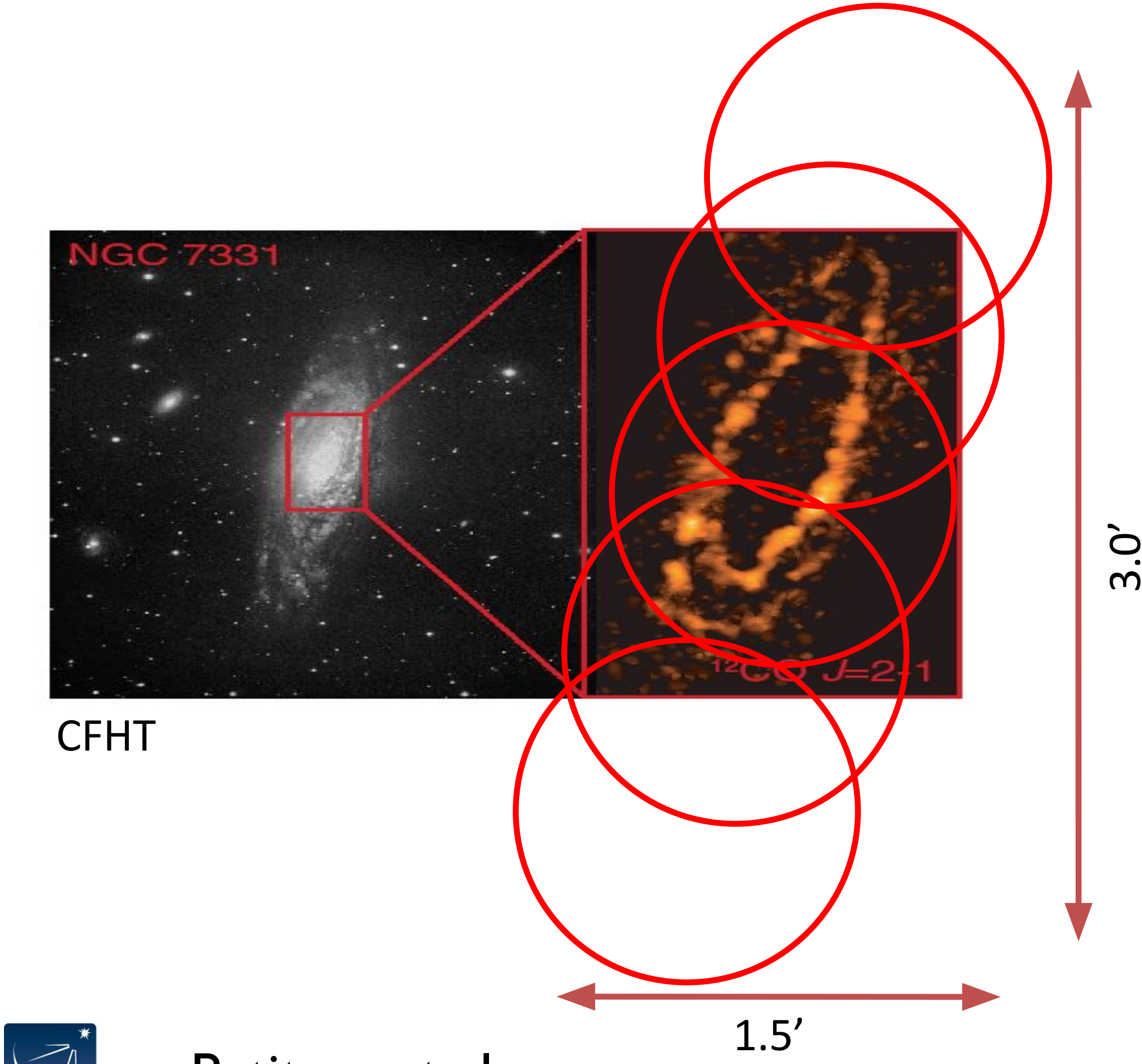
Imaging spectral lines: continuum subtraction

- Generally would like to subtract continuum emission prior to imaging line data.
  - We will see how to identify line-free channels in hands-on session.
- Current best practice is to use `uvcontsub` to do the subtraction in uv plane.



```
CASA <11>: inp
---------> inp()
#  uvcontsub :: Continuum fitting and subtraction in the uv plane
vis                 = 'ngc3256_co.ms'    #  Name of input MS.  Output goes to vis + ".contsub"
field               =           ''       #  Select field(s) using id(s) or name(s)
fitspw              = '0:20~53;71~120'   #  Spectral window:channel selection for fitting the continuum
combine             =           ''       #  Data axes to combine for the continuum estimation (none, or spw and/or scan)
solint              =        'int'       #  Continuum fit timescale (int recommended!)
fitorder            =            0       #  Polynomial order for the fits
spw                 =           ''       #  Spectral window selection for output
want_cont           =        False       #  Create vis + ".cont" to hold the continuum estimate.
async               =        False       #  If true the taskname must be started using uvcontsub(...)
```

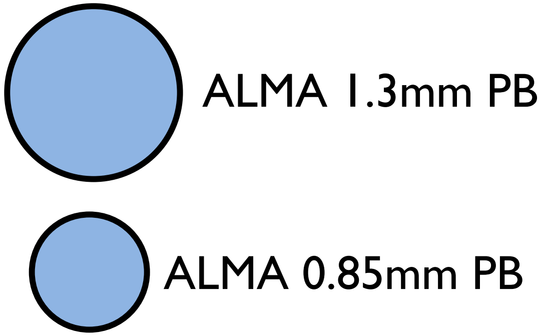
Gridder options: mosaics



Mosaics are common with ALMA particularly at high frequencies

Example: SMA 1.3 mm observations: 5 pointings

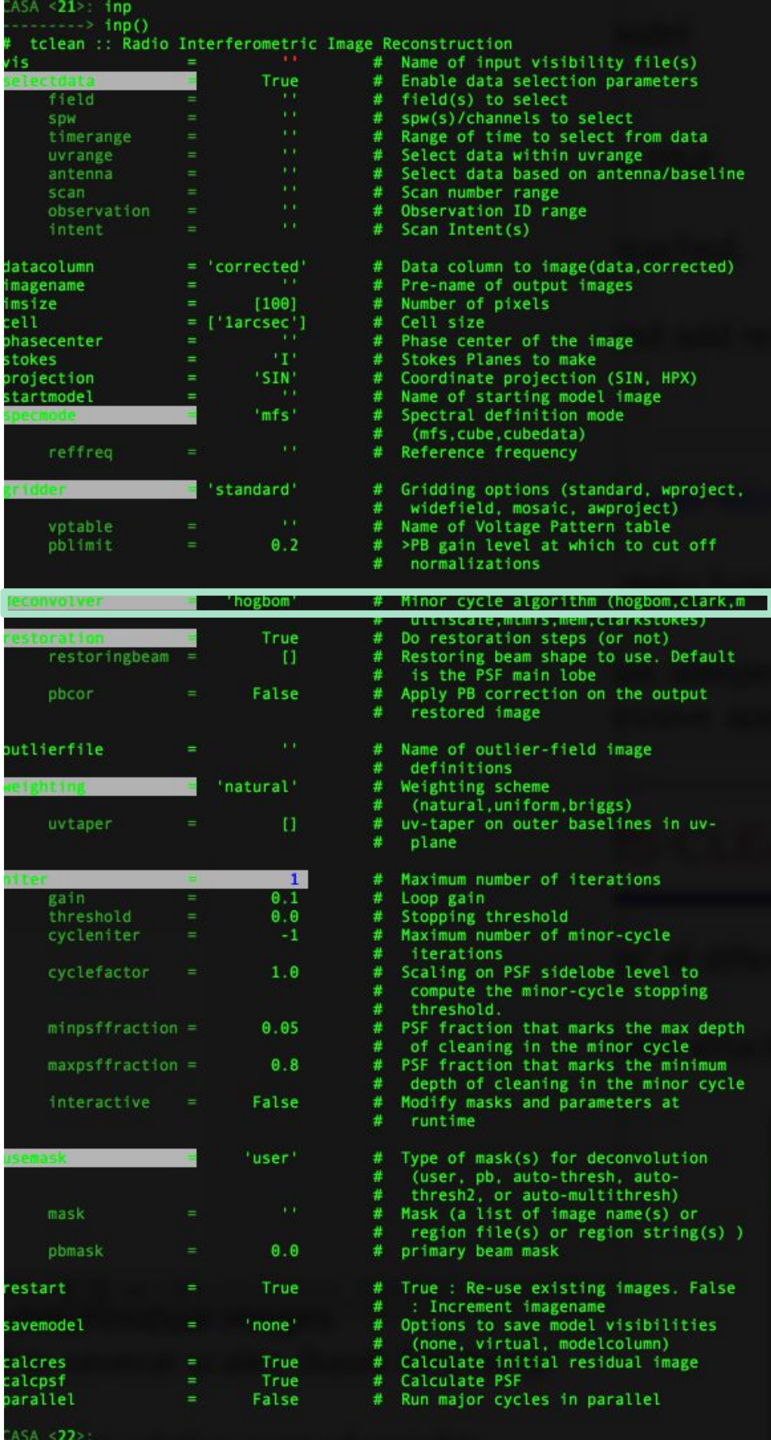
- Primary beam ~1'
- Resolution ~3"



Petitpas et al.

Deconvolver options: PSF sampling choices

- **deconvolver='hogbom'**
  - Subtracts shifted and scaled full PSF from residual image
  - More accurate but can be computationally expensive.
- **deconvolver='clark'**
  - Subtracts small patch of shifted and scaled PSF from residual image
  - Does the major cycle more often to compensate for the above
  - Potentially less accurate, but also less computationally expensive.
- **deconvolver='clarkstokes'**
  - Does the thing as clark, but doing each polarization product separately.



```
CASA <21>: inp
---------> inp()
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =         ''        #  Name of input visibility file(s)
selectdata          =       True        #  Enable data selection parameters
     field          =         ''        #  field(s) to select
     spw            =         ''        #  spw(s)/channels to select
     timerange      =         ''        #  Range of time to select from data
     uvrange        =         ''        #  Select data within uvrange
     antenna        =         ''        #  Select data based on antenna/baseline
     scan           =         ''        #  Scan number range
     observation    =         ''        #  Observation ID range
     intent         =         ''        #  Scan Intent(s)

datacolumn          = 'corrected'       #  Data column to image(data,corrected)
imagename           =         ''        #  Pre-name of output images
imsize              =      [100]        #  Number of pixels
cell                = ['1arcsec']       #  Cell size
phasecenter         =         ''        #  Phase center of the image
stokes              =        'I'        #  Stokes Planes to make
projection          =      'SIN'        #  Coordinate projection (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = 'standard'        #  Gridding options (standard, wproject,
                                        #   widefield, mosaic, awproject)
     vptable        =         ''        #  Name of Voltage Pattern table
     pblimit        =        0.2        #  >PB gain level at which to cut off
                                        #   normalizations

deconvolver         =   'hogbom'        #  Minor cycle algorithm (hogbom,clark,m
                                        #   ultiscale,mtmfs,mem,clarkstokes)
restoration         =       True        #  Do restoration steps (or not)
     restoringbeam  =         []        #  Restoring beam shape to use. Default
                                        #   is the PSF main lobe
     pbcor          =      False        #  Apply PB correction on the output
                                        #   restored image

outlierfile         =         ''        #  Name of outlier-field image
                                        #   definitions
weighting           =  'natural'        #  Weighting scheme
                                        #   (natural,uniform,briggs)
     uvtaper        =         []        #  uv-taper on outer baselines in uv-
                                        #   plane

niter               =          1        #  Maximum number of iterations
     gain           =        0.1        #  Loop gain
     threshold      =        0.0        #  Stopping threshold
     cycleniter     =         -1        #  Maximum number of minor-cycle
                                        #   iterations
     cyclefactor    =        1.0        #  Scaling on PSF sidelobe level to
                                        #   compute the minor-cycle stopping
                                        #   threshold.
     minpsffraction =       0.05        #  PSF fraction that marks the max depth
                                        #   of cleaning in the minor cycle
     maxpsffraction =        0.8        #  PSF fraction that marks the minimum
                                        #   depth of cleaning in the minor cycle
     interactive    =      False        #  Modify masks and parameters at
                                        #   runtime

usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

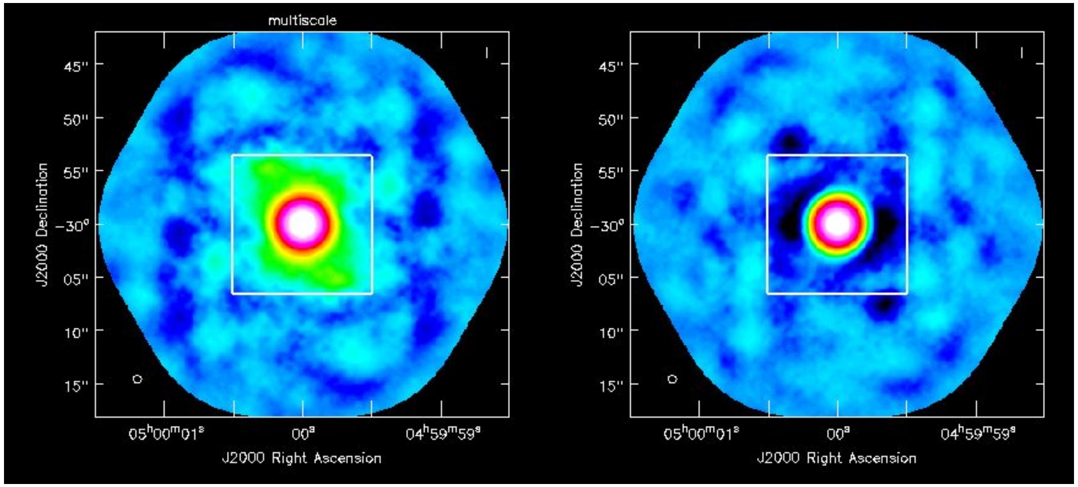
restart             =       True        #  True : Re-use existing images. False
                                        #   : Increment imagename
savemodel           =     'none'        #  Options to save model visibilities
                                        #   (none, virtual, modelcolumn)
calcres             =       True        #  Calculate initial residual image
calcpsf             =       True        #  Calculate PSF
parallel            =      False        #  Run major cycles in parallel

CASA <22>:
```

Deconvolver options: Multi-scale CLEAN

multi-scale

“classic” scale



Instead of using delta functions like hogbom or clark, one can use extended clean components to better match emission scales (multiscales, typically paraboloids)

Suggested scale parameter choice : point source, the second the size of the synthesized beam and the third 3-5 times the synthesized beam, etc.

Selecting scales that are close to the size of your source can lead to poor modeling and divergence in clean.

