Introduction to Imaging in CASA



Emily Moravec

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











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



From Sky Brightness to Visibility

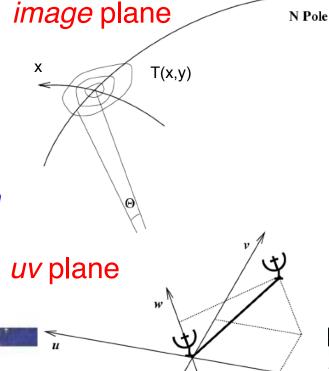
- 1. An interferometer measures the interference pattern observed by pairs of apertures
- The interference pattern is directly related to the source brightness. In particular, for small fields of view, the complex visibility, V(u,v), is the 2D Fourier transform of the brightness on the sky, T(x,y)

(van Cittert-Zernike theorem)

Fourier space/domain

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

Image space/domain



y



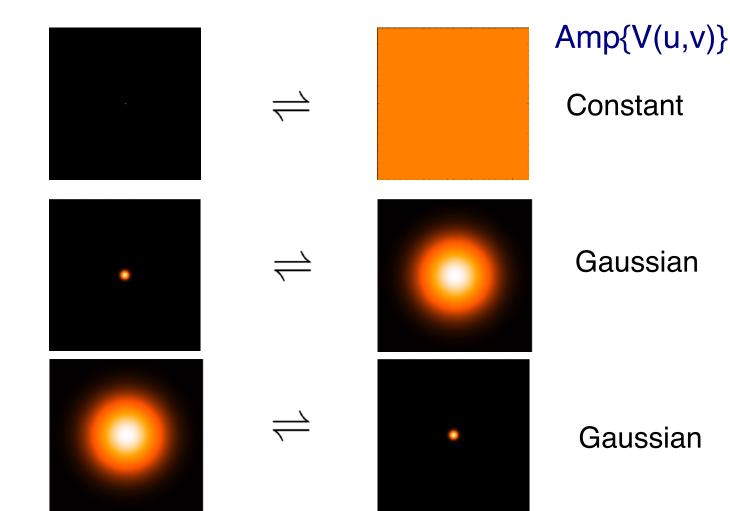
Some 2D Fourier Transform Pairs

T(x,y)

δ Function

Gaussian

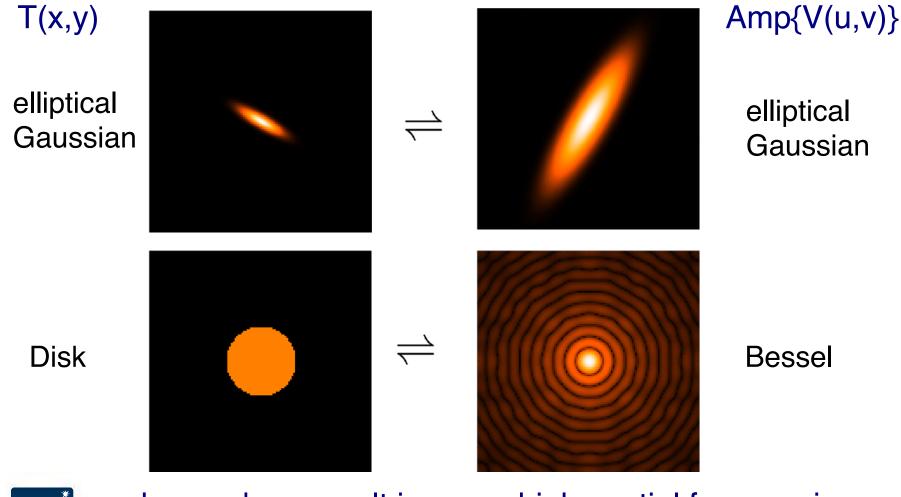
Gaussian





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

More 2D Fourier Transform Pairs





sharp edges result in many high spatial frequencies

(sinc function, "ringing", Gibbs phenomenon)

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



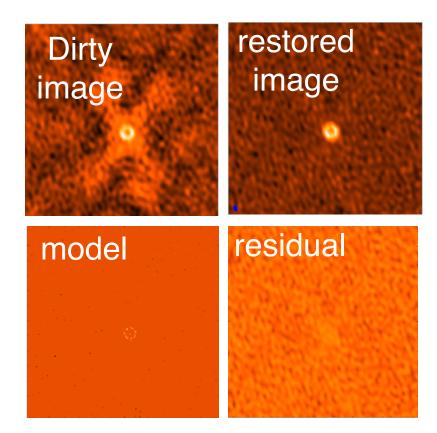
- Fourier transform of sampled visibilities yields the true sky brightness convolved with the point spread function ("dirty beam").
- You need to deconvolve the PSF from the dirty image to reconstruct the source. A commonly used way to do this is called cleaning.





Clean is the most common deconvolution algorithm.

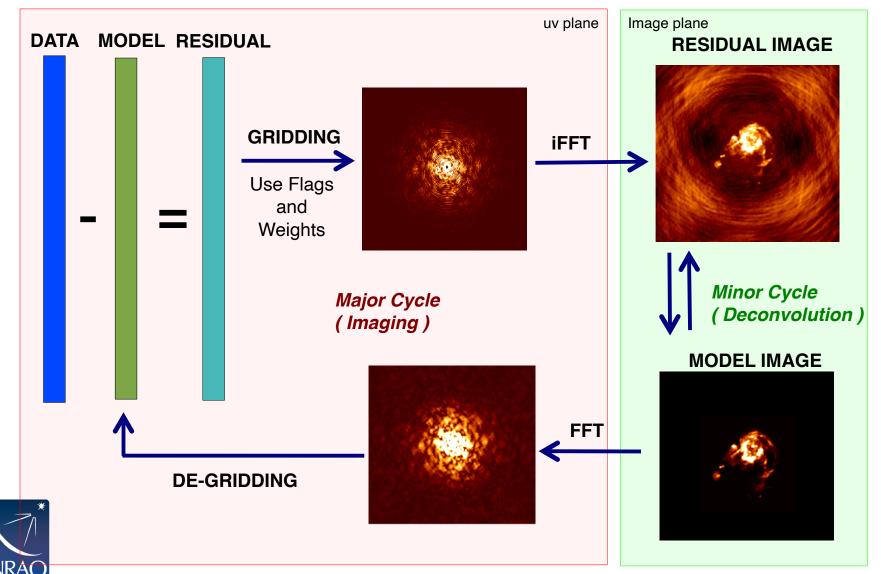
Build up model of data that you convolve with the dirty beam/PSF and add noise to that you compare with the observed data.