Deconvolver options: Multi-scale CLEAN

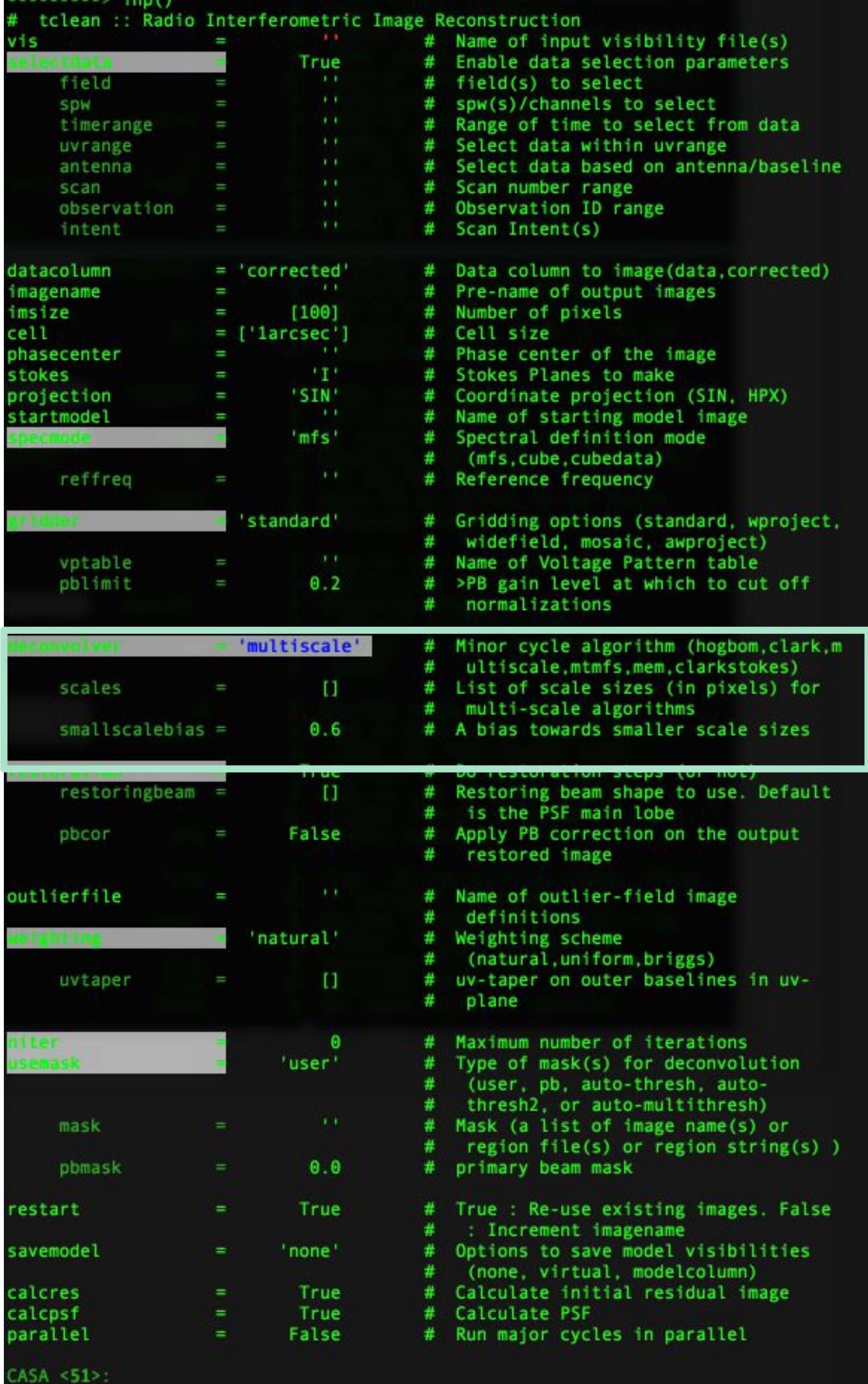
deconvolver='multiscale'

- **only do multiscale**
- line or narrow bandwidth continuum

deconvolver='mtmfs'

- **multiscale+multi-terms**
- wide-fractional bandwidth continuum

- For both need to set scales
  - Note that scales is in **pixels**
  - If beam is 5 pixels across, then scales=[0,5,15] is a pretty good choice.



```
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =         ''        #  Name of input visibility file(s)
selectdata          =       True        #  Enable data selection parameters
     field          =         ''        #  field(s) to select
     spw            =         ''        #  spw(s)/channels to select
     timerange      =         ''        #  Range of time to select from data
     uvrange        =         ''        #  Select data within uvrange
     antenna        =         ''        #  Select data based on antenna/baseline
     scan           =         ''        #  Scan number range
     observation    =         ''        #  Observation ID range
     intent         =         ''        #  Scan Intent(s)

datacolumn          = 'corrected'       #  Data column to image(data,corrected)
imagename           =         ''        #  Pre-name of output images
imsize              =      [100]        #  Number of pixels
cell                = ['1arcsec']       #  Cell size
phasecenter         =         ''        #  Phase center of the image
stokes              =        'I'        #  Stokes Planes to make
projection          =      'SIN'        #  Coordinate projection (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = 'standard'        #  Gridding options (standard, wproject,
                                        #   widefield, mosaic, awproject)
     vptable        =         ''        #  Name of Voltage Pattern table
     pblimit        =        0.2        #  >PB gain level at which to cut off
                                        #   normalizations

deconvolver         = 'multiscale'      #  Minor cycle algorithm (hogbom,clark,m
                                        #   ultiscale,mtmfs,mem,clarkstokes)
     scales         =         []        #  List of scale sizes (in pixels) for
                                        #   multi-scale algorithms
     smallscalebias =        0.6        #  A bias towards smaller scale sizes

restoration         =       True        #  Do restoration steps (or not)
     restoringbeam  =         []        #  Restoring beam shape to use. Default
                                        #   is the PSF main lobe
     pbcor          =      False        #  Apply PB correction on the output
                                        #   restored image

outlierfile         =         ''        #  Name of outlier-field image
                                        #   definitions
weighting           =  'natural'        #  Weighting scheme
                                        #   (natural,uniform,briggs)
     uvtaper        =         []        #  uv-taper on outer baselines in uv-
                                        #   plane

niter               =          0        #  Maximum number of iterations
usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

restart             =       True        #  True : Re-use existing images. False
                                        #   : Increment imagename
savemodel           =     'none'        #  Options to save model visibilities
                                        #   (none, virtual, modelcolumn)
calcres             =       True        #  Calculate initial residual image
calcpsf             =       True        #  Calculate PSF
parallel            =      False        #  Run major cycles in parallel

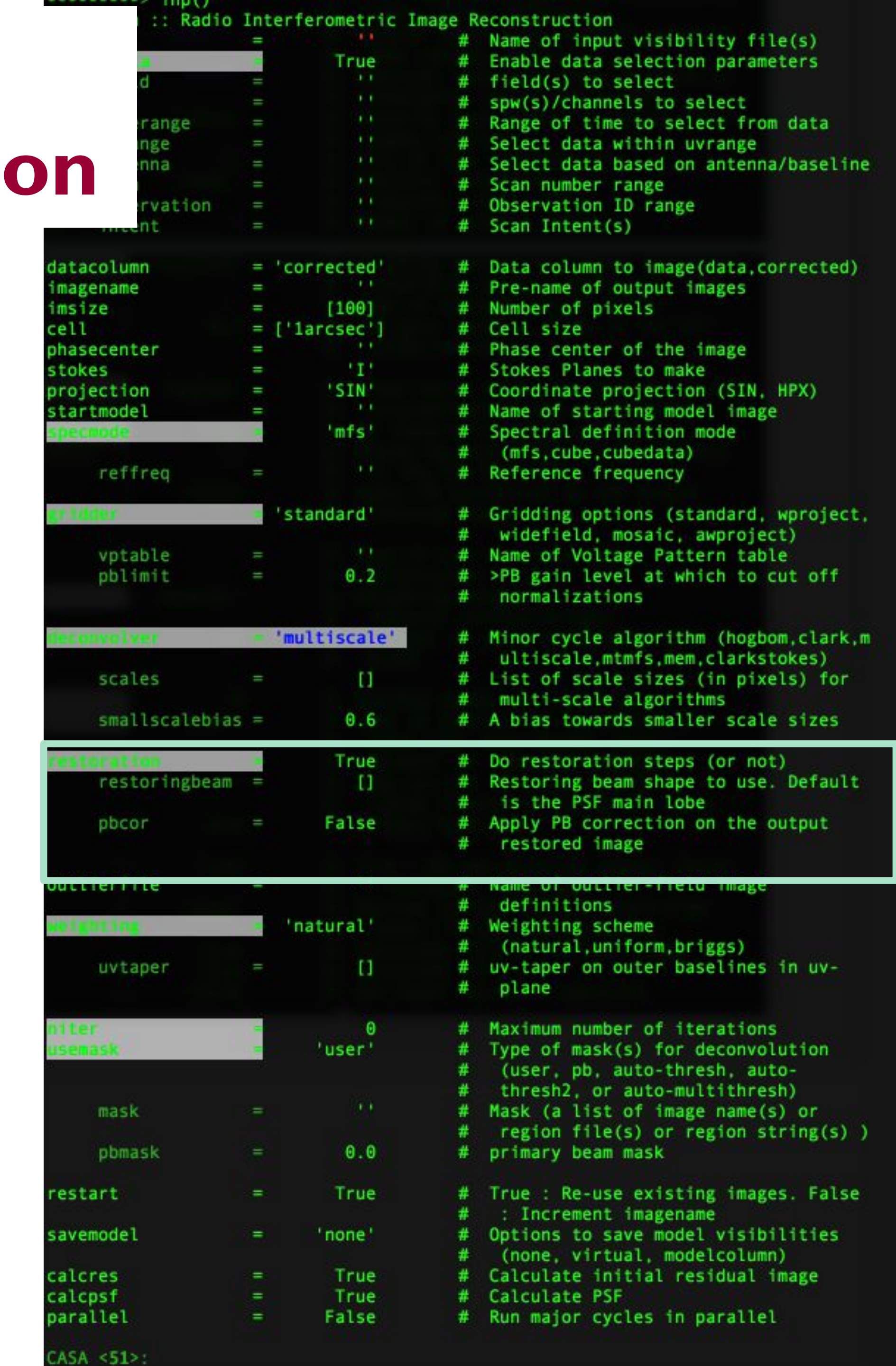
CASA <51>:
```

Restoration options: Primary beam correction

pbcor=True

- Correct the output image for the primary beam (i.e., the beam pattern of the telescope)
- You want to measure things from a primary beam corrected image because it includes the response of the telescope.
- However, the noise is no longer flat across the image, which can make pretty pictures harder to make.

For multi-term mfs primary beam corrections (i.e., nterms=2) use the **widebandpbcor** task instead.



```
                ) :: Radio Interferometric Image Reconstruction
                    =         ''        #   Name of input visibility file(s)
      a             =       True        #   Enable data selection parameters
      d             =         ''        #   field(s) to select
                    =         ''        #   spw(s)/channels to select
      range         =         ''        #   Range of time to select from data
      nge           =         ''        #   Select data within uvrange
      nna           =         ''        #   Select data based on antenna/baseline
                    =         ''        #   Scan number range
      rvation       =         ''        #   Observation ID range
      ntent         =         ''        #   Scan Intent(s)

datacolumn          = 'corrected'       #   Data column to image(data,corrected)
imagename           =         ''        #   Pre-name of output images
imsize              =      [100]        #   Number of pixels
cell                = ['1arcsec']       #   Cell size
phasecenter         =         ''        #   Phase center of the image
stokes              =        'I'        #   Stokes Planes to make
projection          =      'SIN'        #   Coordinate projection (SIN, HPX)
startmodel          =         ''        #   Name of starting model image
specmode            =      'mfs'        #   Spectral definition mode
                                        #    (mfs,cube,cubedata)
     reffreq        =         ''        #   Reference frequency

gridder             = 'standard'        #   Gridding options (standard, wproject,
                                        #    widefield, mosaic, awproject)
     vptable        =         ''        #   Name of Voltage Pattern table
     pblimit        =        0.2        #   >PB gain level at which to cut off
                                        #    normalizations

deconvolver         = 'multiscale'      #   Minor cycle algorithm (hogbom,clark,m
                                        #    ultiscale,mtmfs,mem,clarkstokes)
     scales         =         []        #   List of scale sizes (in pixels) for
                                        #    multi-scale algorithms
     smallscalebias =        0.6        #   A bias towards smaller scale sizes

restoration         =       True        #   Do restoration steps (or not)
     restoringbeam  =         []        #   Restoring beam shape to use. Default
                                        #    is the PSF main lobe
     pbcor          =      False        #   Apply PB correction on the output
                                        #    restored image

outlierfile         =                   #   Name of outlier-field image
                                        #    definitions
weighting           =  'natural'        #   Weighting scheme
                                        #    (natural,uniform,briggs)
     uvtaper        =         []        #   uv-taper on outer baselines in uv-
                                        #    plane

niter               =          0        #   Maximum number of iterations
usemask             =     'user'        #   Type of mask(s) for deconvolution
                                        #    (user, pb, auto-thresh, auto-
                                        #    thresh2, or auto-multithresh)
     mask           =         ''        #   Mask (a list of image name(s) or
                                        #    region file(s) or region string(s) )
     pbmask         =        0.0        #   primary beam mask

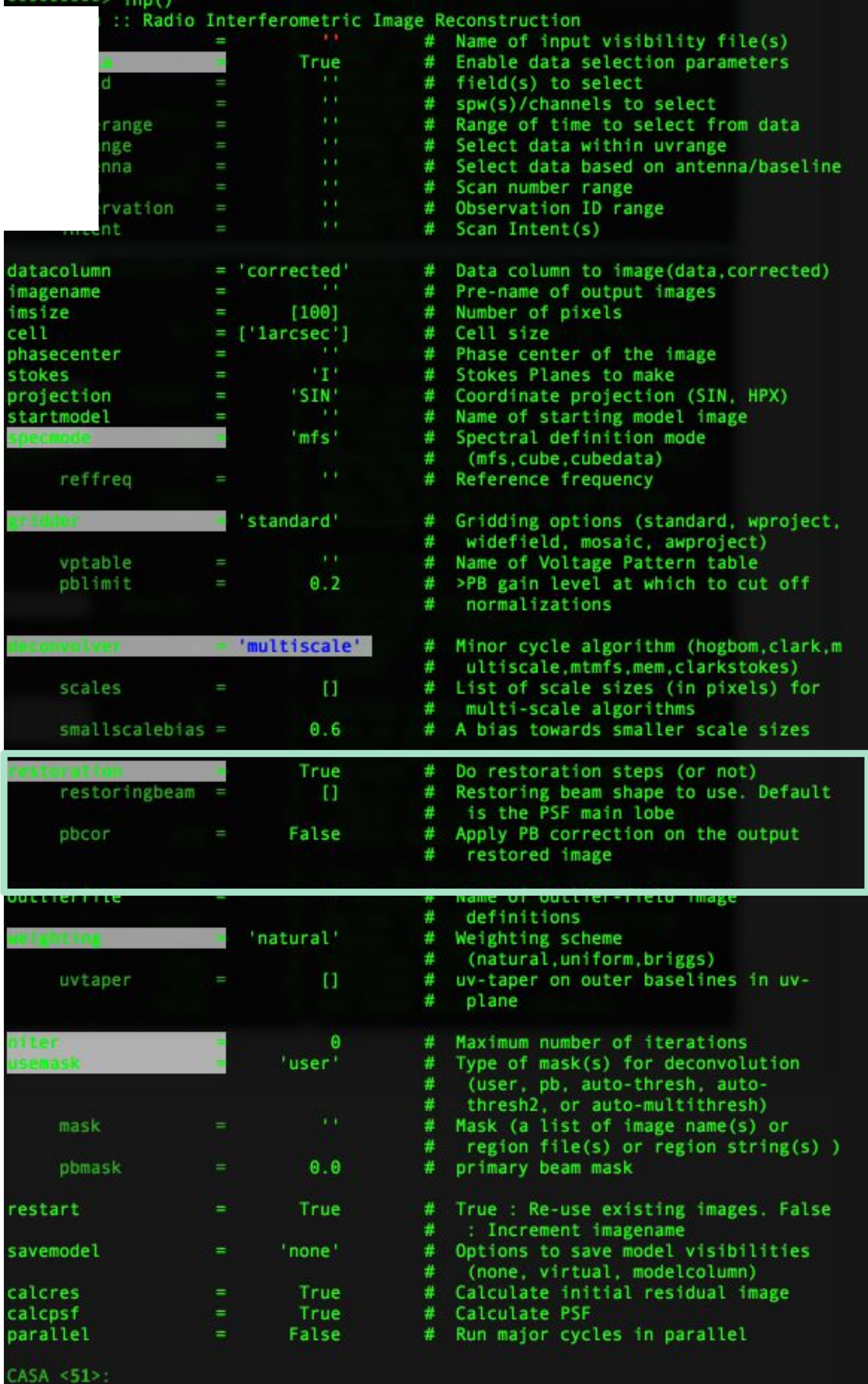
restart             =       True        #   True : Re-use existing images. False
                                        #    : Increment imagename
savemodel           =     'none'        #   Options to save model visibilities
                                        #    (none, virtual, modelcolumn)
calcres             =       True        #   Calculate initial residual image
calcpsf             =       True        #   Calculate PSF
parallel            =      False        #   Run major cycles in parallel

CASA <51>:
```

Restoration options: restoringbeam

restoringbeam='common'