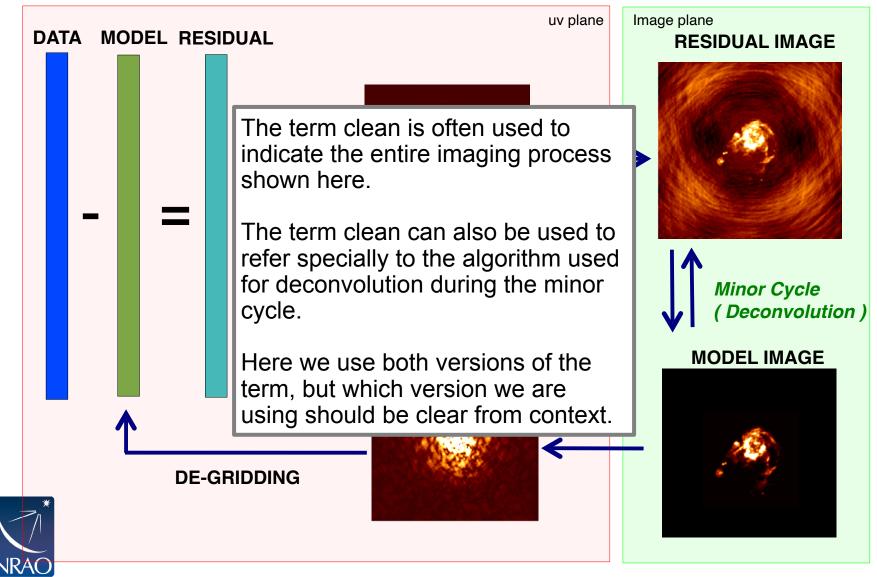
Adapted from slide by Urvashi Rau

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

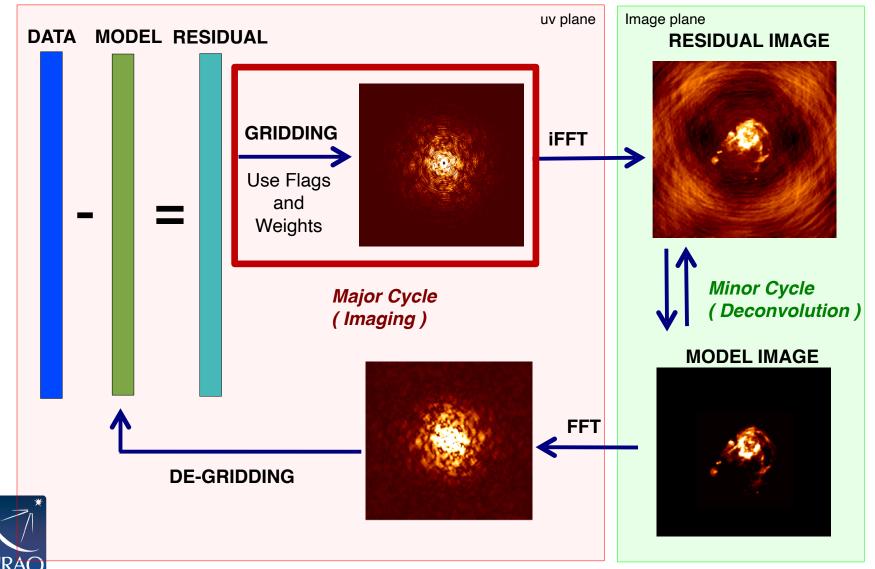


8

A note on terminology



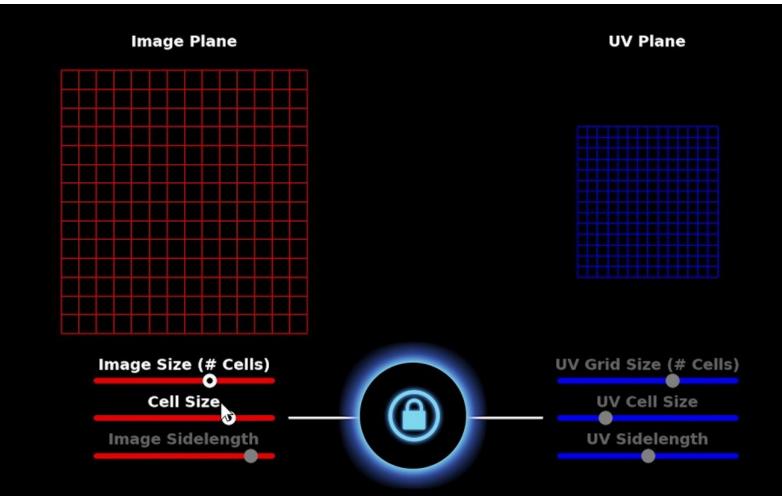
The gridding step requires pixel and image size as well as weighting scheme.



Gridding: Pixel and Image Size

Image size \propto FOV UV plane

FOV image \propto Cell size UV plane



ALMA Primer: https://www.youtube.com/watch?v=hqhZ7g9IJSE

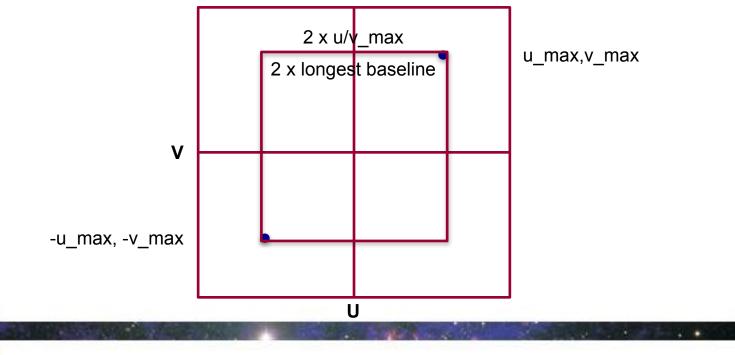
Gridding: Pixel and Image Size

• pixel size: satisfy sampling theorem for longest baselines



NRAC

- in practice, 5 to 8 pixels across dirty beam main lobe to aid deconvolution
- Beam size [arcsec] = 206265.0/(longest baseline in wavelengths)



12

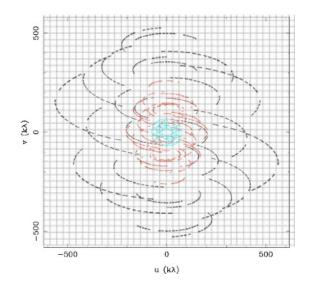
Gridding: Pixel and Image Size

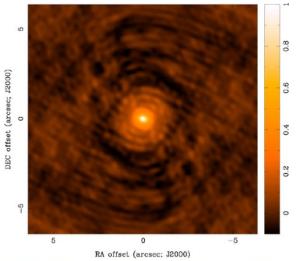
• image size: natural choice often full primary beam A(I,m)

- 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.



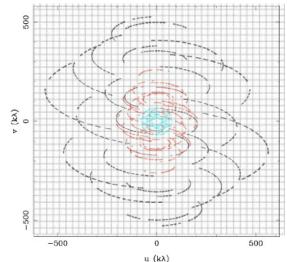
- introduce weighting function W(u,v)
 - modifies sampling function
 - $S(u,v) \to S(u,v)W(u,v)$
 - changes s(l,m), the dirty beam
- "natural" weighting
 - $W(u,v) = 1/\sigma^2$ in occupied cells, where σ^2 is the noise variance
 - maximizes point source sensitivity
 - lowest rms in image
 - generally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

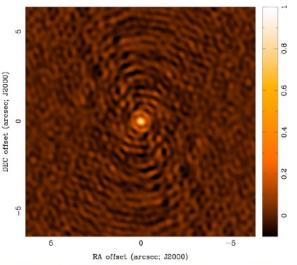






- "uniform" weighting
 - *W*(*u*,*v*) inversely proportional to local density of (*u*,*v*) samples
 - weight for occupied cell = const
 - fills (u,v) plane more uniformly and dirty beam sidelobes are lower
 - gives more weight to long baselines, so angular resolution is enhanced
 - downweights some data,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





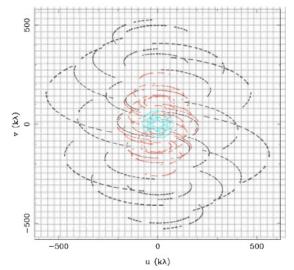


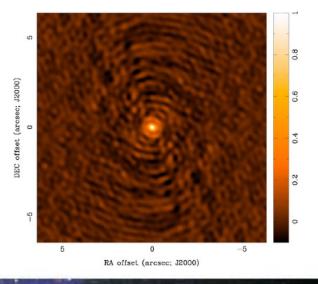
- "robust" (or "Briggs") weighting
 - variant of uniform weighting that avoids giving too much weight to cells with low natural weight
 - software implementations differ
 - e.g. $W(u, v) = \frac{1}{\sqrt{1 + S_N^2/S_{thresh}^2}}$

 S_N is cell natural weight S_{thresh} is a threshold high threshold \rightarrow natural weight low threshold \rightarrow uniform weight

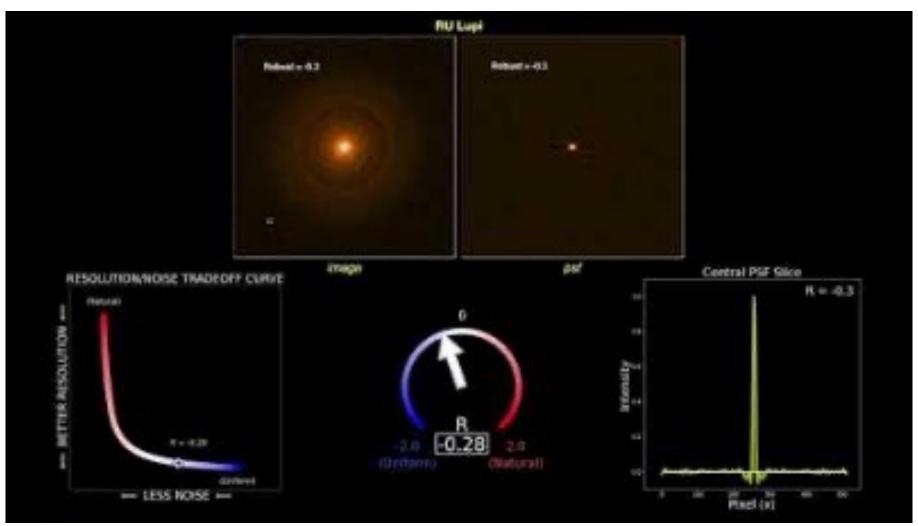
- an adjustable parameter allows for continuous variation between maximum point source sensitivity and resolution
- Use of robust < 0.0 not recommended.

NRAC





Weighting Visualization





https://youtu.be/hqhZ7g9IJSE

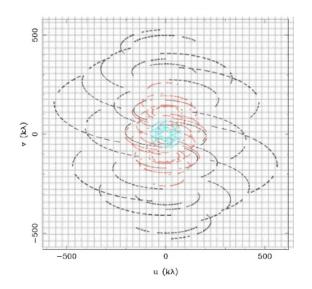
. .

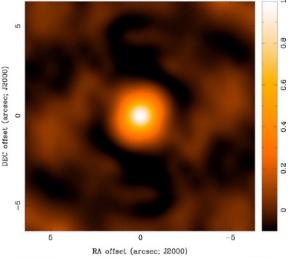
- uvtaper
 - apodize (u,v) sampling by a Gaussian

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

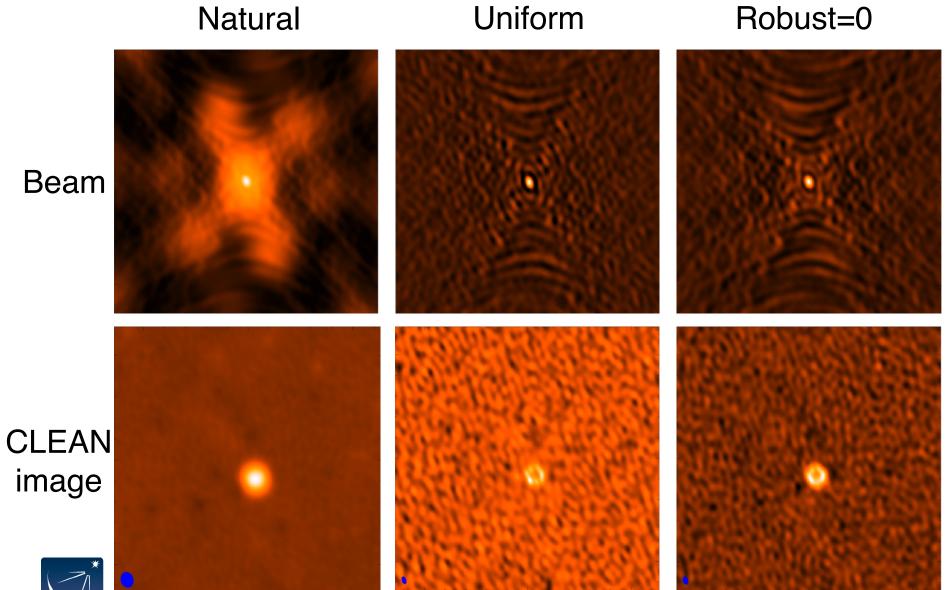
t = adjustable tapering parameter

- 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











NRAC

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

For a video overview of these concepts:



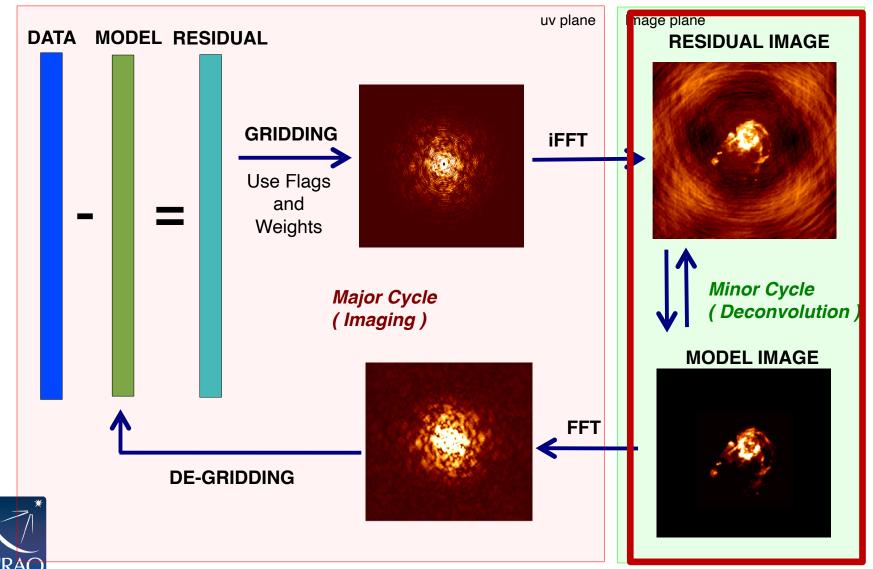
https://youtu.be/OC3IWpRRtEQ

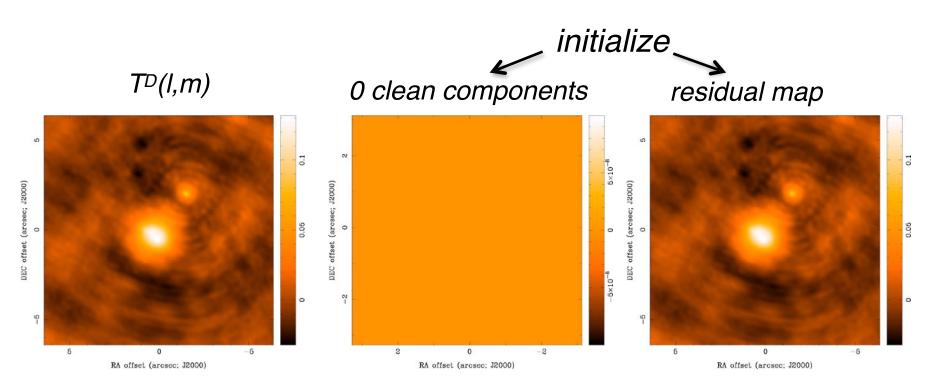
https://youtu.be/EVY7000zAD4

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



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







$T^{D}(I,m)$

\$ 5 0.04 0 0.1 0.03 DEC offset (arcsec; J2000) DEC offset (arcsec; J2000) 0.02 0.05 0.02 0 0 0 0.01 0 φ φ -5 -5 -5 5 0 5 0 5 0 RA offset (arcsec; J2000) RA offset (arcsec; J2000) RA offset (arcsec; J2000)

30 clean components



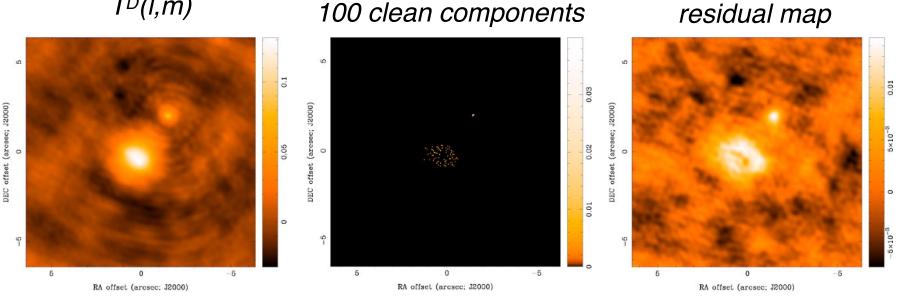
DEC offset (arcsec; J2000)



residual map



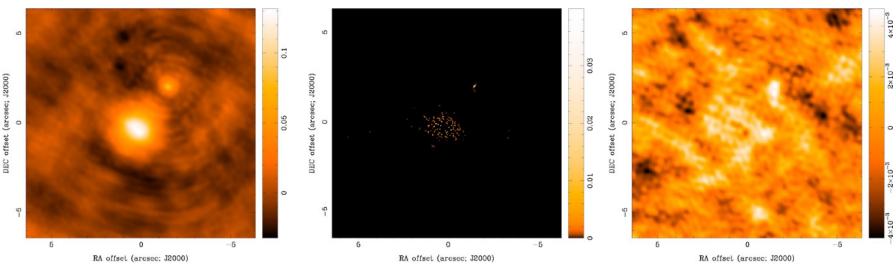
100 clean components





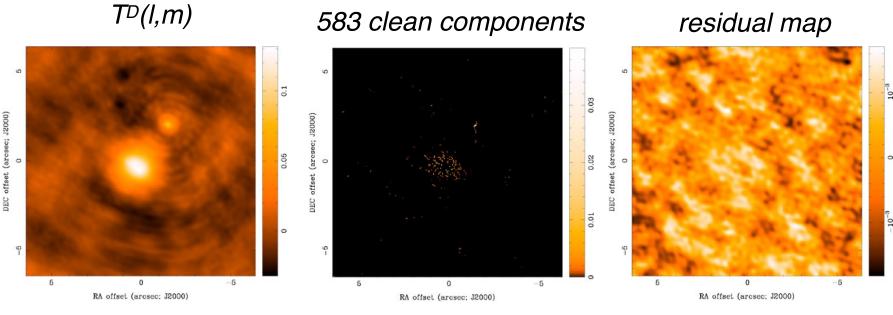






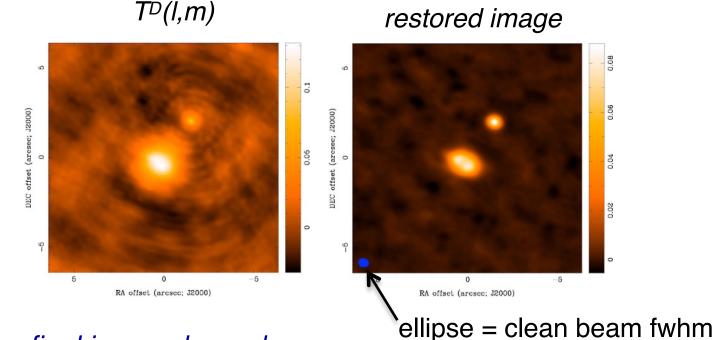


residual map



threshold reached





final image depends on

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



Clean is the most common deconvolution algorithm.