- gives same beam across an entire cube.
- Recommended to run this in serial mode because of how parallel cube mode is currently implemented.
- Can clean cube in parallel mode, then restart in serial mode with restoringbeam='common' to get a common beam
    - This is what the Cycle 7 pipeline does currently.



```
 :: Radio Interferometric Image Reconstruction
                    =         ''          #  Name of input visibility file(s)
    a               =       True          #  Enable data selection parameters
    d               =         ''          #  field(s) to select
                    =         ''          #  spw(s)/channels to select
    range           =         ''          #  Range of time to select from data
    nge             =         ''          #  Select data within uvrange
    nna             =         ''          #  Select data based on antenna/baseline
                    =         ''          #  Scan number range
    rvation         =         ''          #  Observation ID range
    ntent           =         ''          #  Scan Intent(s)

datacolumn          = 'corrected'         #  Data column to image(data,corrected)
imagename           =         ''          #  Pre-name of output images
imsize              =      [100]          #  Number of pixels
cell                = ['1arcsec']         #  Cell size
phasecenter         =         ''          #  Phase center of the image
stokes              =        'I'          #  Stokes Planes to make
projection          =      'SIN'          #  Coordinate projection (SIN, HPX)
startmodel          =         ''          #  Name of starting model image
specmode            =      'mfs'          #  Spectral definition mode
                                          #   (mfs,cube,cubedata)
     reffreq        =         ''          #  Reference frequency

gridder             = 'standard'          #  Gridding options (standard, wproject,
                                          #   widefield, mosaic, awproject)
     vptable        =         ''          #  Name of Voltage Pattern table
     pblimit        =        0.2          #  >PB gain level at which to cut off
                                          #   normalizations

deconvolver         = 'multiscale'        #  Minor cycle algorithm (hogbom,clark,m
                                          #   ultiscale,mtmfs,mem,clarkstokes)
     scales         =         []          #  List of scale sizes (in pixels) for
                                          #   multi-scale algorithms
     smallscalebias =        0.6          #  A bias towards smaller scale sizes

restoration         =       True          #  Do restoration steps (or not)
     restoringbeam  =         []          #  Restoring beam shape to use. Default
                                          #   is the PSF main lobe
     pbcor          =      False          #  Apply PB correction on the output
                                          #   restored image

outlierfile         =                     #  Name of outlier-field image
                                          #   definitions
weighting           =  'natural'          #  Weighting scheme
                                          #   (natural,uniform,briggs)
     uvtaper        =         []          #  uv-taper on outer baselines in uv-
                                          #   plane

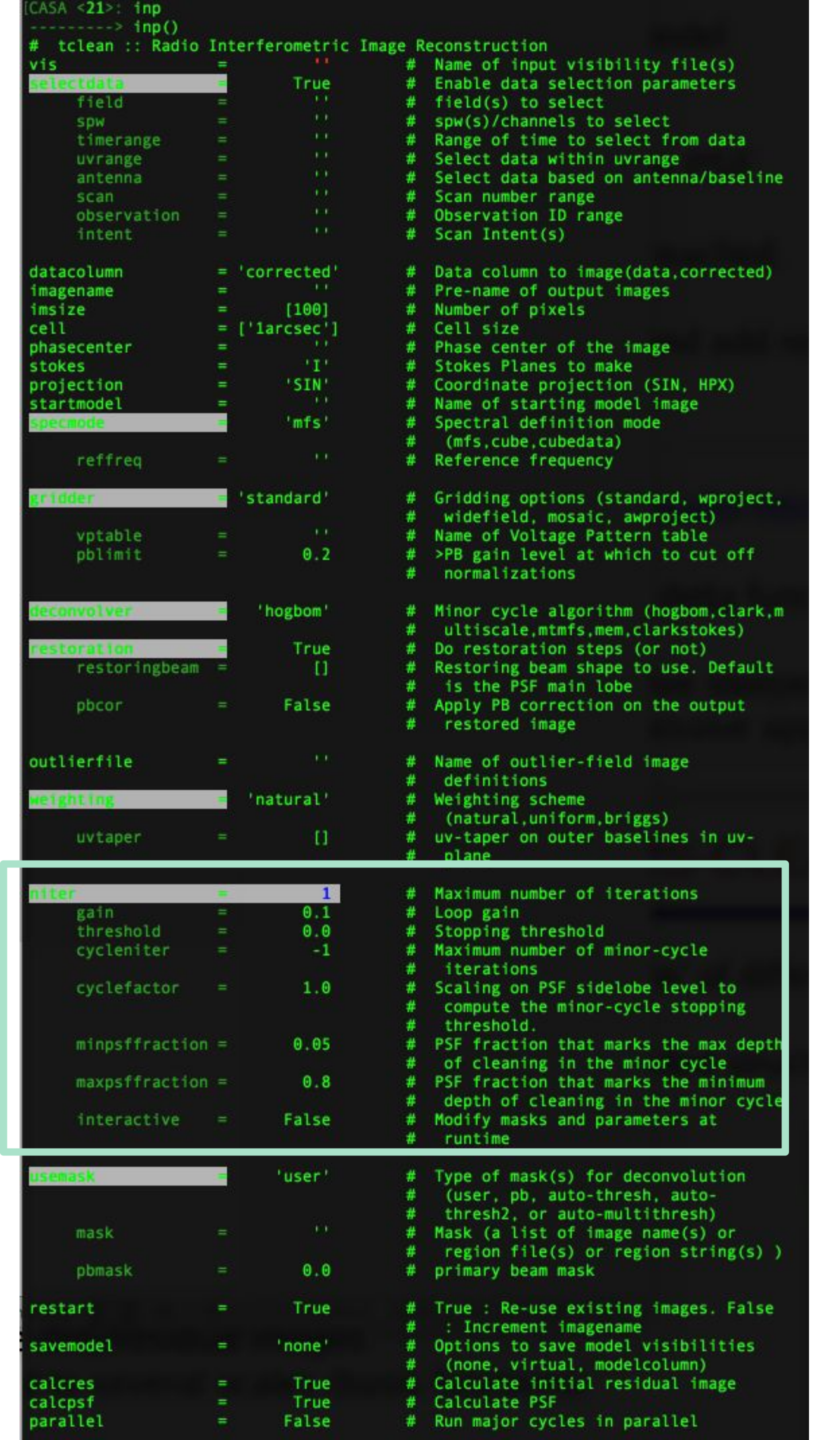
niter               =          0          #  Maximum number of iterations
usemask             =     'user'          #  Type of mask(s) for deconvolution
                                          #   (user, pb, auto-thresh, auto-
                                          #   thresh2, or auto-multithresh)
     mask           =         ''          #  Mask (a list of image name(s) or
                                          #   region file(s) or region string(s) )
     pbmask         =        0.0          #  primary beam mask

restart             =       True          #  True : Re-use existing images. False
                                          #   : Increment imagename
savemodel           =     'none'          #  Options to save model visibilities
                                          #   (none, virtual, modelcolumn)
calcres             =       True          #  Calculate initial residual image
calcpsf             =       True          #  Calculate PSF
parallel            =      False          #  Run major cycles in parallel

CASA <51>:
```

Stopping parameters

- Setting **niter**>0 exposes stopping parameters
- tclean stops when it completes the maximum number of iterations or when residuals go below the threshold level, whatever comes first.
  - Set **niter** to a large, but not too large, number
    - 1000 is a decent starting point
    - The more complex your image is the larger niter you will need
  - **threshold**='3mJy'
    - Usually some multiple of your noise level (1-3 sigma)
- **Interactive**=True
  - Allows you interactive control of tclean through the viewer
  - Choice of niter and threshold can be controlled through viewer
- Other parameters largely for power users
  - Gain can be useful for cases with extended emission (although see multi-scale clean)
  - cyclefactor, cycleniter, minpsffraction,maxpsffraction all control how often the minor cycle happens.



```
[CASA <21>: inp
---------> inp()
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =         ''        #  Name of input visibility file(s)
selectdata          =       True        #  Enable data selection parameters
     field          =         ''        #  field(s) to select
     spw            =         ''        #  spw(s)/channels to select
     timerange      =         ''        #  Range of time to select from data
     uvrange        =         ''        #  Select data within uvrange
     antenna        =         ''        #  Select data based on antenna/baseline
     scan           =         ''        #  Scan number range
     observation    =         ''        #  Observation ID range
     intent         =         ''        #  Scan Intent(s)

datacolumn          = 'corrected'       #  Data column to image(data,corrected)
imagename           =         ''        #  Pre-name of output images
imsize              =      [100]        #  Number of pixels
cell                = ['1arcsec']       #  Cell size
phasecenter         =         ''        #  Phase center of the image
stokes              =        'I'        #  Stokes Planes to make
projection          =      'SIN'        #  Coordinate projection (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             = 'standard'        #  Gridding options (standard, wproject,
                                        #   widefield, mosaic, awproject)
     vptable        =         ''        #  Name of Voltage Pattern table
     pblimit        =        0.2        #  >PB gain level at which to cut off
                                        #   normalizations

deconvolver         =   'hogbom'        #  Minor cycle algorithm (hogbom,clark,m
                                        #   ultiscale,mtmfs,mem,clarkstokes)
restoration         =       True        #  Do restoration steps (or not)
     restoringbeam  =         []        #  Restoring beam shape to use. Default
                                        #   is the PSF main lobe
     pbcor          =      False        #  Apply PB correction on the output
                                        #   restored image

outlierfile         =         ''        #  Name of outlier-field image
                                        #   definitions
weighting           =  'natural'        #  Weighting scheme
                                        #   (natural,uniform,briggs)
     uvtaper        =         []        #  uv-taper on outer baselines in uv-
                                        #   plane

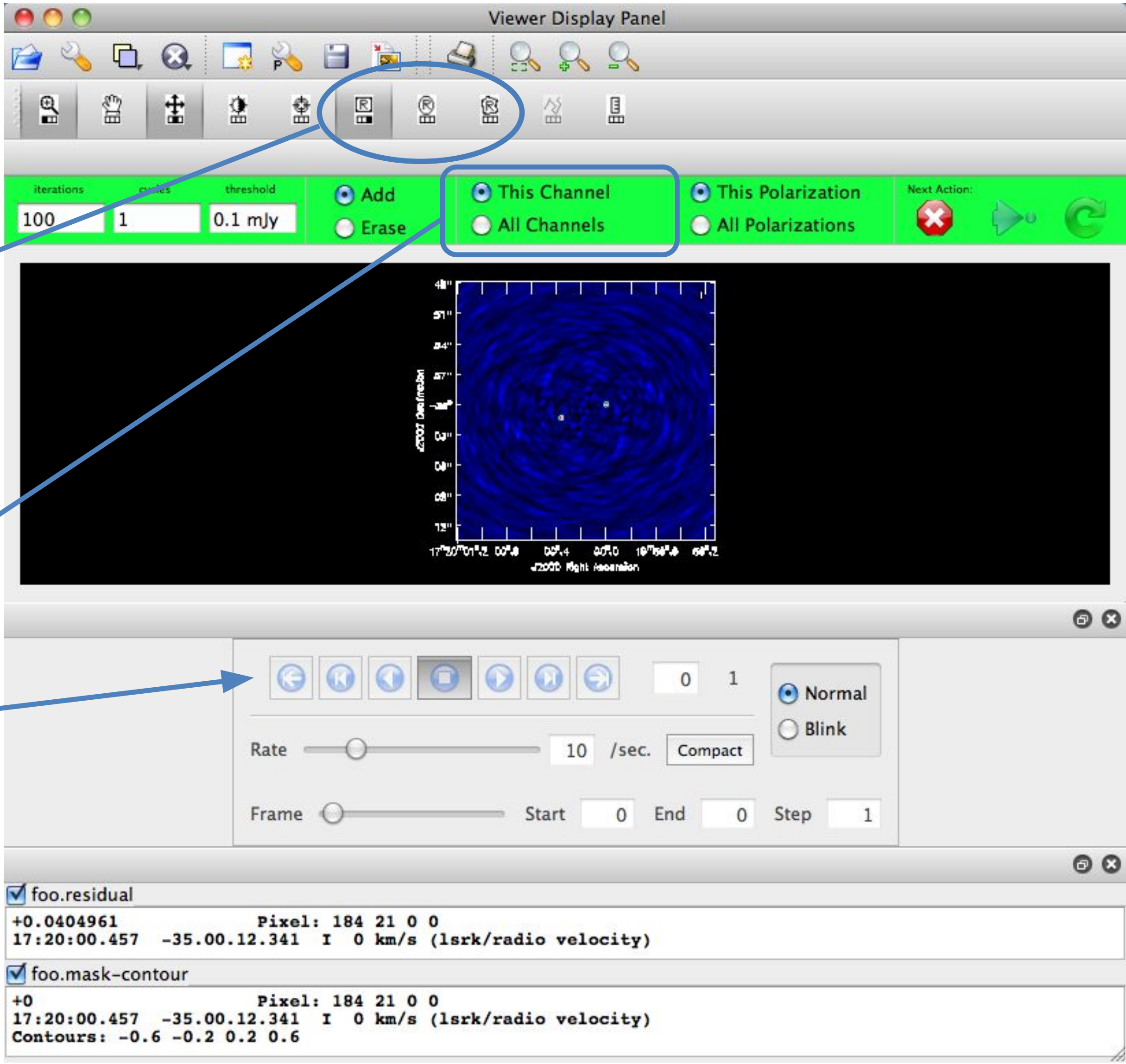
niter               =          1        #  Maximum number of iterations
     gain           =        0.1        #  Loop gain
     threshold      =        0.0        #  Stopping threshold
     cycleniter     =         -1        #  Maximum number of minor-cycle
                                        #   iterations
     cyclefactor    =        1.0        #  Scaling on PSF sidelobe level to
                                        #   compute the minor-cycle stopping
                                        #   threshold.
     minpsffraction =       0.05        #  PSF fraction that marks the max depth
                                        #   of cleaning in the minor cycle
     maxpsffraction =        0.8        #  PSF fraction that marks the minimum
                                        #   depth of cleaning in the minor cycle
     interactive    =      False        #  Modify masks and parameters at
                                        #   runtime

usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

restart             =       True        #  True : Re-use existing images. False
                                        #   : Increment imagename
savemodel           =     'none'        #  Options to save model visibilities
                                        #   (none, virtual, modelcolumn)
calcres             =       True        #  Calculate initial residual image
calcpsf             =       True        #  Calculate PSF
parallel            =      False        #  Run major cycles in parallel
```

Running TCLEAN interactively

- residual image in viewer
- define a mask with defining a mouse button on shape type
- define the same mask for all channels
- or iterate through the channels with the tape deck and define separate masks



iterations 100 cycles 1 threshold 0.1 mJy

● Add ○ Erase

● This Channel ○ All Channels

● This Polarization ○ All Polarizations

0 1 ● Normal ○ Blink

Rate 10 /sec.

Frame Start 0 End 0 Step 1

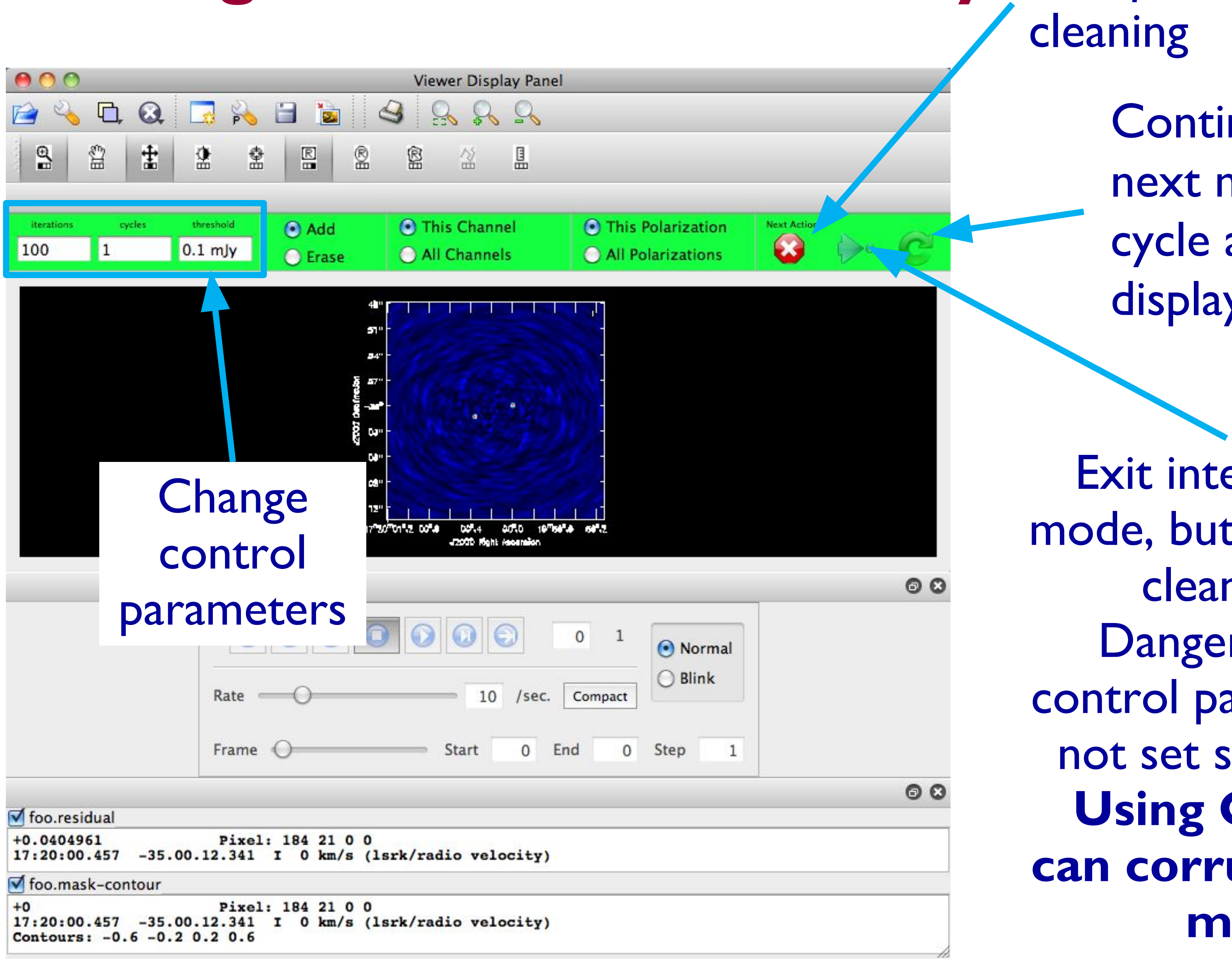
☑ foo.residual

```
+0.0404961            Pixel: 184 21 0 0
17:20:00.457  -35.00.12.341  I  0 km/s (lsrk/radio velocity)
```