Sky Model : List of delta-functions

(1) Construct the observed (dirty) image and PSF

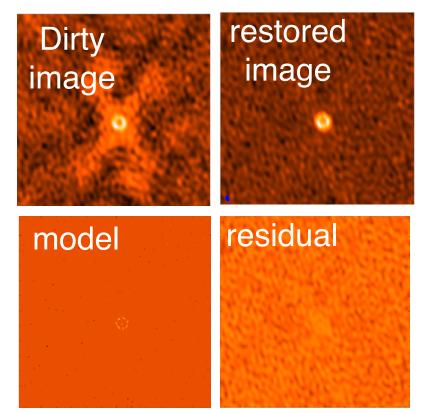
(2) Search for the location of peak amplitude.

(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

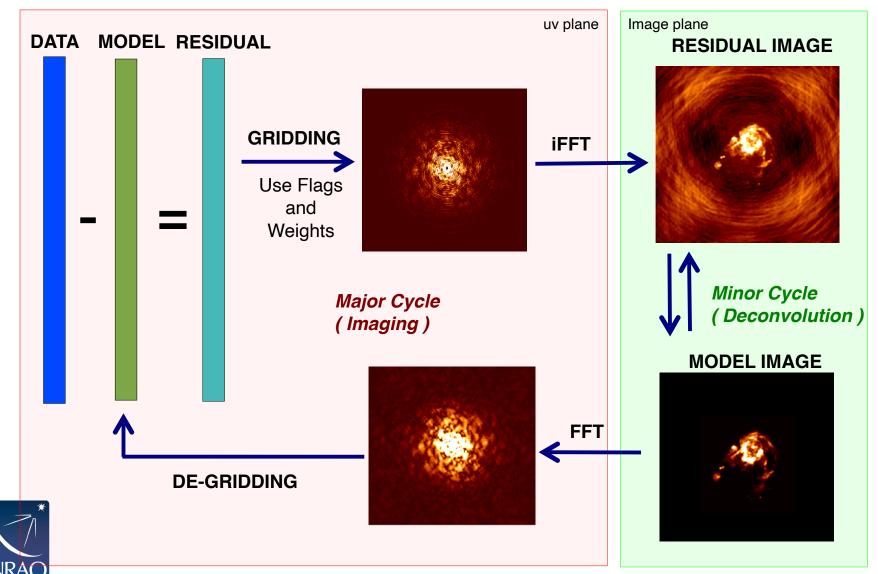




Choices: what and how much PSF to subtract and when to stop

Adapted from slide by Urvashi Rau 29

How do we do all this in practice?



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 → tclean is 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.



> inp(tclea	an)	
<pre># tclean :: Radio</pre>		i
vis selectdata		
	True	
field spw		
timerange		
uvrange		
antenna		
scan		
observation		
intent		
datacolumn	= 'corrected	
imagename		
imsize	= [100]	
cell	= ['larcsec']
phasecenter	=	
stokes	= 'I'	
projection	= 'SIN'	
startmodel	= [100] = ['larcsec' = 'I' = 'I' = 'SIN' = 'SIN' = ''mfs'	
specmode		
reffreq		
gridder	= 'standard'	
vptable		
pblimit	= 0.2	
deconvolver	= 'hogbom'	
restoration	= True	
restoringbeam		
pbcor	= False	
outlierfile		
weighting	= 'natural'	
uutanan		
uvtaper	= []	
niter	0	
usemask	= 'user'	
mask		
pbmask	= 0.0	
restart	= True	
savemodel	= 'none'	
calcres	= True	
calcpsf	= True	
parallel	= False	

inn telos

CASA <7>:

Scan number range # Observation ID range # Scan Intent(s) # Data column to image(data,corrected)

spw(s)/channels to select Range of time to select from data Select data within uvrange

Name of input visibility file(s)

Enable data selection parameters

Select data based on antenna/baseline

Pre-name of output images

field(s) to select

- # Number of pixels
- # Cell size

Image Reconstruction

- # Phase center of the image
- # Stokes Planes to make
- # Coordinate projection (SIN, HPX)
- # Name of starting model image # Spectral definition mode
- # Spectral definition mo
- # (mfs,cube,cubedata)
 # Reference frequency
- # Gridding options (standard, wproject,
- # widefield, mosaic, awproject)
- # Name of Voltage Pattern table
- # >PB gain level at which to cut off
- normalizations
- # Minor cycle algorithm (hogbom,clark,m
- # ultiscale,mtmfs,mem,clarkstokes)
- # Do restoration steps (or not)
- # Restoring beam shape to use. Default
- # is the PSF main lobe
- # Apply PB correction on the output
- # restored image
- # Name of outlier-field image
- # definitions
- # Weighting scheme
- # (natural,uniform,briggs)
- # uv-taper on outer baselines in uv-
- ‡ plane
- # Maximum number of iterations
- Type of mask(s) for deconvolution
- # (user, pb, auto-thresh, auto-
- # thresh2, or auto-multithresh)
- # Mask (a list of image name(s) or
- # region file(s) or region string(s))
- # primary beam mask
- # True : Re-use existing images. False
- # : Increment imagename
- # Options to save model visibilities
- # (none, virtual, modelcolumn)
- # Calculate initial residual image
- # Calculate PSF
- # Run major cycles in parallel

TCLEAN in CASA

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

imagename = whatever you want



> inp(tclea	an)	
# tolean ··· Radio	Inte	rferometric I
selectdata	_	Irue
field	-	1100
spw		
timerange		
uvrange		
antenna		
scan		
observation		
intent		
datacolumn		corrected'
imagename	=	11
TIIISTZE		[100]
cell	= ['larcsec']
phasecenter		
stokes		'I'
projection		'SIN'
startmodel	= = =	
specmode	=	'mfs'
reffreq		
gridder	=	standard'
vptable		
pblimit		0.2
deconvolver	-	'hogbom'
deconvolver	=	'hogbom'
	=	'hogbom' True
deconvolver restoration restoringbeam	=	
restoration	=	True
<mark>restoration</mark> restoringbeam		True []
restoration restoringbeam pbcor		True [] False
restoration restoringbeam pbcor outlierfile		True [] False
restoration restoringbeam pbcor outlierfile weighting	=	True [] False '' 'natural'
restoration restoringbeam pbcor outlierfile weighting uvtaper niter	=	True [] False '' 'natural' [] 0
restoration restoringbeam pbcor outlierfile weighting uvtaper niter usemask	=	True [] False '' 'natural' [] 0 'user'
restoration restoringbeam pbcor outlierfile weighting uvtaper niter usemask mask	=	True [] False '' 'natural' [] 0 'user'
restoration restoringbeam pbcor outlierfile weighting uvtaper niter usemask mask pbmask	=	True [] False '' 'natural' [] () () user' '' user' ''
restoration restoringbeam pbcor outlierfile weighting uvtaper niter usemask mask pbmask restart savemodel	=	True [] False '' 'natural' [] 'user' '' 0.0 True 'none'
restoration restoringbeam pbcor outlierfile weighting uvtaper niter usemask mask pbmask restart savemodel calcres	=	True [] False '' 'natural' [] 0'user' '' 0.0 True 'none' True
restoration restoringbeam pbcor outlierfile weighting uvtaper niter usemask mask pbmask restart savemodel	=	True [] False '' 'natural' [] 'user' '' 0.0 True 'none'

CASA <6>: inn tclear

\SA <7>:

terferometric Image Reconstruction

- # Name of input visibility file(s)
 # Enable data selection parameters
- # field(s) to select
- # TIELO(S) to select
 # spw(s)/chappels to s
- # spw(s)/channels to select
 # Range of time to select from data
- # Select data within uvrange
- Select data based on antenna/baseline
- # Scan number range
- Observation ID range
- # Scan Intent(s)
- # Data column to image(data,corrected)
- # Pre-name of output images
- # Number of pixels
 # Collector
- # Cell size
- # Phase center of the image
- # Stokes Planes to make
- # Coordinate projection (SIN, HPX)
- # Name of starting model image
- # Spectral definition mode
 # (after subscript)
- # (mfs,cube,cubedata)
- # Reference frequency
- # Gridding options (standard, wproject,
- # widefield, mosaic, awproject)
- # Name of Voltage Pattern table
- * >PB gain level at which to cut off
- normalizations
- # Minor cycle algorithm (hogbom,clark,m
- # ultiscale,mtmfs,mem,clarkstokes)
- # Do restoration steps (or not)
- # Restoring beam shape to use. Default
- # is the PSF main lobe
- # Apply PB correction on the output
- # restored image
- # Name of outlier-field image
- definitions
- # Weighting scheme
- # (natural,uniform,briggs)
- # uv-taper on outer baselines in uv-
- # plane
- # Maximum number of iterations
- Type of mask(s) for deconvolution
- # (user, pb, auto-thresh, auto-
- # thresh2, or auto-multithresh)
- # Mask (a list of image name(s) or
- # region file(s) or region string(s))
 # primary beam mask
- # True : Re-use existing images. False
- # : Increment imagename
- # Options to save model visibilities
- # (none, virtual, modelcolumn)
 # Calculate initial residual image
- # Calculate initial residual image
 # Calculate DSE
- # Calculate PSF
- # 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)



CASA <6>: inp tclea	an	
> inp(tclea	an)	
<pre># tclean :: Radio</pre>	Int	erferometric In
vis	_	True
selectdata field		True
spw		
timerange		
uvrange		
antenna		
scan		
observation		
intent		
datacolumn		'corrected'
imsize	-	[100]
cell		['larcsec']
Unseconter		[Idi cocc]
stokes		111
projection		'SIN'
startmodel		
specmode	=	'mfs'
reffreq	=	
gridder	=	'standard'
vptable		
pblimit		0.2
deconvolver		'hogbom'
		nogoom
restoration	=	True
restoringbeam	=	U U
pbcor		False
outlierfile	=	
weighting	-	'natural'
inc raine ma		nacurat
uvtaper		0
niter	=	Θ
usemask	=	'user'
mente		
mask		
pbmask		Θ.Θ
politosk		0.0
restart		True
savemodel		Inonel
savemodel		'none'
calcres		True
calcpsf		True
parallel		False

- # Observation ID range
 # Scan Intent(s)
- # Data column to image(data,corrected)

Select data based on antenna/baseline

Name of input visibility file(s) Enable data selection parameters

- # Pre-name of output images
- # Number of pixels
 # Cell size

age Reconstruction

- # Cell Size
- # Phase center of the image # Stokes Planes to make

field(s) to select
spw(s)/channels to select
Range of time to select from data
Select data within uvrange

Scan number range

- # Coordinate projection (SIN, HPX)
- # Name of starting model image
- # Spectral definition mode
- # (mfs,cube,cubedata)
- # Reference frequency
- # Gridding options (standard, wproject,
- # widefield, mosaic, awproject)
- # Name of Voltage Pattern table
- # >PB gain level at which to cut off
- normalizations
- # Minor cycle algorithm (hogbom,clark,m
- # ultiscale,mtmfs,mem,clarkstokes)
- # Do restoration steps (or not)
- # Restoring beam shape to use. Default
- # is the PSF main lobe
 # tople PSF main lobe
- # Apply PB correction on the output
- # restored image
- # Name of outlier-field image
- # definitions
- # Weighting scheme
- # (natural,uniform,briggs)
- # uv-taper on outer baselines in uv-
- # plane
- # Maximum number of iterations
- f Type of mask(s) for deconvolution
- # (user, pb, auto-thresh, auto-
- # thresh2, or auto-multithresh)
 # Mark (a list of investigation)
- # Mask (a list of image name(s) or
 # region file(s) or region string(s))
- # primary beam mask
- # : Increment imagename
- # Options to save model visibilities
- # (none, virtual, modelcolumn)
 # Calculate initial residual image
- # Calculate initial residual image
 # Calculate DC5
- # Calculate PSF
- # Run major cycles in parallel

Key tclean parameters

The **specmode** parameter controls whether you image the continuum or line emission.

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)

SA < 23 >: inp > inp()				
tclean :: Radio	In	terferometric	: Image R	
S	=		#	Name of input visibility file(s)
lectdata field	=	True	#	Enable data selection parameters 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)
ta a a 1		Iconnected		
tacolumn		'corrected'	#	Data column to image(data,corrected) Pre-name of output images
agename size			#	Number of pixels
11		['larcsec']	#	Cell size
asecenter		11	#	Phase center of the image
okes		111	#	Stokes Planes to make
ojection		'SIN'	#	Coordinate projection (SIN, HPX)
ar cmodel	_			Name of starting model image
ecmode	=	'mfs'	#	Spectral definition mode
			#	(mfs,cube,cubedata)
reffreq			#	Reference frequency
		Lobordond I		Cuiddles and the dependent superior
idder	=	'standard'	#	Gridding options (standard, wproject,
untable			#	widefield, mosaic, awproject)
vptable pblimit			#	Name of Voltage Pattern table >PB gain level at which to cut off
pormite		0.2	#	normalizations
				norma erza erons
convolver	=	'mtmfs'	#	Minor cycle algorithm (hogbom,clark,m
			#	ultiscale,mtmfs,mem,clarkstokes)
scales		0	#	List of scale sizes (in pixels) for
			#	multi-scale algorithms
nterms		2	#	Number of Taylor coefficients in the
			#	spectral model
storation	-	True		Do rectoration stops (or not)
storation	-	True	#	Do restoration steps (or not) Restoring beam shape to use Default
restoringbeam		n	#	Restoring beam shape to use. Default is the PSF main lobe
pbcor		False	#	Apply PB correction on the output
pocor		, acse	#	restored image
				i cotor ca image
tlierfile			#	Name of outlier-field image
			#	definitions
ighting	-	'natural'	#	Weighting scheme
			#	(natural,uniform,briggs)
uvtaper			#	uv-taper on outer baselines in uv-
			#	plane
		•		Mandaum auches of descentions
ter	-	0 'user'	#	Maximum number of iterations
emask	-	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
start		True	#	True : Re-use existing images. False
			#	: Increment imagename
vemodel		'none'	#	Options to save model visibilities
leres		-	#	(none, virtual, modelcolumn)
lcres			#	Calculate initial residual image Calculate PSF
lcpsf rallel		False	#	Calculate FSF Run major cycles in narallel

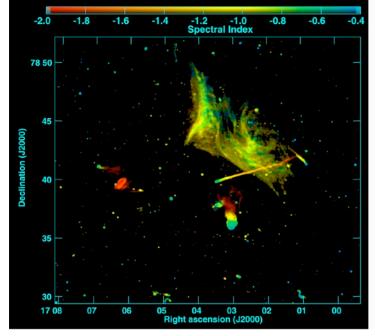


Specmode options: Continuum Imaging

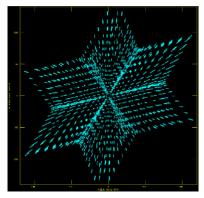
- specmode='mfs' if narrow bandwidth
- add deconvolver='mtmfs' if you have a fractional bandwidth for the aggregate continuum greater than 10% to use multi-term multifrequency synthesis.
 - Only in ALMA Band 3 and the lower end of Band 4 can have fractional bandwidths of greater than 10% and only when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



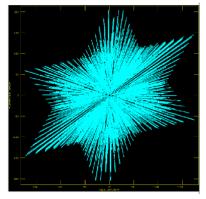
*takes at least nterms longer (image size dependent)



Abell 2256; Owen et al. (2014)

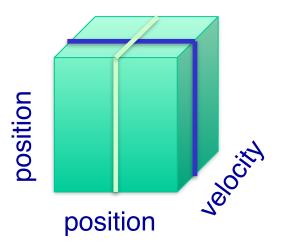


Narrow BW

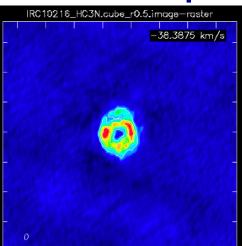


wide BW (better uv-coverage)

Specmode options: Imaging spectral lines



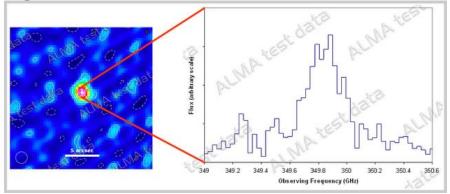
Channel map



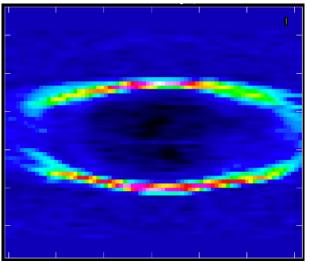


Fixed velocity, polarization, etc.

Spectrum



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)
- <CASA 6.2: If imaging large cubes, set chanchunks=-1. Default (1) tries to put entire cube in memory, which can fail for large cubes.
- >=CASA 6.2: chanchunks parameter has no effect
- perchanweightdensity = True weights each channel independently to give flat noise and beams (CASA >=6.2)
- weighting='briggsbwtaper' will give similar beams between cube and mfs. (CASA >=6.2)

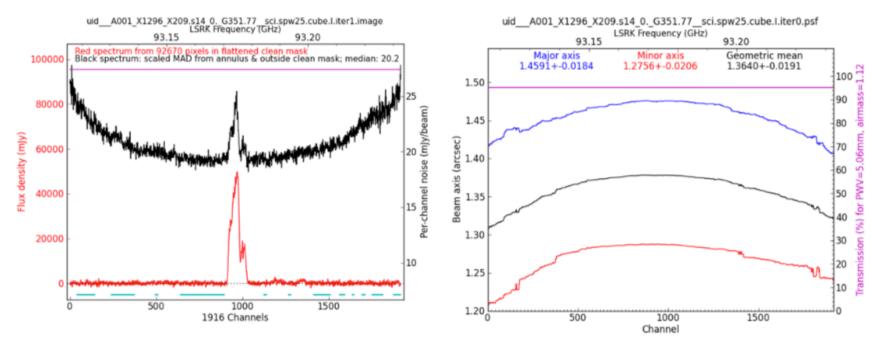


tclean will calculate the Doppler corrections for you! No need to realign beforehand. If needed, **cvel2** will do it for you, e.g. when self-calibrating.