☑ foo.mask-contour

```
+0                    Pixel: 184 21 0 0
17:20:00.457  -35.00.12.341  I  0 km/s (lsrk/radio velocity)
Contours: -0.6 -0.2 0.2 0.6
```

Running TCLEAN interactively



iterations	cycles	threshold
100	1	0.1 mJy

● Add ○ Erase

● This Channel ○ All Channels

● This Polarization ○ All Polarizations

0 1

● Normal ○ Blink

Rate 10 /sec. Compact

Frame Start 0 End 0 Step 1

☑ foo.residual

```
+0.0404961              Pixel: 184 21 0 0
17:20:00.457  -35.00.12.341   I   0 km/s (lsrk/radio velocity)
```

☑ foo.mask-contour

```
+0                      Pixel: 184 21 0 0
17:20:00.457  -35.00.12.341   I   0 km/s (lsrk/radio velocity)
Contours: -0.6 -0.2 0.2 0.6
```

Change control parameters

Stop cleaning

Continue for next major cycle and display residual

Exit interactive mode, but continue cleaning. Dangerous if control parameters not set sensibly!! **Using Ctrl+C can corrupt your ms.**

Output of TCLEAN

Minimally:

my_image.pb	Primary beam model
my_image.image	Cleaned and restored image (Jy/clean beam)
my_image.mask	Clean “boxes”
my_image.model	Clean components (Jy/pixel)
my_image.psf	Dirty beam
my_image.residual	Residual (Jy/dirty beam)
my_image.sumwt	Sum of weights

Wide-field imaging, multi-term, and parallel imaging will produce additional products.

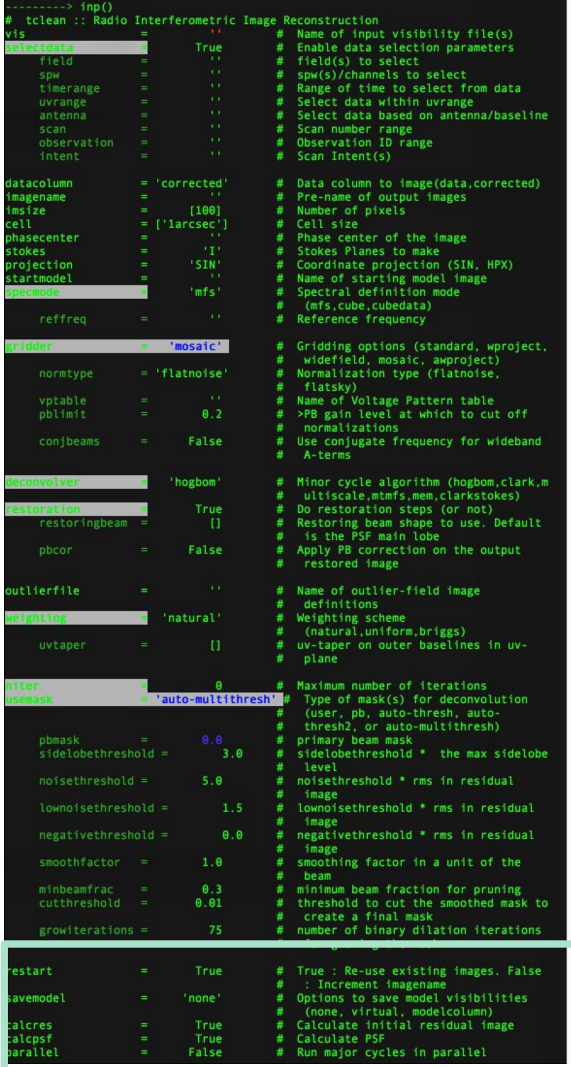
Together images can be used in subsequent tclean runs if necessary. It’s good practice not to delete subsets of images.

Advanced usage: tclean can be restarted

- restart=True
  - If tclean is started again with same image name, it will try to continue deconvolution from where it left off. Make sure this is what you want. If not, give a new name or remove existing files with rmtables('my_image.*')
- restart=False
  - If tclean is started again with same image name, increment the image name, and start the clean process from the beginning.
- calcpsf and calcresid
  - Controls whether or not tclean calculates the psf and residual or uses what's on disk.
- Also: try NOT to do CTRL+C as it could corrupt your MS when it touches the visibilities in a major cycle.

Advanced usage: automasking

- **usemask='auto-multithresh'**
- Used by the ALMA Pipeline starting in Cycle 5. Also available to users as a tclean option.
- Default parameters generally good for ALMA 12m data
- General purpose algorithm so works for ALMA, VLA, ATCA, etc.
- casaguide: https://casaguides.nrao.edu/index.php/Automasking_Guide
- Paper: Kepley et al. 2020, PASP, 132, 1008, 02405



```
---------> inp()
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =         ''         #  Name of input visibility file(s)
selectdata          =       True         #  Enable data selection parameters
     field          =         ''         #  field(s) to select
     spw            =         ''         #  spw(s)/channels to select
     timerange      =         ''         #  Range of time to select from data
     uvrange        =         ''         #  Select data within uvrange
     antenna        =         ''         #  Select data based on antenna/baseline
     scan           =         ''         #  Scan number range
     observation    =         ''         #  Observation ID range
     intent         =         ''         #  Scan Intent(s)

datacolumn          = 'corrected'        #  Data column to image(data,corrected)
imagename           =         ''         #  Pre-name of output images
imsize              =      [100]         #  Number of pixels
cell                = ['1arcsec']        #  Cell size
phasecenter         =         ''         #  Phase center of the image
stokes              =        'I'         #  Stokes Planes to make
projection          =      'SIN'         #  Coordinate projection (SIN, HPX)
startmodel          =         ''         #  Name of starting model image
specmode            =      'mfs'         #  Spectral definition mode
                                         #   (mfs,cube,cubedata)
     reffreq        =         ''         #  Reference frequency

gridder             =   'mosaic'         #  Gridding options (standard, wproject,
                                         #   widefield, mosaic, awproject)
     normtype       = 'flatnoise'        #  Normalization type (flatnoise,
                                         #   flatsky)
     vptable        =         ''         #  Name of Voltage Pattern table
     pblimit        =        0.2         #  >PB gain level at which to cut off
                                         #   normalizations
     conjbeams      =      False         #  Use conjugate frequency for wideband
                                         #   A-terms

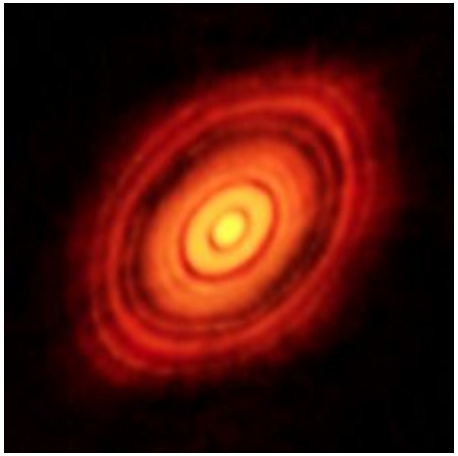
deconvolver         =   'hogbom'         #  Minor cycle algorithm (hogbom,clark,m
                                         #   ultiscale,mtmfs,mem,clarkstokes)
restoration         =       True         #  Do restoration steps (or not)
     restoringbeam  =         []         #  Restoring beam shape to use. Default
                                         #   is the PSF main lobe
     pbcor          =      False         #  Apply PB correction on the output
                                         #   restored image

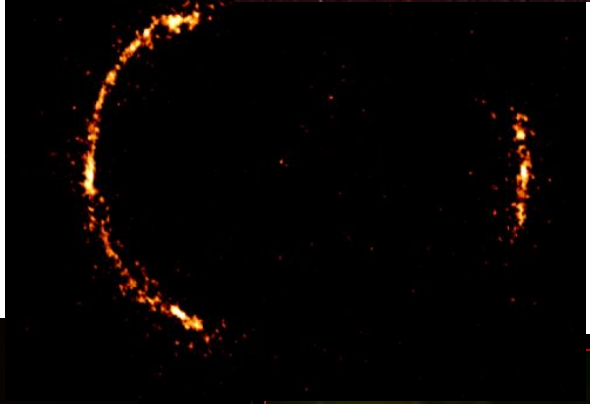
outlierfile         =         ''         #  Name of outlier-field image
                                         #   definitions
weighting           =  'natural'         #  Weighting scheme
                                         #   (natural,uniform,briggs)
     uvtaper        =         []         #  uv-taper on outer baselines in uv-
                                         #   plane

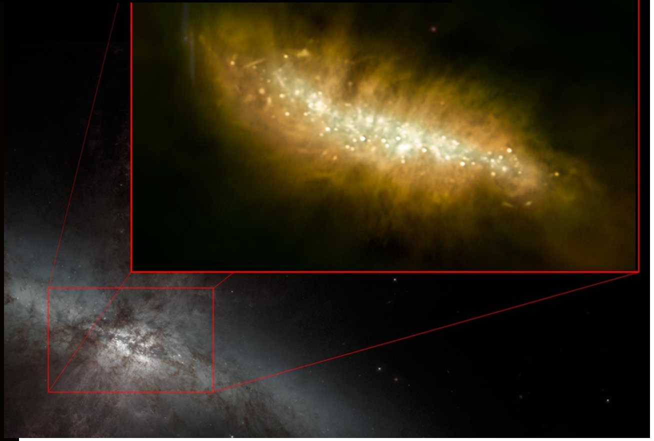
niter               =          0         #  Maximum number of iterations
usemask             = 'auto-multithresh' #  Type of mask(s) for deconvolution
                                         #   (user, pb, auto-thresh, auto-
                                         #   thresh2, or auto-multithresh)
     pbmask         =        0.0         #  primary beam mask
     sidelobethreshold =        3.0      #  sidelobethreshold *  the max sidelobe
                                         #   level
     noisethreshold =        5.0         #  noisethreshold * rms in residual
                                         #   image
     lownoisethreshold =        1.5      #  lownoisethreshold * rms in residual
                                         #   image
     negativethreshold =        0.0      #  negativethreshold * rms in residual
                                         #   image
     smoothfactor   =        1.0         #  smoothing factor in a unit of the
                                         #   beam
     minbeamfrac    =        0.3         #  minimum beam fraction for pruning
     cutthreshold   =       0.01         #  threshold to cut the smoothed mask to
                                         #   create a final mask
     growiterations =         75         #  number of binary dilation iterations

estart              =       True         #  True : Re-use existing images. False
                                         #   : Increment imagename
avemodel            =     'none'         #  Options to save model visibilities
                                         #   (none, virtual, modelcolumn)
alcres              =       True         #  Calculate initial residual image
alcpsf              =       True         #  Calculate PSF
arallel             =      False         #  Run major cycles in parallel
```

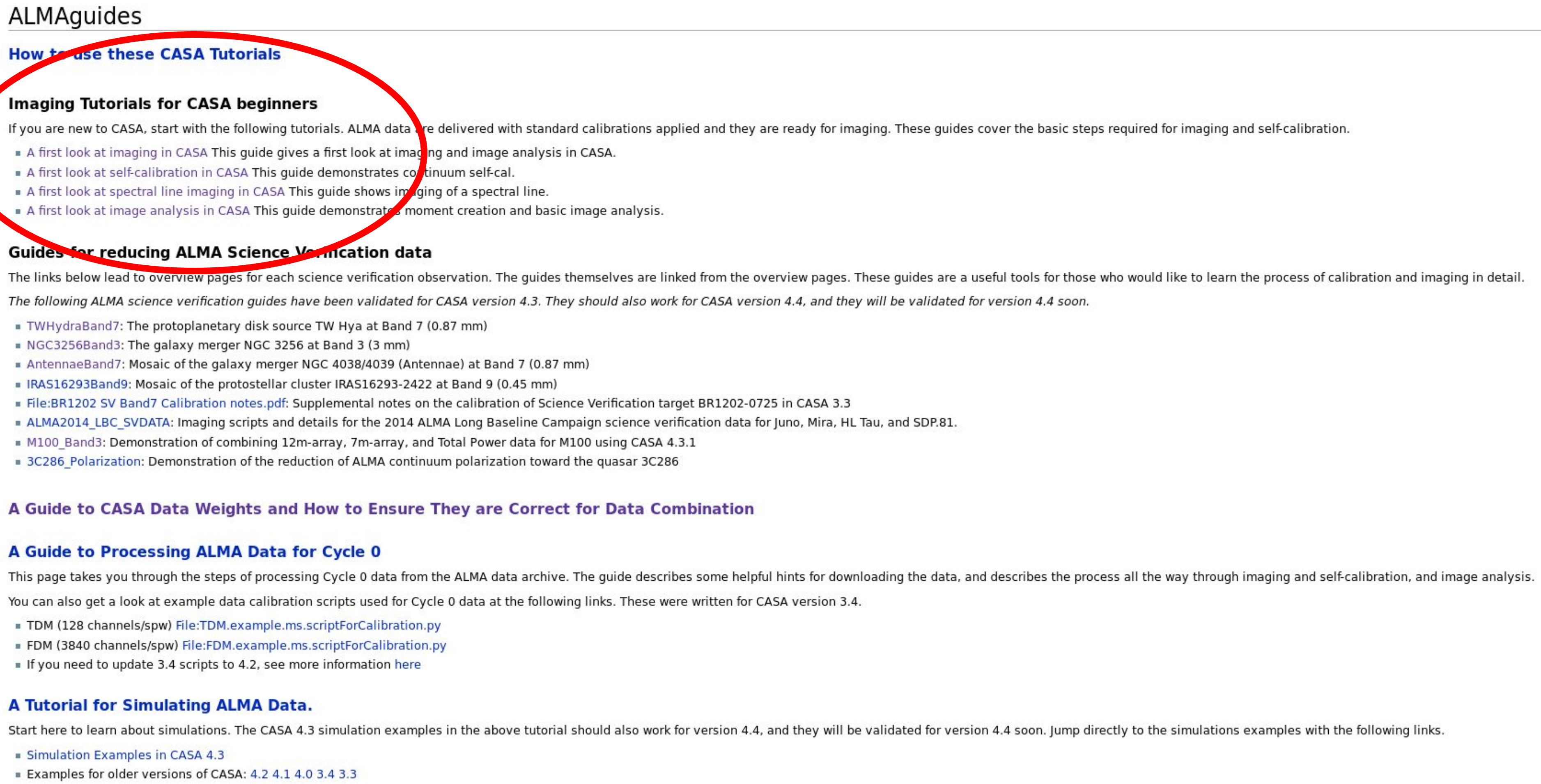
… some CASA images…







Looking ahead …



ALMAguides

How to use these CASA Tutorials

Imaging Tutorials for CASA beginners

If you are new to CASA, start with the following tutorials. ALMA data are delivered with standard calibrations applied and they are ready for imaging. These guides cover the basic steps required for imaging and self-calibration.

- A first look at imaging in CASA This guide gives a first look at imaging and image analysis in CASA.
- A first look at self-calibration in CASA This guide demonstrates continuum self-cal.
- A first look at spectral line imaging in CASA This guide shows imaging of a spectral line.
- A first look at image analysis in CASA This guide demonstrates moment creation and basic image analysis.

Guides for reducing ALMA Science Verification data

The links below lead to overview pages for each science verification observation. The guides themselves are linked from the overview pages. These guides are a useful tools for those who would like to learn the process of calibration and imaging in detail.

The following ALMA science verification guides have been validated for CASA version 4.3. They should also work for CASA version 4.4, and they will be validated for version 4.4 soon.

- TWHydraBand7: The protoplanetary disk source TW Hya at Band 7 (0.87 mm)
- NGC3256Band3: The galaxy merger NGC 3256 at Band 3 (3 mm)
- AntennaeBand7: Mosaic of the galaxy merger NGC 4038/4039 (Antennae) at Band 7 (0.87 mm)
- IRAS16293Band9: Mosaic of the protostellar cluster IRAS16293-2422 at Band 9 (0.45 mm)
- File:BR1202 SV Band7 Calibration notes.pdf: Supplemental notes on the calibration of Science Verification target BR1202-0725 in CASA 3.3
- ALMA2014_LBC_SVDATA: Imaging scripts and details for the 2014 ALMA Long Baseline Campaign science verification data for Juno, Mira, HL Tau, and SDP.81.
- M100_Band3: Demonstration of combining 12m-array, 7m-array, and Total Power data for M100 using CASA 4.3.1
- 3C286_Polarization: Demonstration of the reduction of ALMA continuum polarization toward the quasar 3C286

A Guide to CASA Data Weights and How to Ensure They are Correct for Data Combination

A Guide to Processing ALMA Data for Cycle 0

This page takes you through the steps of processing Cycle 0 data from the ALMA data archive. The guide describes some helpful hints for downloading the data, and describes the process all the way through imaging and self-calibration, and image analysis.

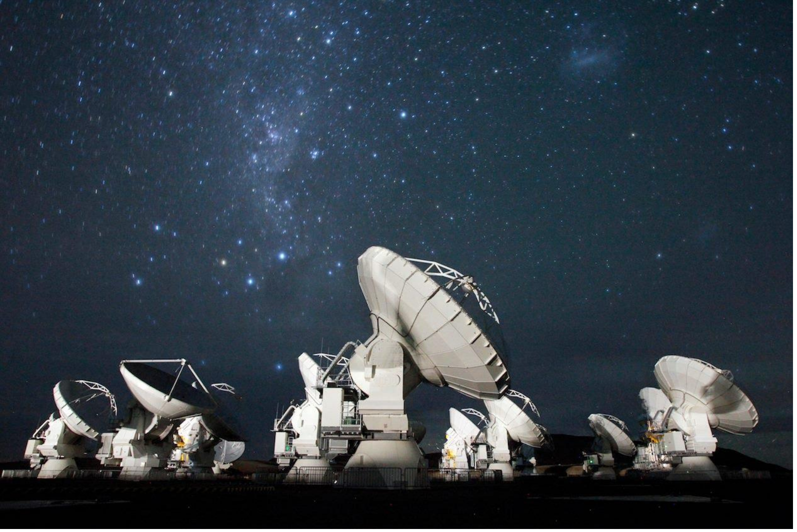
You can also get a look at example data calibration scripts used for Cycle 0 data at the following links. These were written for CASA version 3.4.

- TDM (128 channels/spw) File:TDM.example.ms.scriptForCalibration.py
- FDM (3840 channels/spw) File:FDM.example.ms.scriptForCalibration.py
- If you need to update 3.4 scripts to 4.2, see more information here

A Tutorial for Simulating ALMA Data.

Start here to learn about simulations. The CASA 4.3 simulation examples in the above tutorial should also work for version 4.4, and they will be validated for version 4.4 soon. Jump directly to the simulations examples with the following links.

- Simulation Examples in CASA 4.3
- Examples for older versions of CASA: 4.2 4.1 4.0 3.4 3.3



For more info:

http://www.almaobservatory.org

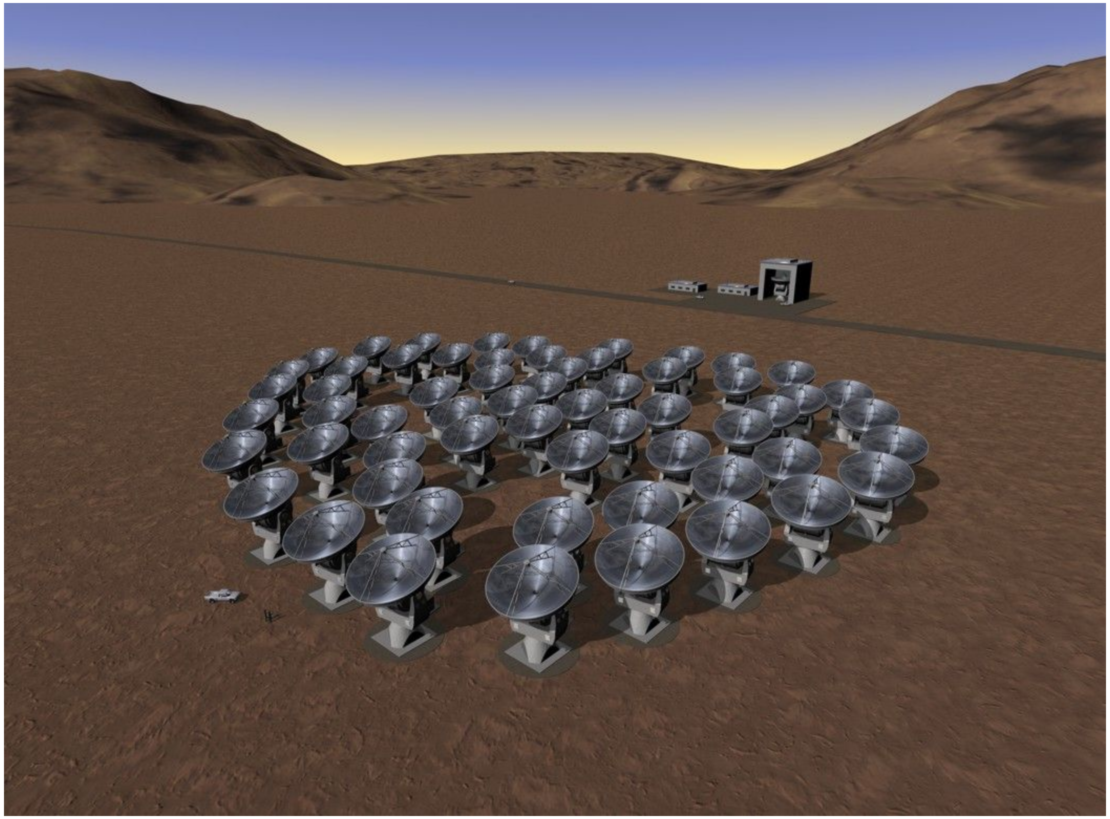
The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is a partnership of the European Organisation for Astronomical Research in the Southern Hemisphere (ESO), the U.S. National Science Foundation (NSF) and the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Republic of Chile. ALMA is funded by ESO on behalf of its Member States, by NSF in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and by NINS in cooperation with the Academia Sinica (AS) in Taiwan and the Korea Astronomy and Space Science Institute (KASI). ALMA construction and operations are led by ESO on behalf of its Member States; by the National Radio Astronomy Observatory (NRAO), managed by Associated Universities, Inc. (AUI), on behalf of North America; and by the National Astronomical Observatory of Japan (NAOJ) on behalf of East Asia. The Joint ALMA Observatory (JAO) provides the unified leadership and management of the construction, commissioning and operation of ALMA.

Additional Slides

Interferometry Basics

Single dish: diameter gives resolution

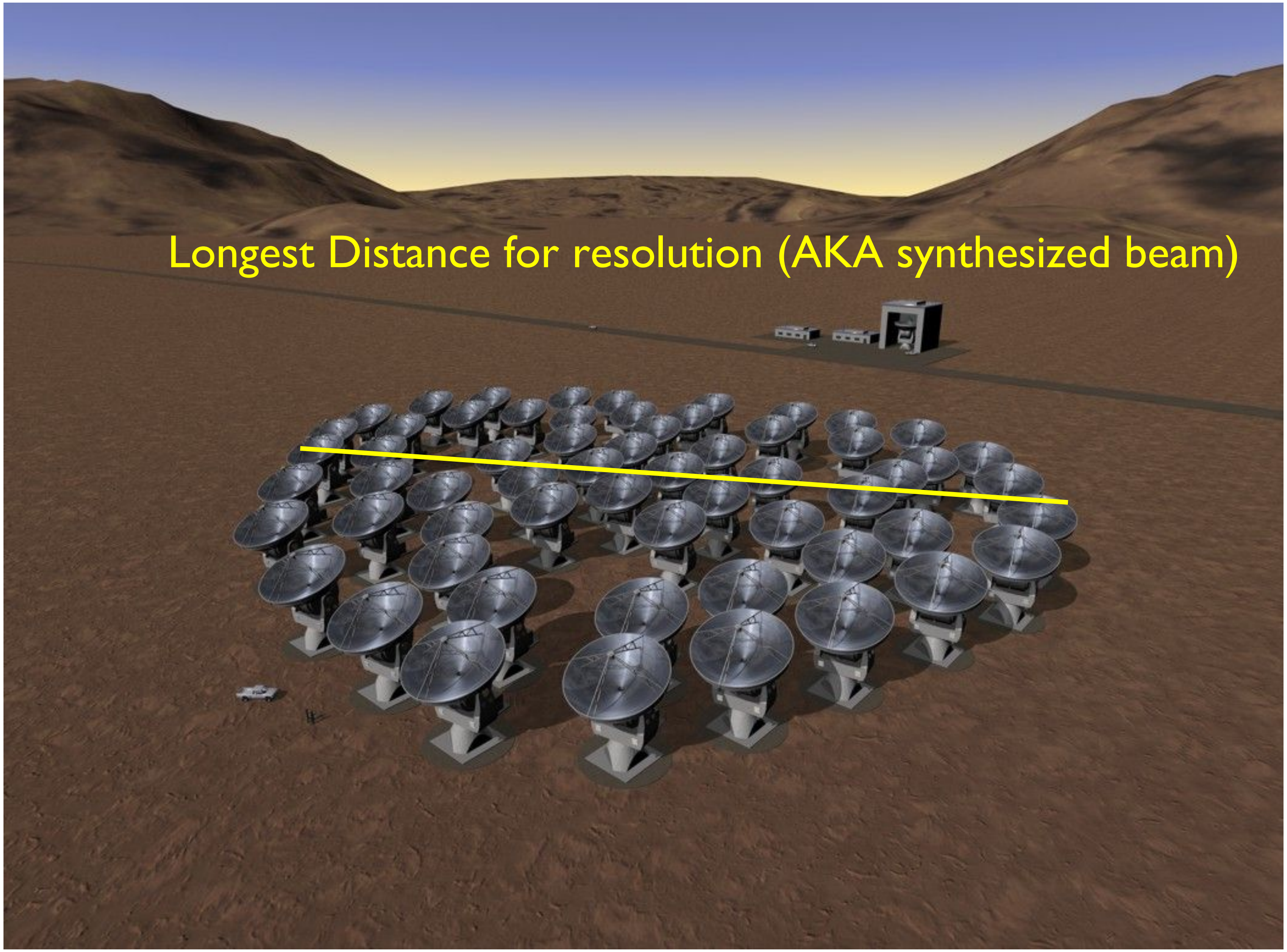
Interferometer: diameter gives FOV and the separation gives resolution



Interferometry Basics

Single dish: diameter gives resolution

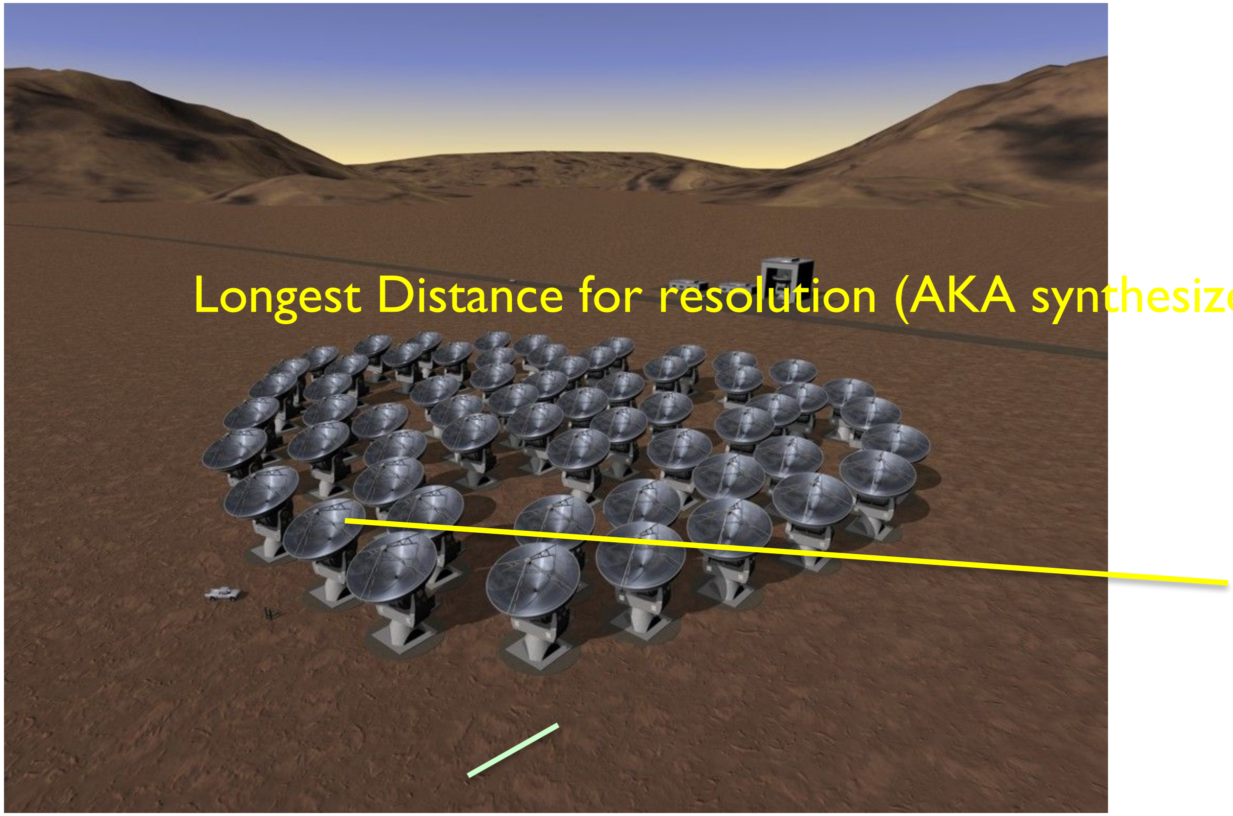
Interferometer: diameter gives FOV and the separation gives resolution



Interferometry Basics

Single dish: diameter gives resolution

Interferometer: diameter gives FOV and the separation gives resolution



Longest Distance for resolution (AKA synthesized beam)

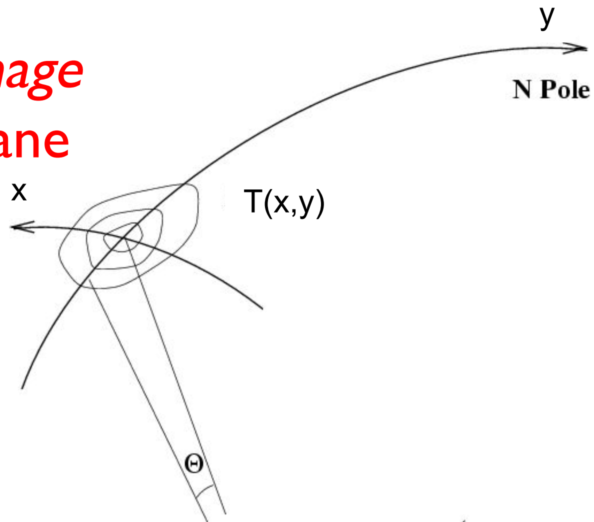
Diameter of Single element: Field of View (AKA primary beam)

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)