SA < 40>: inp tcle > inp(tcle	an an)		
tclean :: Radio	Interferometr		
s lectdata	= True	# #	Name of input visibility file(s) Enable data selection parameters
field		#	field(s) to select
spw timerange		#	spw(s)/channels to select Range of time to select from data
uvrange	= ''	#	Select data within uvrange
antenna scan	= ''	#	Select data based on antenna/baseline Scan number range
observation		#	Observation ID range
intent		#	Scan Intent(s)
tacolumn	= 'corrected	• #	Data column to image(data,corrected)
agename	= ''	#	Pre-name of output images
size ll	= [100] = ['1arcsec']	# 1 #	Number of pixels Cell size
asecenter		, #	Phase center of the image
okes	= 'I'	#	Stokes Planes to make
ojection artmodel	= 'SIN' = ''	#	Coordinate projection (SIN, HPX) Name of starting model image
ecmode	= 'cube'		Spectral definition mode
nchan		#	(mfs,cube,cubedata) Number of channels in the output
		#	image
start		#	First channel (e.g. start=3, start='1.
width		#	1GHz',start='15343km/s') Channel width (e.g. width=2,width='0.
		#	1MHz',width='10km/s')
outframe		#	Spectral reference frame in which to interpret 'start' and 'width'
veltype	= 'radio'		Velocity type (radio, z, ratio, beta,
		#	gamma, optical) List of rest frequencies
restfreq interpolation	= [] = 'linear'	#	List of rest frequencies Spectral interpolation
meerporacton		#	(nearest,linear,cubic)
chanchunks		#	Number of channel chunks
idder	<pre>'standard'</pre>	#	Gridding options (standard, wproject,
vptable		#	widefield, mosaic, awproject) Name of Voltage Pattern table
pblimit	= Θ.2	#	>PB gain level at which to cut off
		#	normalizations
convolver	= 'hogbom'	#	Minor cycle algorithm (hogbom,clark,m
		#	ultiscale,mtmfs,mem,clarkstokes)
storation restoringbeam	= True = []	#	Do restoration steps (or not) Restoring beam shape to use. Default
rescor ingocum		#	is the PSF main lobe
pbcor	= False	#	Apply PB correction on the output
		#	restored image
tlierfile		#	Name of outlier-field image
ighting	<pre>inatural'</pre>	#	definitions Weighting scheme
	nacarac	#	(natural,uniform,briggs)
uvtaper	= []	#	uv-taper on outer baselines in uv- plane
		*	prane
ter	= <u>0</u>	#	Maximum number of iterations
emask	= 'user'	#	Type of mask(s) for deconvolution
		#	(user, pb, auto-thresh, auto- thresh2, or auto-multithresh)
mask		#	<pre>Mask (a list of image name(s) or region file(s) or region string(s))</pre>
pbmask	= 0.0		primary beam mask
start	= True	#	True : Re-use existing images. False : Increment imagename
vemodel	= 'none'	#	Options to save model visibilities (none, virtual, modelcolumn)
lcres	= True	#	(none, virtual, modelcolumn) Calculate initial residual image
lcpsf	= True	#	Calculate PSF
rallel	= False	#	Run major cycles in parallel

Perchanweightdensity=False

Introduces curvature in the noise spectrum and beams with frequency.

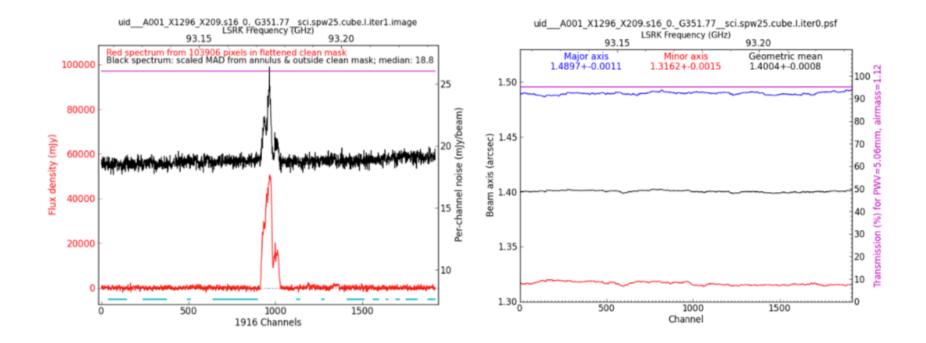


The former is particularly impactful when identifying lines either in the pipeline (findcont and associated heuristics) or using the data for analysis.



Perchanweightdensity=True

Noise spectrum and beams are flat with frequency





But gives cube beams that are larger than mfs beams!

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.

NRÃO

ASA <21>: inp				
<pre>> inp() tclean :: Radio 1</pre>	Int	erferometric		econstruction
is	=		#	Name of input visibility file(s)
electdata	-	True	#	Enable data selection parameters
field	=		#	field(s) to select
spw			#	<pre>spw(s)/channels to select</pre>
timerange			#	Range of time to select from data
uvrange			#	Select data within uvrange
antenna scan			#	Select data based on antenna/baseline
observation			#	Scan number range Observation ID range
intent			#	Scan Intent(s)
				Sean Incent(S)
latacolumn		'corrected'	#	Data column to image(data,corrected)
magename			#	Pre-name of output images
msize		[100]	#	Number of pixels
ell		['larcsec']	#	Cell size
hasecenter		111	#	Phase center of the image
tokes projection		'SIN'	#	Stokes Planes to make Coordinate projection (SIN, HPX)
tartmodel		511	#	Name of starting model image
pecmode	-	'mfs'	#	Spectral definition mode
			#	(mfs,cube,cubedata)
reffreq			#	Reference frequency
ridder	=	'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
				normatizations
leconvolver	-	'hogbom'	#	Minor cycle algorithm (hogbom,clark,m
			#	ultiscale,mimis,mem,clarkstokes)
estoration	=	True	#	Do restoration steps (or not)
restoringbeam		[]	#	Restoring beam shape to use. Default
a basa a		5-1	#	is the PSF main lobe
pbcor		False	#	Apply PB correction on the output
				restored image
utlierfile			#	Name of outlier-field image
			#	definitions
eighting	=	'natural'	#	Weighting scheme
			#	Weighting scheme (natural,uniform,briggs)
uvtaper		[]	#	uv-taper on outer baselines in uv-
			#	plane
iter	=	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
minneffraction		0.05	# #	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
		lunnt		True of markets) for descents labor
isemask	-	'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
			#	<pre>region file(s) or region string(s))</pre>
pbmask		0.0	#	primary beam mask
estart		True	#	True : Re-use existing images. False
avemodel		'none'	#	: Increment imagename Options to save model visibilities
		none	#	(none, virtual, modelcolumn)
alcres		True	#	Calculate initial residual image
alcpsf		True	#	Calculate initial residual image Calculate PSF
arallel		False	#	Run major cycles in parallel
ASA <22>:				

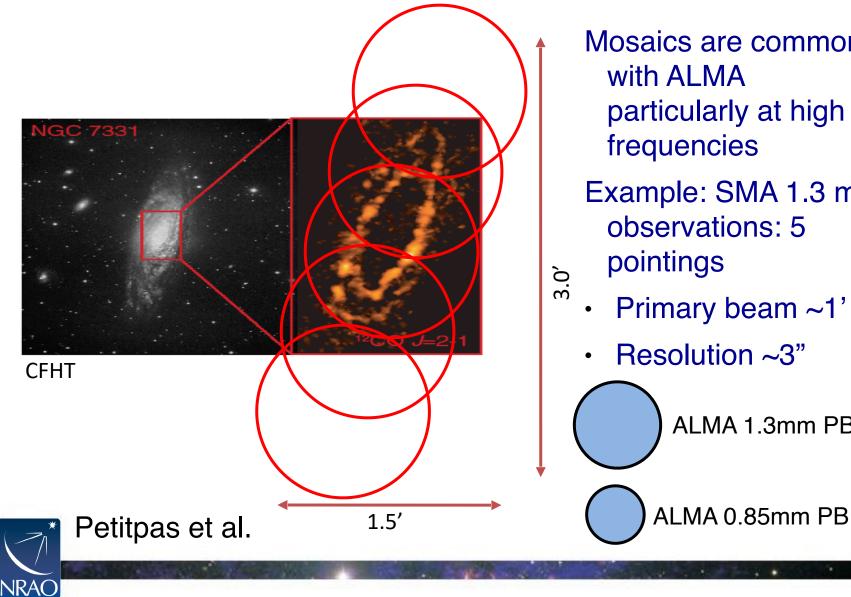
Imaging spectral lines: continuum subtraction

- 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())			
		itting and	subt	raction in the uv plane
vis				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

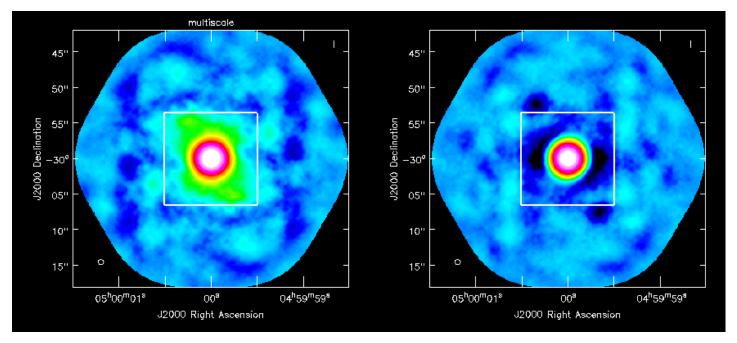
- Example: SMA 1.3 mm observations: 5 pointings
- Primary beam ~1'
- Resolution ~3"

ALMA 1.3mm PB

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. 44

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.