(van Cittert-Zernike theorem)

image plane



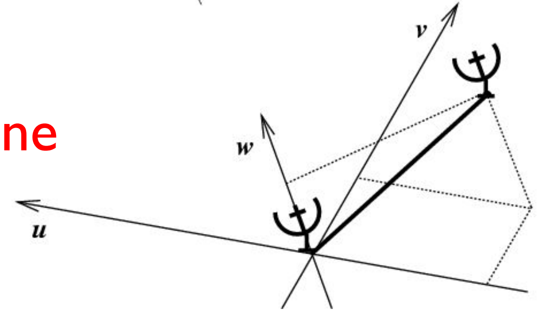
Fourier space/domain

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

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

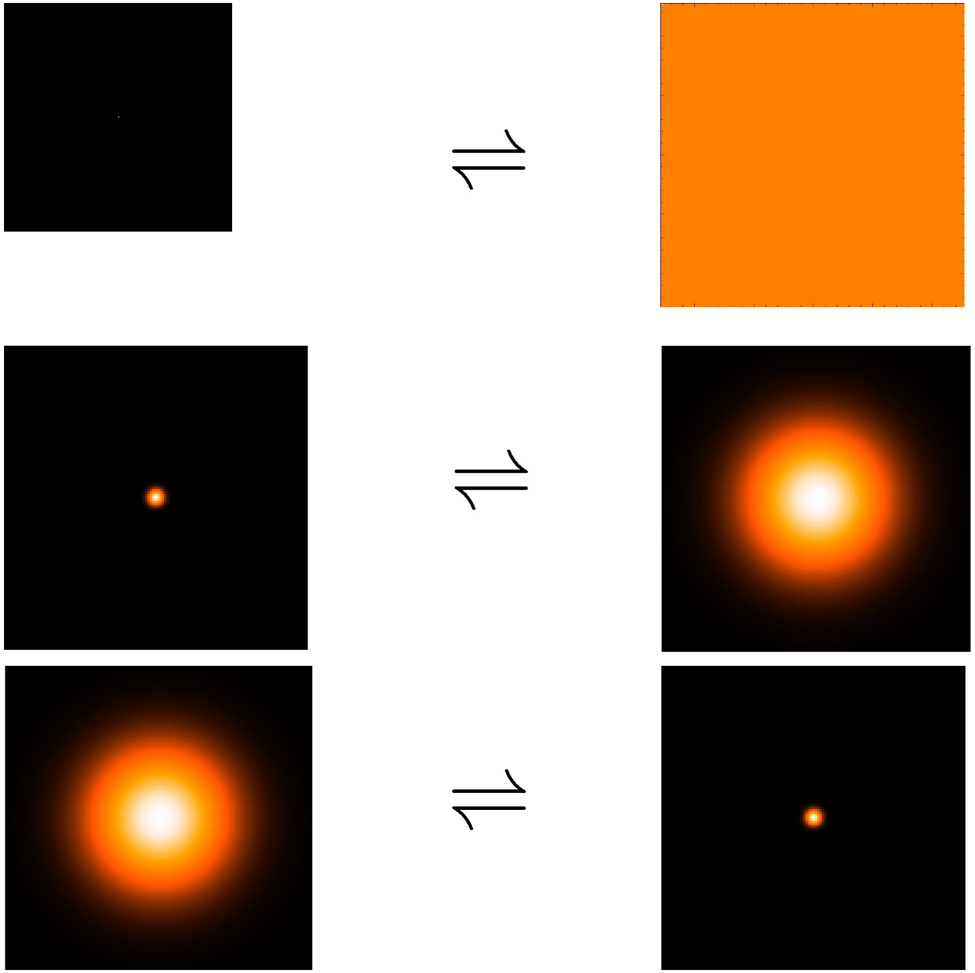
Image space/domain

uv plane



Some 2D Fourier Transform Pairs

T(x,y) Amp{V(u,v)}



δ Function Constant

Gaussian Gaussian

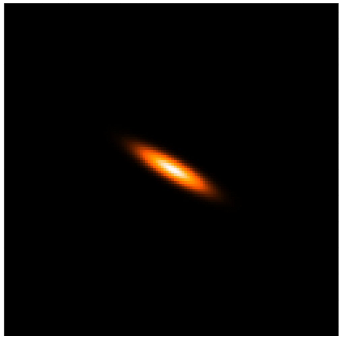
Gaussian Gaussian

narrow features transform to wide features (and vice-versa)

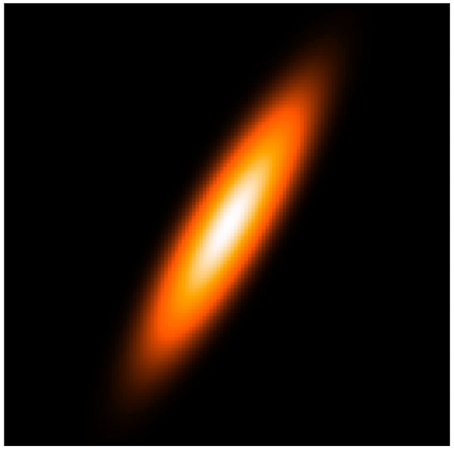
More 2D Fourier Transform Pairs

T(x,y) Amp{V(u,v)}

elliptical Gaussian

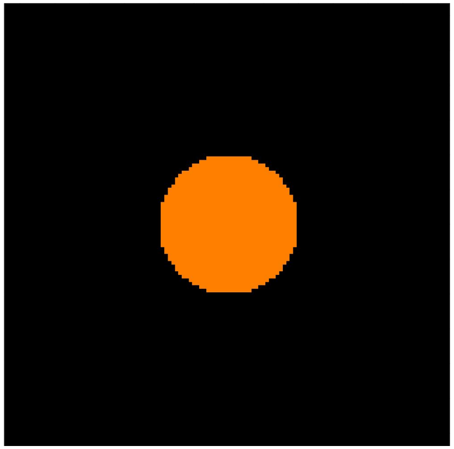


$\rightleftharpoons$

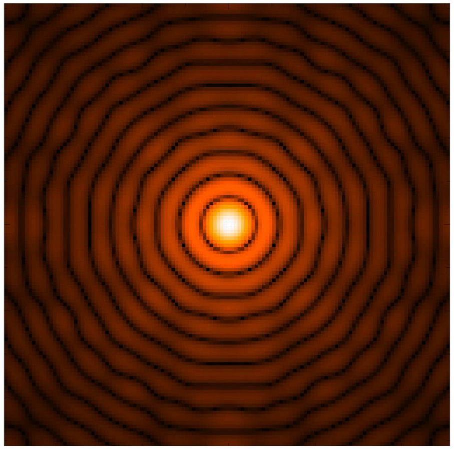


elliptical Gaussian

Disk



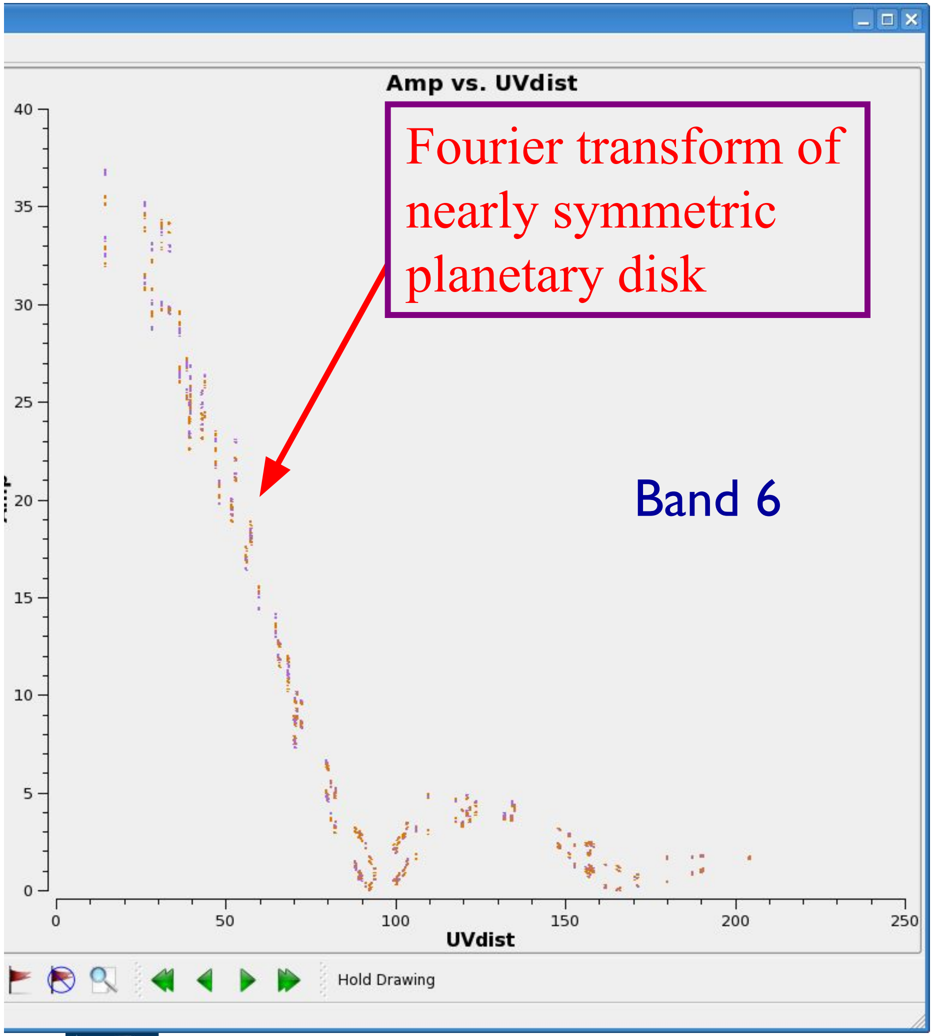
$\rightleftharpoons$



Bessel

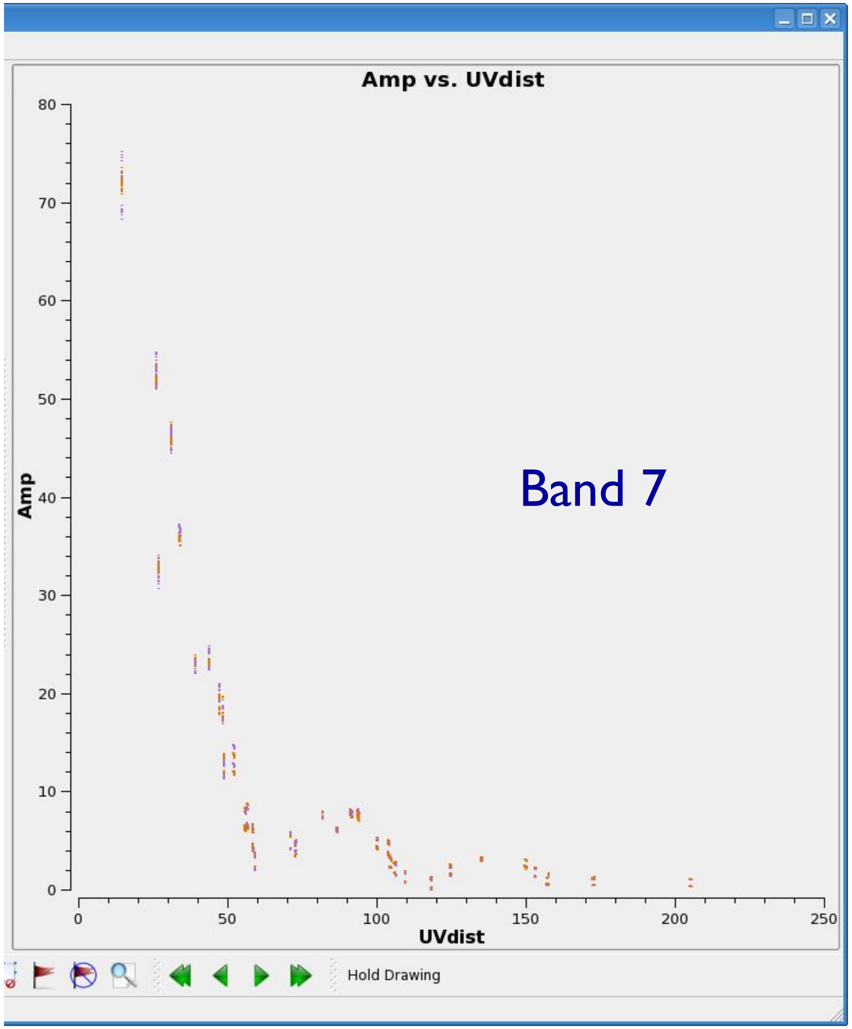
sharp edges result in many high spatial frequencies (sinc function, “ringing”, Gibbs phenomenon)

ALMA observes planetary disk



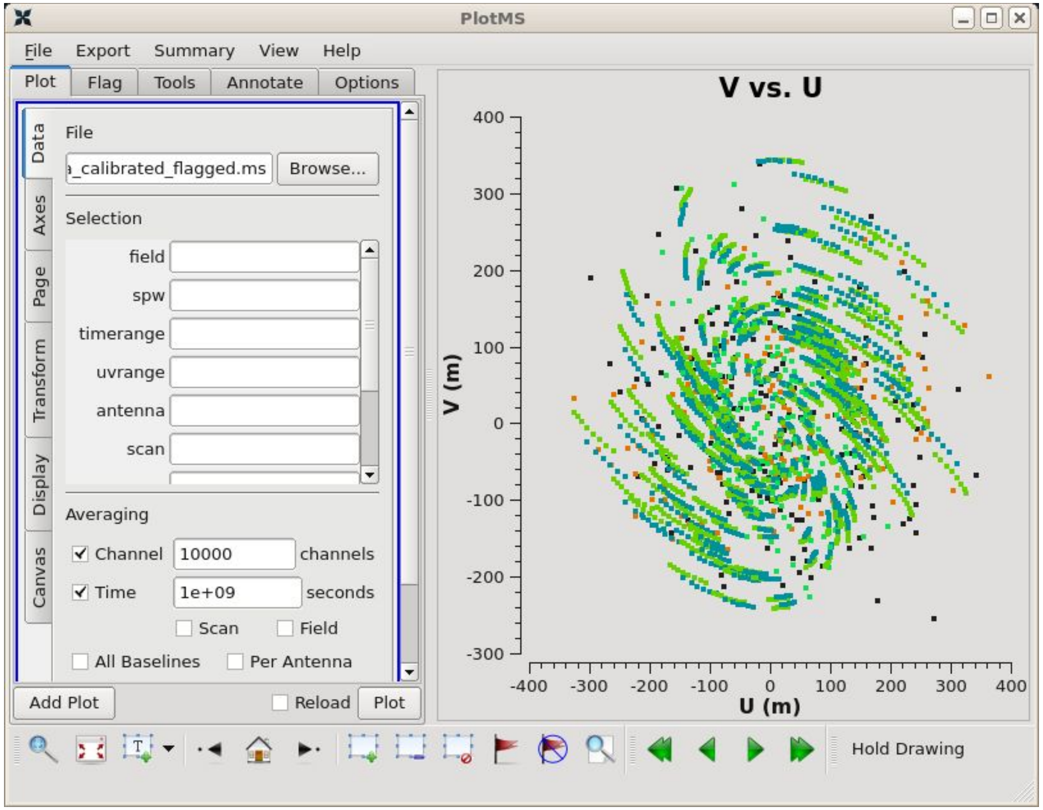
Fourier transform of nearly symmetric planetary disk

Band 6



Band 7

You can use the plotms task in CASA to examine your visibilities.



File

a_calibrated_flagged.ms

Selection

field

spw

timerange

uvrange

antenna

scan

Averaging

☑ Channel 10000 channels

☑ Time 1e+09 seconds

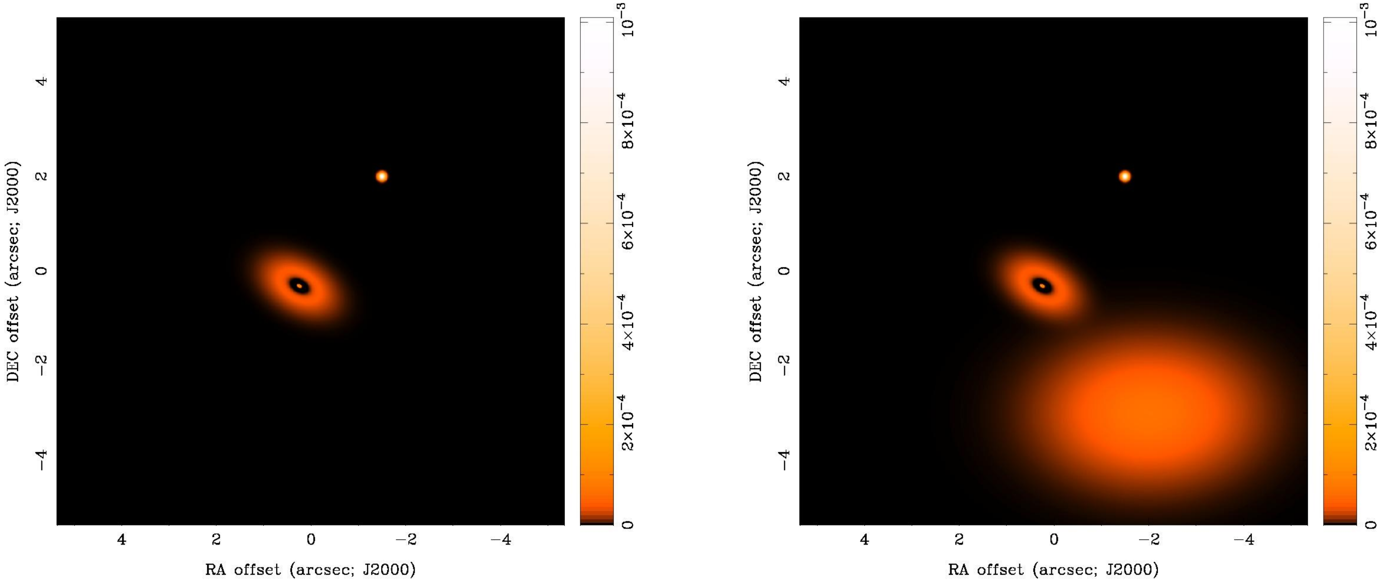
□ Scan □ Field

□ All Baselines □ Per Antenna

□ Reload

Remember: Important structure may be missed in central hole of (u,v) coverage

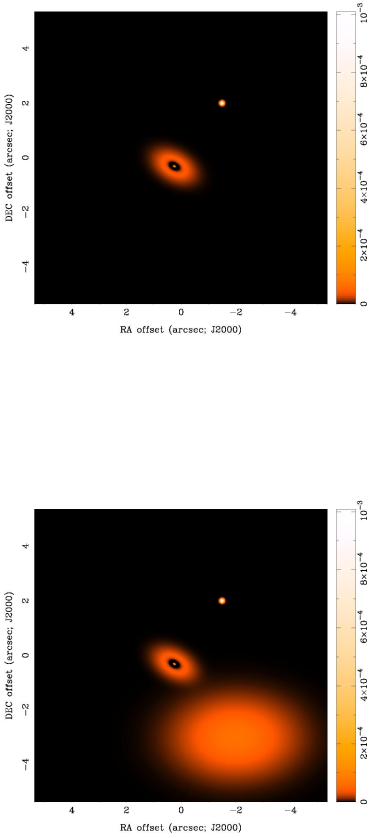
Do the visibilities observed in our example discriminate between these two models of the sky brightness distribution *T(l,m)*?



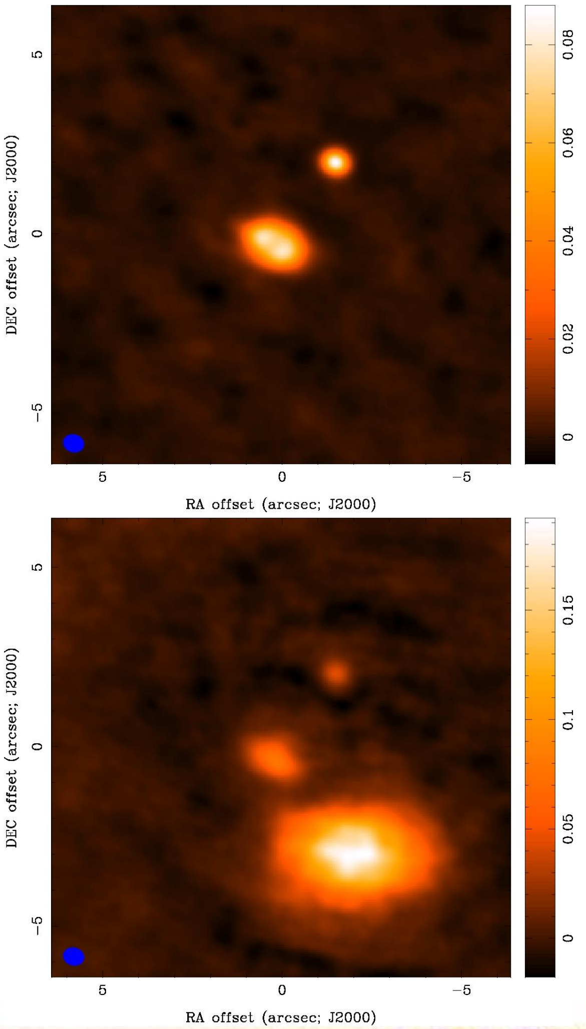
- Yes… but only on baselines shorter than about 75 kλ

Missing Short Spacings: Demonstration

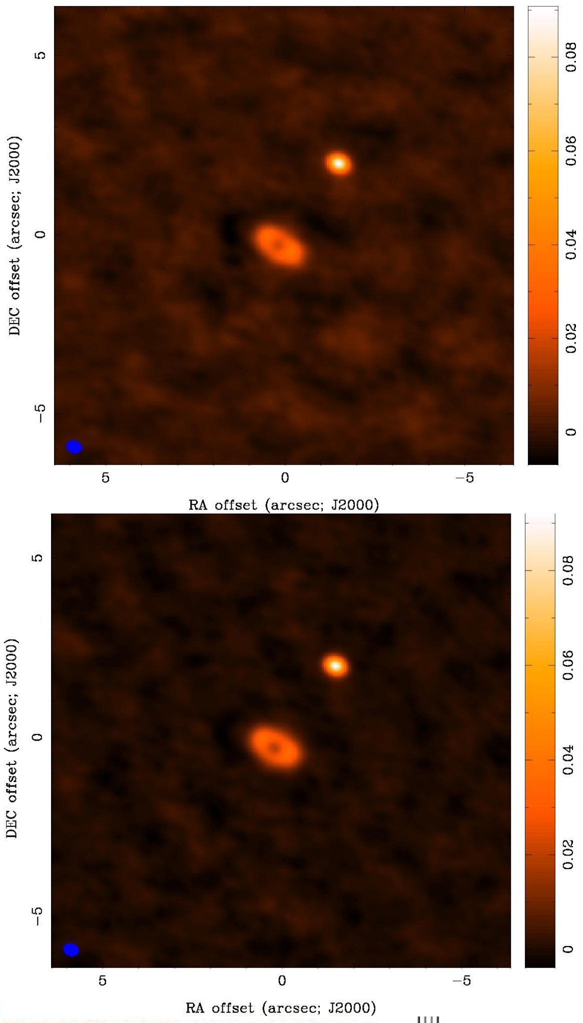
Sky Model



Full range of spatial scales

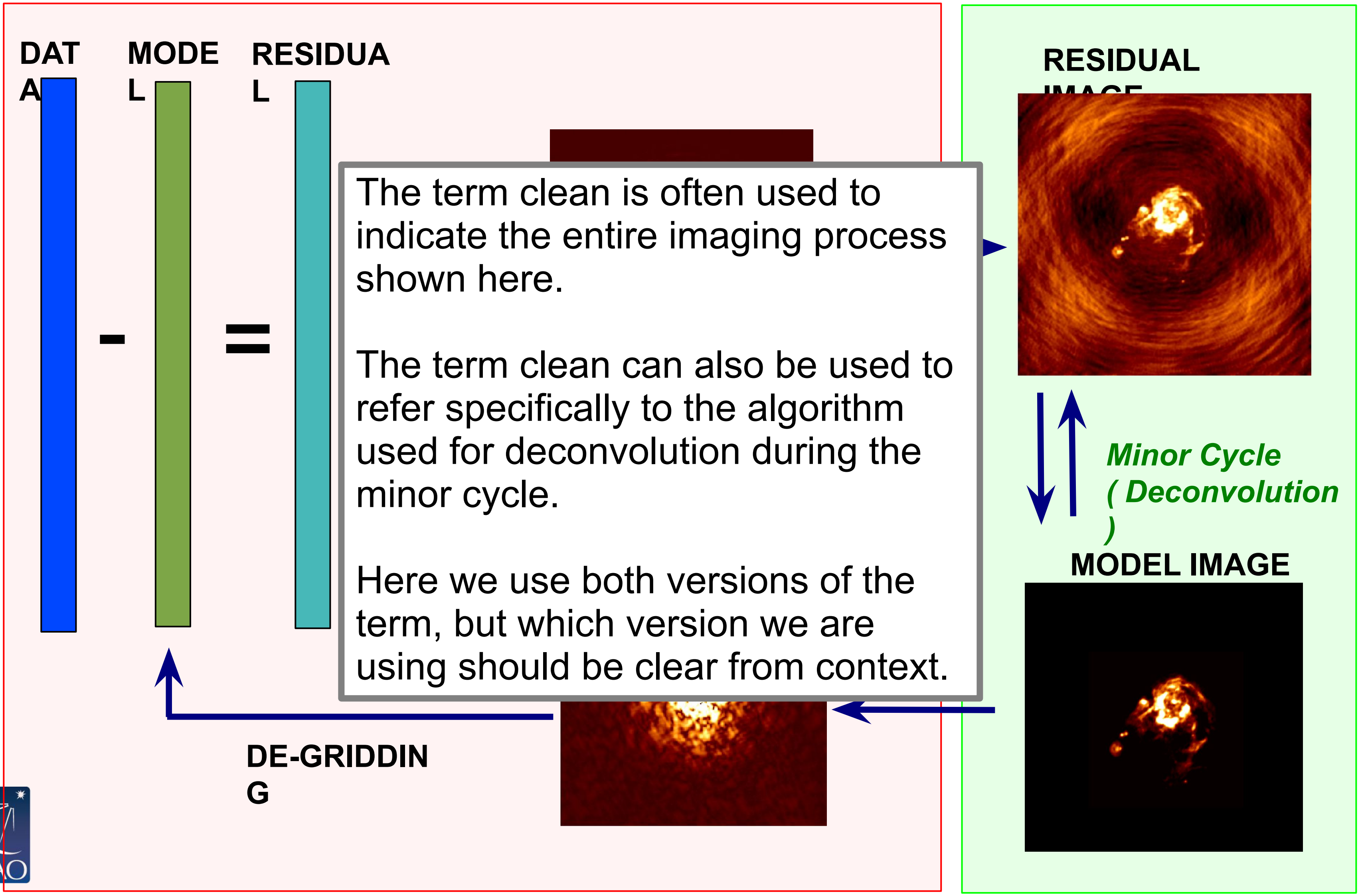


> 75 kλ i.e. cutting out a central hole



Courtesy D. Wilner

A note on terminology



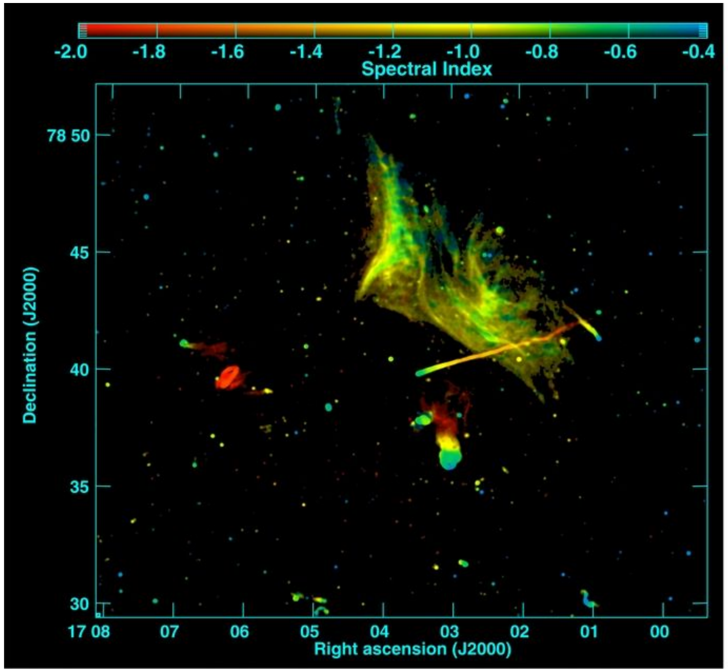
The term clean is often used to indicate the entire imaging process shown here.

The term clean can also be used to refer specifically to the algorithm used for deconvolution during the minor cycle.

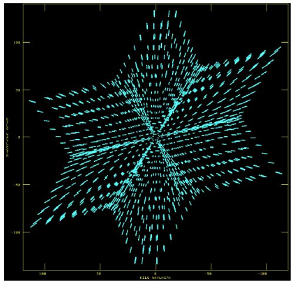
Here we use both versions of the term, but which version we are using should be clear from context.

Specmode options: Continuum Imaging

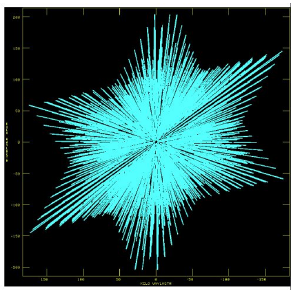
- specmode='mfs' if narrow bandwidth
- add deconvolver='mtmfs' if you have a fractional bandwidth for the aggregate continuum greater than 10% to use multi-term multi-frequency synthesis.
  - Only in ALMA Band 3 and the lower end of Band 4 can have fractional bandwidths of greater than 10% and only when both sidebands are employed.
  - nterm=2 compute spectral index, 3 for curvature etc.
  - tt0 average intensity, tt1 alpha*tt0, alpha images output
  - takes at least nterms longer (image size dependent)



Abell 2256; Owen et al. (2014)



Narrow BW



wide BW

(better uv-coverage)

Gridder options: mosaics

gridder='mosaic'

mosweight=True

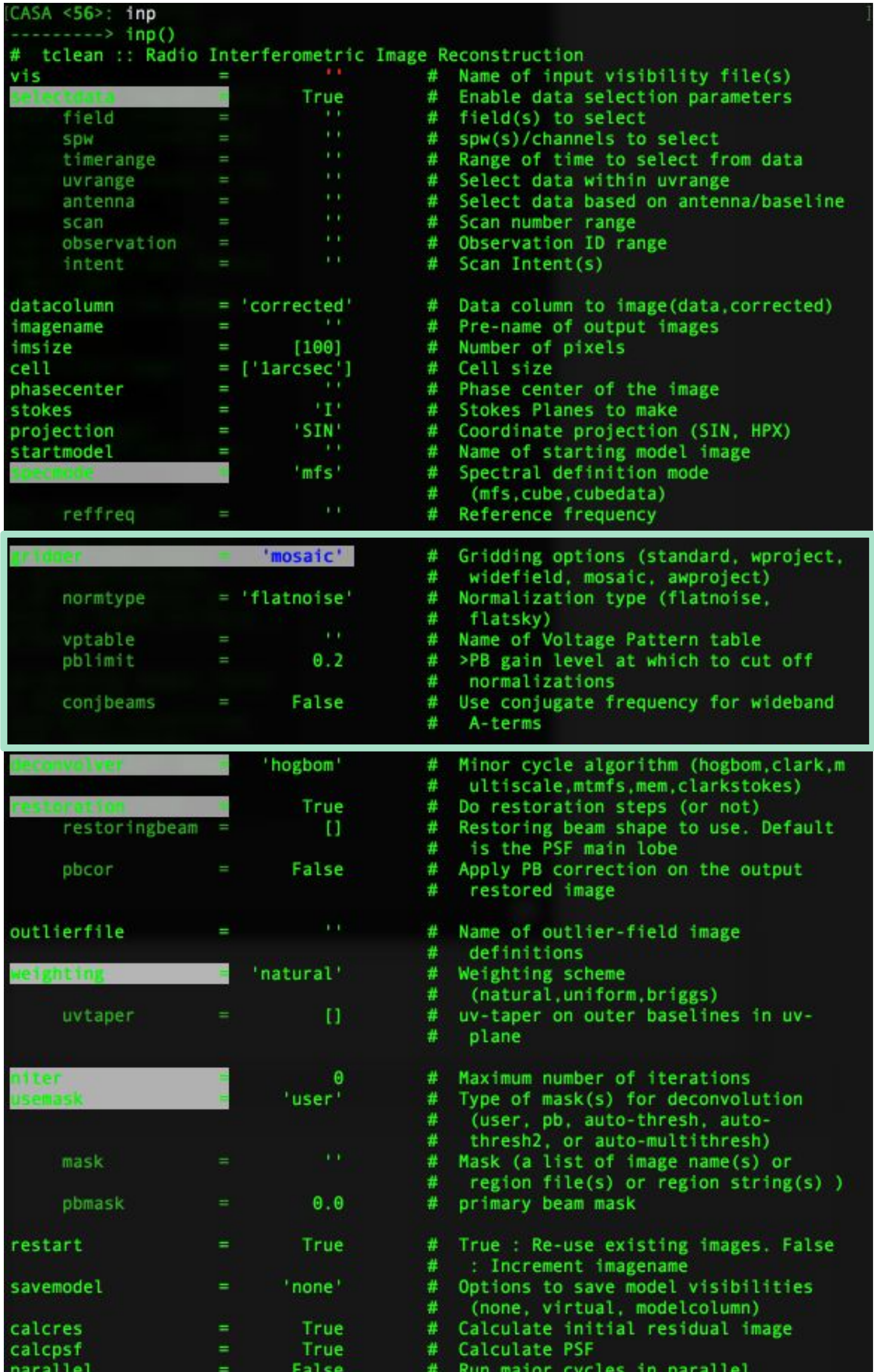
conjbeams=False

specify field for data, e.g., field='1~6'

Setting mosweight=True weights each field in the mosaic independently to avoid issues with non-uniform sensitivity for more uniform Briggs weighting values and poor uv-coverage.