		Image Reconstruction
vis	= "	<pre># Name of input visibility file(s)</pre>
selectoata	True	<pre># Enable data selection parameters</pre>
field		<pre># field(s) to select # coursele to colort</pre>
spw	= 0.000	<pre># spw(s)/channels to select # Range of time to select from data</pre>
timerange	=	# Range of time to select from data # Select data within uvrange
uvrange		# Select data within uvrange # Select data based on antenna/baseling
antenna scan		# Scan number range
observation		# Observation ID range
intent		# Scan Intent(s)
meene		# Scall Incenc(s)
datacolumn	= 'corrected'	<pre># Data column to image(data,corrected)</pre>
imagename		<pre># Pre-name of output images</pre>
imsize	= [100]	<pre># Number of pixels</pre>
cell	= ['larcsec']	# Cell size
phasecenter		# Phase center of the image
stokes	= 'I'	# Stokes Planes to make
projection	= 'SIN'	<pre># Coordinate projection (SIN, HPX)</pre>
startmodel		# Name of starting model image
specmode	= 'mfs'	<pre># Spectral definition mode</pre>
		<pre># (mfs,cube,cubedata)</pre>
reffreq		# Reference frequency
gridder	<pre>= 'standard'</pre>	# Gridding options (standard, wproject
		<pre># widefield, mosaic, awproject)</pre>
vptable		# Name of Voltage Pattern table
pblimit	= 0.2	# >PB gain level at which to cut off
		<pre># normalizations</pre>
deconvolver	= 'multiscale'	# Minor cycle algorithm (hogbom, clark,
		<pre># ultiscale,mtmfs,mem,clarkstokes) # ultiscale.mtmfs,mem,clarkstokes)</pre>
scales	= []	<pre># List of scale sizes (in pixels) for #</pre>
		<pre># multi-scale algorithms # the scale algorithms</pre>
smallscalebias	= 0.6	<pre># A bias towards smaller scale sizes</pre>
restoringbeam	= []	<pre># Restoring beam shape to use. Default</pre>
restor mgseam		<pre># is the PSF main lobe</pre>
pbcor	= False	<pre># Apply PB correction on the output</pre>
pocor	1 a to c	# restored image
		" rescored mage
outlierfile		<pre># Name of outlier-field image</pre>
		# definitions
weighting	<pre>- 'natural'</pre>	# Weighting scheme
	ind correct	# (natural,uniform,briggs)
uvtaper	= []	<pre># uv-taper on outer baselines in uv-</pre>
ar cape:		# plane
niter	= 0	<pre># Maximum number of iterations</pre>
usemask	= 'user'	<pre># Type of mask(s) for deconvolution</pre>
		<pre># (user, pb, auto-thresh, auto-</pre>
		<pre># thresh2, or auto-multithresh)</pre>
mask		<pre># Mask (a list of image name(s) or</pre>
		<pre># region file(s) or region string(s)</pre>
pbmask	= 0.0	<pre># primary beam mask</pre>
restart	= True	# True : Re-use existing images. False
		# : Increment imagename
savemodel	= 'none'	# Options to save model visibilities
		<pre># (none, virtual, modelcolumn)</pre>
calcres	= True	# Calculate initial residual image
calcpsf	= True	# Calculate PSF
parallel	= False	# Run major cycles in parallel
CASA <51>+		

ASA <**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.
- The noise will no longer be flat across the image.

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



	:: Radio	Int	erferometric	Image	Re	2
		-		*		
	d	=	True	#		ł
	a					
	range			#		ł
	inge			÷		
	nna					
				- #		
	rvation			- +		(
	nt			#		
datacolum			'corrected'	#		I
imagename				#		
imsize			[100]	#		
cell			['larcsec']	#		(
phasecent	er			#		
stokes			'I'	#		
projectio			SIN	#		
startmode specmode		-	'mfs'	*		
specilloue		-	m15	*		
reff	reg			*		
Terr	req					
gridder		=	'standard'	#		(
a root			o canaar a	#		
vpta	ble			#		
pbli			0.2	#		
				#		
				_		
deconvolv	er	=	'multiscale'			
				· *		
scal	es		[]	#		
cmal	lscalebias		0.6	#		,
Siliat	ISCALEDIAS		0.0			1
restorati	on	=	True	#		
rest	oringbeam		[]	#	1	
				#	1	
pbco			False	#		
				#		
outtrent	LC.					
und ab billing			Inchungli	#		
weighting		-	'natural'	#		١
uvta	ner		0	*		l
uvca	per			#		
niter		=	Θ	#	1	1
usemask		-	'user'	#	1	
				#		
				#		
mask				#		
				#		
pbma	SK		0.0	#		
rectant			Teur	#		
restart		-	True	#		
savemodel		=	'none'	*		(
Savenouel			none			
calcres			True			(
calcpsf			True			(

baralle

ASA <51>

Image R	econstr	ruction		
#	Name o	of input	visibility	file(

- # Enable data selection parameters
- # field(s) to select
- # spw(s)/channels to select
- # Range of time to select from data
- # Select data within uvrange
- # Select data based on antenna/baseline
 # Select data
- # Scan number range
- # Observation ID range
 # Scan Intent(s)
- # Data column to image(data,corrected)
- # Pre-name of output images
- # Number of pixels
- # Cell size
- # Phase center of the image
- # Stokes Planes to make
- # Coordinate projection (SIN, HPX)
 #
- # Name of starting model image
- # Spectral definition mode
 # (mfs_cube_cubedata)
- (mfs,cube,cubedata)
 Reference frequency
- Reference Trequency
- Gridding options (standard, wproject,
- # widefield, mosaic, awproject)
 # Name of Voltage Pattern table
- # Name of Voltage Pattern table # >PB gain level at which to cut off
- # normalizations

scale'	<pre># Minor cycle algorithm (hogbom,clark,m</pre>
[]	<pre># List of scale sizes (in pixels) for</pre>
	<pre># multi-scale algorithms</pre>
0.6	# A bias towards smaller scale sizes
True	<pre># Do restoration steps (or not)</pre>
[]	<pre># Restoring beam shape to use. Default</pre>
	<pre># is the PSF main lobe</pre>
alse	# Apply PB correction on the output
	<pre># restored image</pre>
	# Name of outtref*fretu image
	# definitions
ral'	# Weighting scheme
	<pre># (natural,uniform,briggs)</pre>
D	<pre># uv-taper on outer baselines in uv- # plane</pre>
Θ	<pre># Maximum number of iterations</pre>
ser'	<pre># Type of mask(s) for deconvolution</pre>
	<pre># (user, pb, auto-thresh, auto-</pre>
	<pre># thresh2, or auto-multithresh)</pre>
	# Mask (a list of image name(s) or
	<pre># region file(s) or region string(s))</pre>
0.0	# primary beam mask
True	# True : Re-use existing images. False
	# : Increment imagename
one'	<pre># Options to save model visibilities</pre>
	<pre># (none, virtual, modelcolumn)</pre>
True	# Calculate initial residual image
True	# Calculate PSF
alse	# Run maior cycles in parallel

Run major cycles in parallel

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



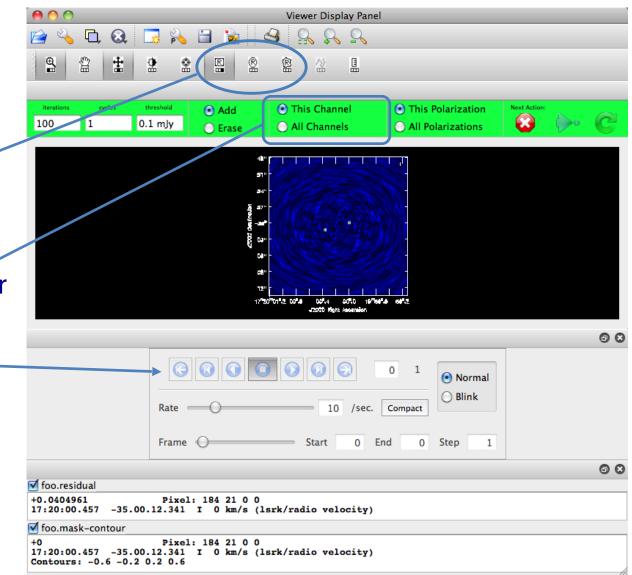
- Gain can be useful for cases with extended emission (although see multi-scale clean)
- cyclefactor, cycleniter,