ALMA recommends conjbeams=False (do not take into account the primary beam scaling with frequency).

There's a tool ("ia.linearmosaic") to stitch all pointings together entirely in the image domain after cleaning each pointing individually.



```
CASA <56>: inp
---------> inp()
#  tclean :: Radio Interferometric Image Reconstruction
vis                 =         ''        #  Name of input visibility file(s)
selectdata          =       True        #  Enable data selection parameters
     field          =         ''        #  field(s) to select
     spw            =         ''        #  spw(s)/channels to select
     timerange      =         ''        #  Range of time to select from data
     uvrange        =         ''        #  Select data within uvrange
     antenna        =         ''        #  Select data based on antenna/baseline
     scan           =         ''        #  Scan number range
     observation    =         ''        #  Observation ID range
     intent         =         ''        #  Scan Intent(s)

datacolumn          = 'corrected'       #  Data column to image(data,corrected)
imagename           =         ''        #  Pre-name of output images
imsize              =      [100]        #  Number of pixels
cell                = ['1arcsec']       #  Cell size
phasecenter         =         ''        #  Phase center of the image
stokes              =        'I'        #  Stokes Planes to make
projection          =      'SIN'        #  Coordinate projection (SIN, HPX)
startmodel          =         ''        #  Name of starting model image
specmode            =      'mfs'        #  Spectral definition mode
                                        #   (mfs,cube,cubedata)
     reffreq        =         ''        #  Reference frequency

gridder             =   'mosaic'        #  Gridding options (standard, wproject,
                                        #   widefield, mosaic, awproject)
     normtype       = 'flatnoise'       #  Normalization type (flatnoise,
                                        #   flatsky)
     vptable        =         ''        #  Name of Voltage Pattern table
     pblimit        =        0.2        #  >PB gain level at which to cut off
                                        #   normalizations
     conjbeams      =      False        #  Use conjugate frequency for wideband
                                        #   A-terms

deconvolver         =   'hogbom'        #  Minor cycle algorithm (hogbom,clark,m
                                        #   ultiscale,mtmfs,mem,clarkstokes)
restoration         =       True        #  Do restoration steps (or not)
     restoringbeam  =         []        #  Restoring beam shape to use. Default
                                        #   is the PSF main lobe
     pbcor          =      False        #  Apply PB correction on the output
                                        #   restored image

outlierfile         =         ''        #  Name of outlier-field image
                                        #   definitions
weighting           =  'natural'        #  Weighting scheme
                                        #   (natural,uniform,briggs)
     uvtaper        =         []        #  uv-taper on outer baselines in uv-
                                        #   plane

niter               =          0        #  Maximum number of iterations
usemask             =     'user'        #  Type of mask(s) for deconvolution
                                        #   (user, pb, auto-thresh, auto-
                                        #   thresh2, or auto-multithresh)
     mask           =         ''        #  Mask (a list of image name(s) or
                                        #   region file(s) or region string(s) )
     pbmask         =        0.0        #  primary beam mask

restart             =       True        #  True : Re-use existing images. False
                                        #   : Increment imagename
savemodel           =     'none'        #  Options to save model visibilities
                                        #   (none, virtual, modelcolumn)
calcres             =       True        #  Calculate initial residual image
calcpsf             =       True        #  Calculate PSF
parallel            =      False        #  Run major cycles in parallel
```

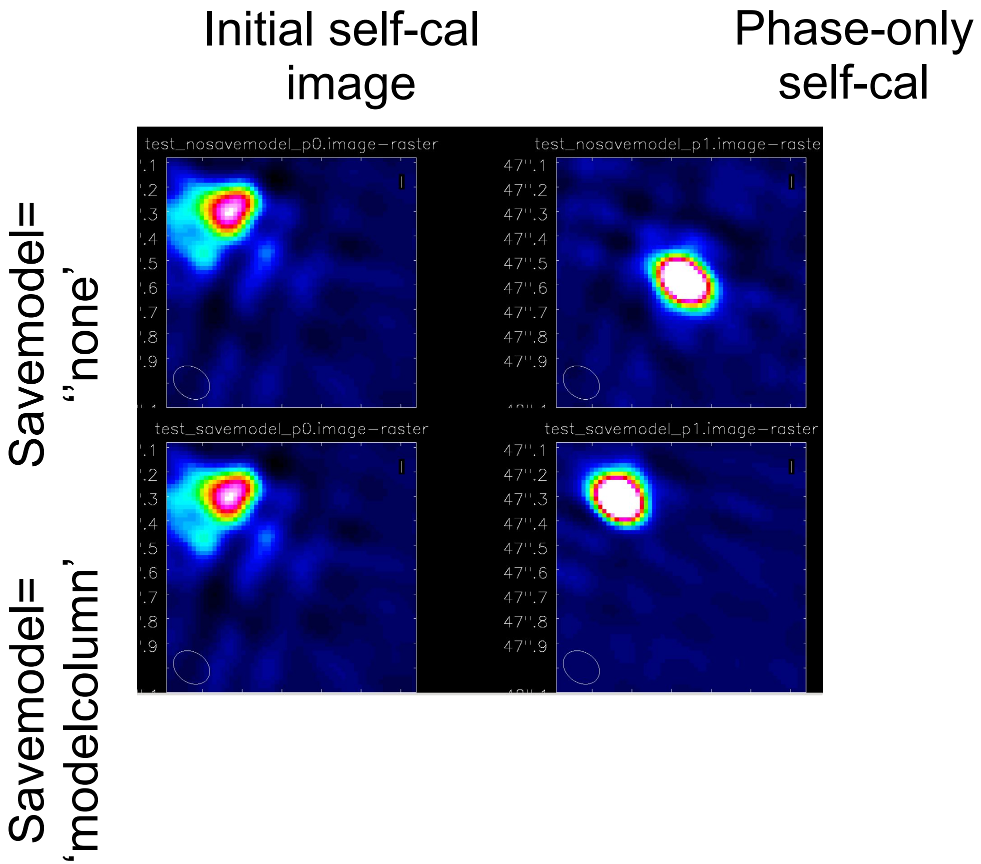
Advanced Usage: parallel mode

- Tclean can be run in parallel to speed up processing of images and cubes.
- The parallelization is very simple: it just splits up the work between nodes and then puts it back together at the end.
    - For cubes, this means that each chunk of channels is processed by a different node.
- This will cause statistically insignificant differences between parallel and serial processing.
- Setting this up requires a few extra steps:
    - Start casa in mpi mode: mpicasa –n 8 casa
    - The –n parameter specifies how many cores you have available. One will be used for control and n-1 will be used for processing
    - In your tclean command, set parallel=True
    - Run your tclean command.
- The nodes all dump their information to a single log file.
- Cube parallelization is being refactor in CASA 6.1, which will change the above behavior.

Advanced usage: self-calibration

Make sure to set savemodel='modelcolumn' if self-calibrating!

- CASA measurement sets nominally have three columns (data, model, corrected) data
- tclean does not save model by default to save disk space.
- However if you are self-calibrating, you need the model.
- If you don't do this, gaincal will use the default model (point source at the phase center).
- The end result is your source appearing to move to the center of the image and possibly becoming more point-like.



- For self-cal and other imaging examples see the NA ALMA imaging script template: https://github.com/aakepley/ALMAImagingScript

Combining with single-dish or other interferometric maps

- If you have only images:
  - feather (or “casafeather”)
- If you have an image and an MS:
  - Can use CLEAN with the image as the model and/or feather
- If you have multiple MS plus an image:
  - Same as above, input to clean will be all the MS’es
- See GBT Memo 300 for information on how combining GBT cubes with ALMA data.
- New single dish and interferometric deconvolution task coming in CASA 6.1. See Rau, Naik, & Braun, AJ, 158, 1 for details of algorithm.
- Useful info from 2019 image combination workshop: https://github.com/teuben/dc2019

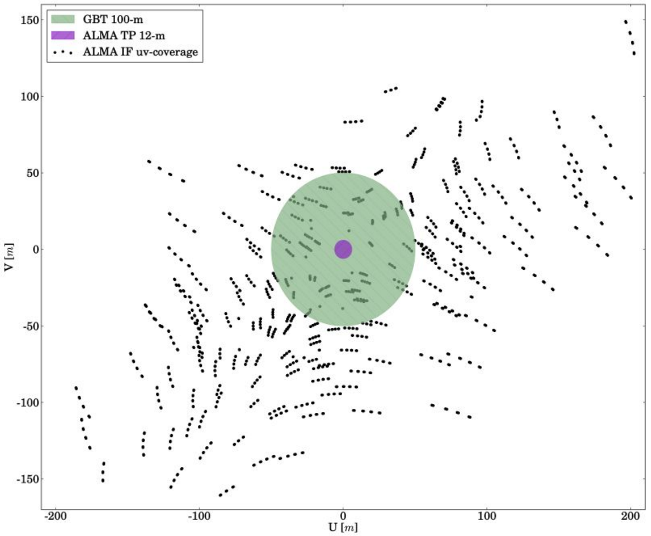
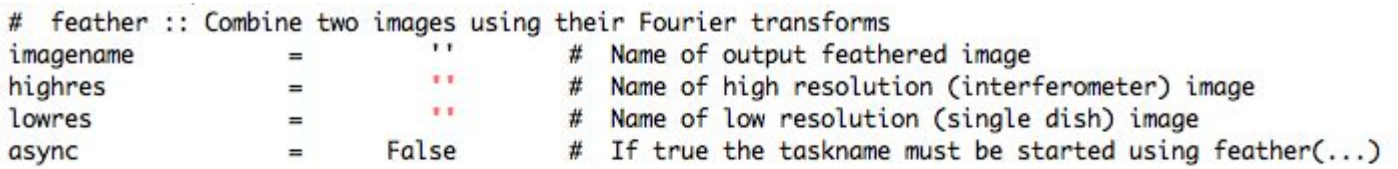


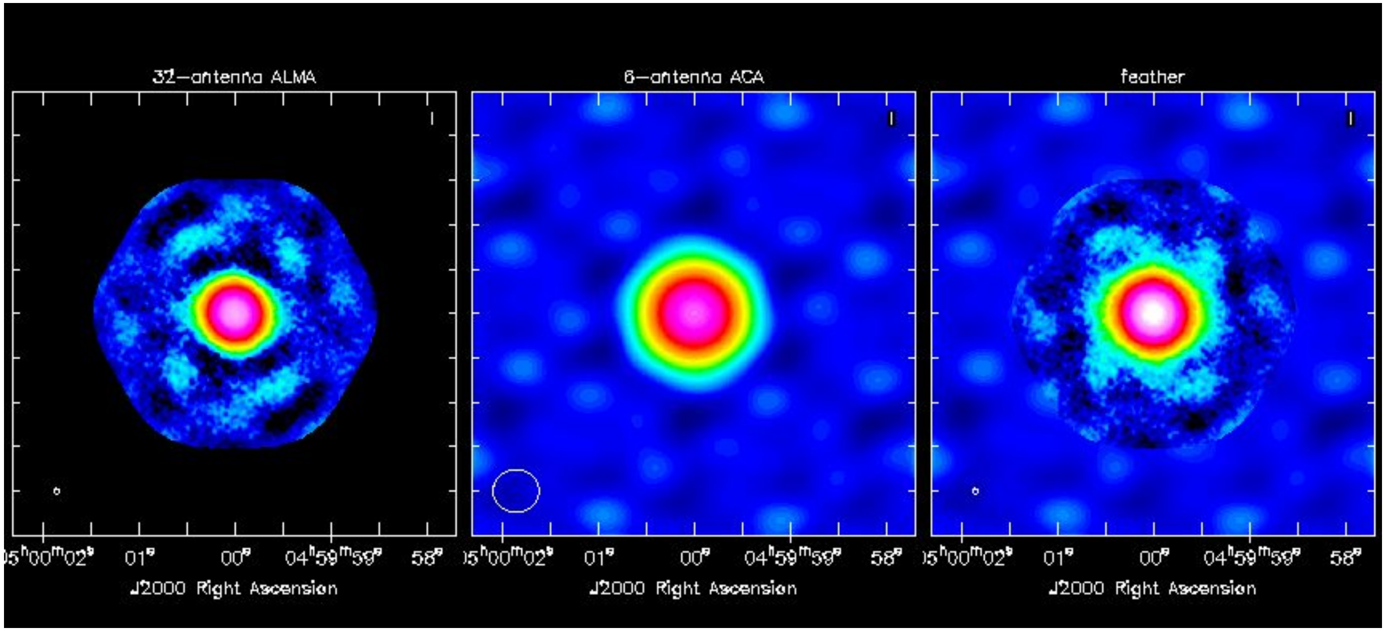
Figure 1: *uv*-coverage of the ALMA 12m+7m array for the data used in this memo with the GBT (green) and ALMA TP (purple) coverages overlaid. The GBT data has significant overlap with the ALMA 12-m array uv-coverage.

From GBT Memo 300 (Hoffman and Kepley)

Combining with other data: feather

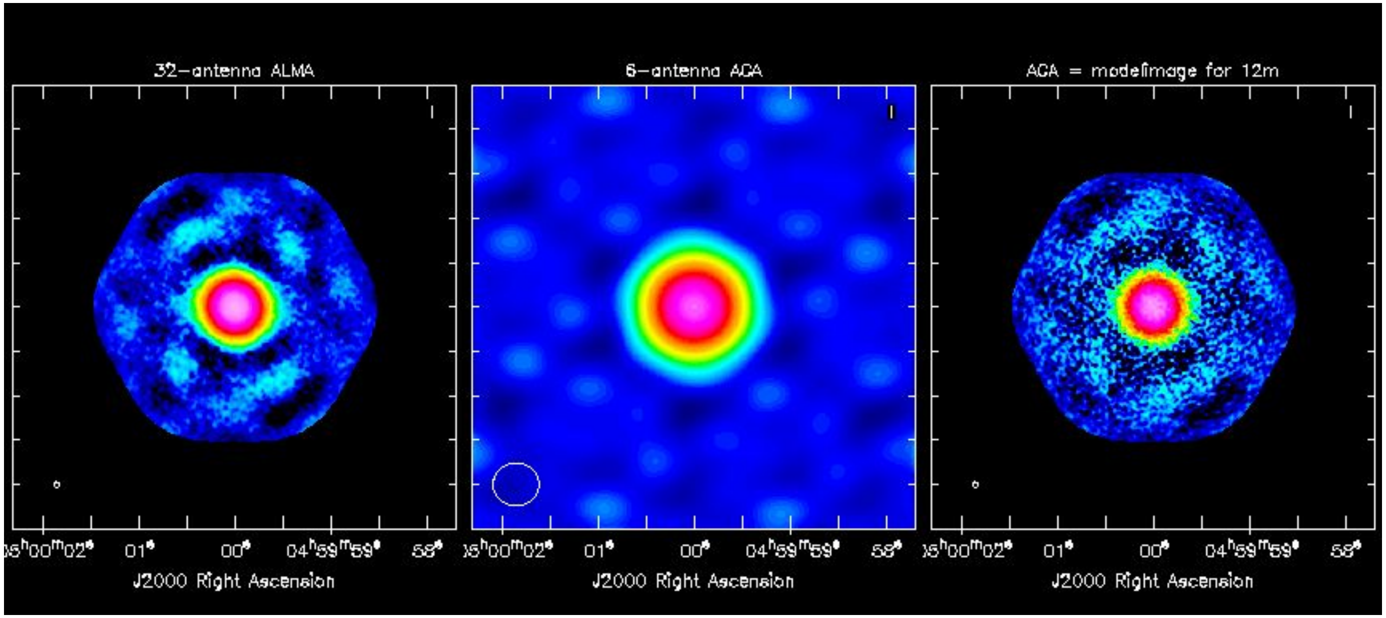


```
#  feather :: Combine two images using their Fourier transforms
imagename          =         ''        #  Name of output feathered image
highres            =         ''        #  Name of high resolution (interferometer) image
lowres             =         ''        #  Name of low resolution (single dish) image
async              =      False        #  If true the taskname must be started using feather(...)
```



We also have a graphical tool: CASAfeather

Combining with other data: model for clean



In tclean, set startmodel='mymodel.model'
Units for model image: Jy/pixel

Be careful to mask a large enough region!