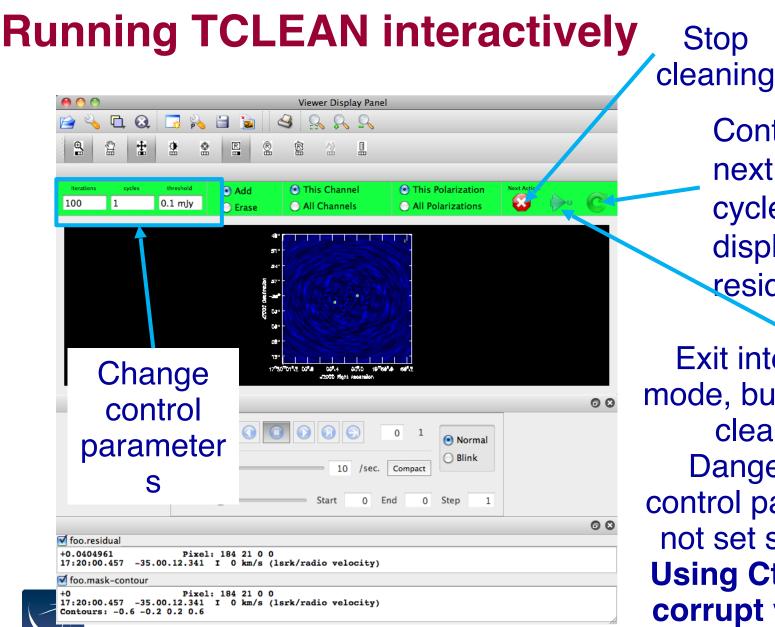
CACA 2345. 4mm			
[CASA < 21 >: inp > inp()			
# tclean :: Radio	Interferomet	ric Image R	Reconstruction
vis		• #	Name of input visibility file(s)
selectdata	= Tru	e #	Enable data selection parameters
field	= '		field(s) to select
spw		*	<pre>spw(s)/channels to select</pre>
timerange			Range of time 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	= 'correcte	d' #	Data column to image(data,corrected)
imagename	= '		Pre-name of output images
imsize	= [100]		Number of pixels
cell	= ['larcsec		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	<pre>'standard</pre>		Gridding options (standard, wproject,
		. #	widefield, mosaic, awproject)
vptable			Name of Voltage Pattern table
pblimit	= 0.1		>PB gain level at which to cut off
		#	normalizations
deconvolver	Iboghom	• #	Minor cucle algorithm (boghom clark-m
deconvolver	= 'hogbom	#	Minor cycle algorithm (hogbom,clark,m ultiscale,mtmfs,mem,clarkstokes)
restoration	- Tru		Do restoration steps (or not)
restoringbeam	= []		Restoring beam shape to use. Default
i co cor rigocum		, #	is the PSF main lobe
pbcor	= Fals		Apply PB correction on the output
		#	restored image
outlierfile		'#	Name of outlier-field image
		#	definitions
weighting	Inatural		Weighting scheme
		#	(natural,uniform,briggs)
uvtaper	= []		uv-taper on outer baselines in uv-
		#	plane
niter	_	1 #	Mavinum number of iterations
gain	= 0.1		Maximum number of iterations
threshold	= 0.0		Loop gain Stopping threshold
cycleniter	= -		Maximum number of minor-cycle
cycremiter		- #	iterations
cyclefactor	= 1.		Scaling on PSF sidelobe level to
		#	compute the minor-cycle stopping
		#	threshold.
minpsffraction	= 0.0	5 #	PSF fraction that marks the max depth
		#	of cleaning in the minor cycle PSF fraction that marks the minimum
maxpsffraction	= 0.3		PSF fraction that marks the minimum
		#	depth of cleaning in the minor cycle
interactive	= Fals		Modify masks and parameters at
		#	runtime
usemask	user		Tupe of $mack(c)$ for deconvolution
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
ing an		#	<pre>Mask (a list of image name(s) or region file(s) or region string(s))</pre>
pbmask	= 0.0		primary beam mask
restart	= Tru	e #	True : Re-use existing images. False
		#	: Increment imagename
savemodel	= 'none	#	Options to save model visibilities
		#	(none, virtual, modelcolumn)
calcres	= Tru		Calculate initial residual image Calculate PSF
calcpsf	= Tru		
parallel	= Fals	e #	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







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
- my_image.image
- my_image.mask
- my_image.model
- my_image.psf
- my_image.residual
- my_image.sumwt

Primary beam model Cleaned and restored image (Jy/clean bea Clean "boxes" Clean components (Jy/pixel) Dirty beam Residual (Jy/dirty beam) 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: 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: <u>https://</u>
- <u>casaguides.nrao.edu/index.php/</u> <u>Automasking_Guide</u>
- Paper: <u>Kepley et al. 2020, PASP, 132,</u> 1008, 02405



ASA < 58>: inp		
> inp()		
	Interferometric	Image Reconstruction
s	<u> </u>	<pre># Name of input visibility file(s)</pre>
electdata	True	<pre># Enable data selection parameters</pre>
field		<pre># field(s) to select # select</pre>
spw	= ''	<pre># spw(s)/channels to select # Range of time to select from data</pre>
timerange		# Range of time to select from data # Select data within uvrange
uvrange antenna		# Select data writin dvrange # Select data based on antenna/baselin
scan		# Scan number range
observation		# Observation ID range
intent		<pre># Scan Intent(s)</pre>
atacolumn	= 'corrected'	# Data column to image(data,corrected)
nagename		# Pre-name of output images
nsize	= [100]	<pre># Number of pixels</pre>
e11	= ['larcsec']	# Cell size
hasecenter	=	# Phase center of the image
tokes	= 'I'	<pre># Stokes Planes to make</pre>
rojection	= 'SIN' = ''	<pre># Coordinate projection (SIN, HPX)</pre>
tartmodel		<pre># Name of starting model image # Granted addition model</pre>
pecmode	= 'mfs'	<pre># Spectral definition mode # (afe auto autodate)</pre>
		<pre># (mfs,cube,cubedata) # Reference frequency</pre>
reffreq		# Reference frequency
ridder	- Improduct	# Gridding options (standard, wproject
ruuer	= 'mosaic'	
normtype	= 'flatnoise'	<pre># widefield, mosaic, awproject) # Normalization type (flatnoise,</pre>
normeype	- reactionse	
vptable		<pre># flatsky) # Name of Voltage Pattern table </pre>
pblimit	= 0.2	# >PB gain level at which to cut off
portinite	v	<pre># normalizations</pre>
conjbeams	= False	# Use conjugate frequency for wideband
		# A-terms
econvolver	= 'hogbom'	<pre># Minor cycle algorithm (hogbom,clark</pre>
		<pre># ultiscale,mtmfs,mem,clarkstokes)</pre>
estoration	True	<pre># Do restoration steps (or not)</pre>
restoringbeam	= []	# Restoring beam shape to use. Default
		<pre># is the PSF main lobe</pre>
pbcor	= False	# Apply PB correction on the output
		<pre># restored image</pre>
utlierfile	= ''	# Name of outlier-field image
	1	# definitions
eighting	= 'natural'	<pre># Weighting scheme</pre>
		<pre># (natural,uniform,briggs) # uv-taper on outer baselines in uv-</pre>
uvtaper	= []	
		# plane
iter		# Maximum number of iterations
semask	= 'auto-multith	
Jennesk		# (user, pb, auto-thresh, auto-
		<pre># thresh2, or auto-multithresh)</pre>
pbmask		# primary beam mask
sidelobethresh		<pre># sidelobethreshold * the max sidelol</pre>
		# level
noisethreshold	= 5.Θ	<pre># noisethreshold * rms in residual</pre>
		# image
lownoisethresh	nold = 1.5	<pre># lownoisethreshold * rms in residual</pre>
		# image
negativethresh	nold = 0.0	
		# image
smoothfactor	= 1.0	# smoothing factor in a unit of the
		# beam
minbeamfrac	= 0.3	<pre># minimum beam fraction for pruning</pre>
cutthreshold	= 0.01	<pre># threshold to cut the smoothed mask # create a final mask</pre>
		# create a final mask
growiterations	; = 75	# number of binary dilation iteration:
		<pre># for growing the mask</pre>
Start		
us car u	- 1100	<pre># inde . Re-use existing images. rais # : Increment imagename</pre>
avemodel	= 'none'	# Options to save model visibilities
	none	<pre># Options to save model visibilities # (none, virtual, modelcolumn)</pre>
alcres	= True	<pre># Calculate initial residual image</pre>
lenef	- True	# Calculate DCE

arallel

False

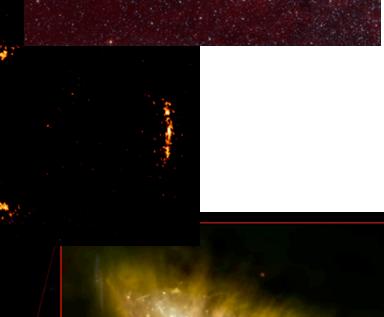
Run major cycles in parallel

... some CASA images..













More Detailed Help - CASA Guides: https://casaguides.nrao.edu/index.php?title=ALMAguides







www.nrao.edu science.nrao.edu

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

