Imaging

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Overview

Fundamentals of Radio Interferometric Imaging.

- Van Cittert Zernike Theorem
- Imaging as a minimization problem

Task *tclean* and how it maps to the fundamentals of imaging.

Mapping your data onto the image

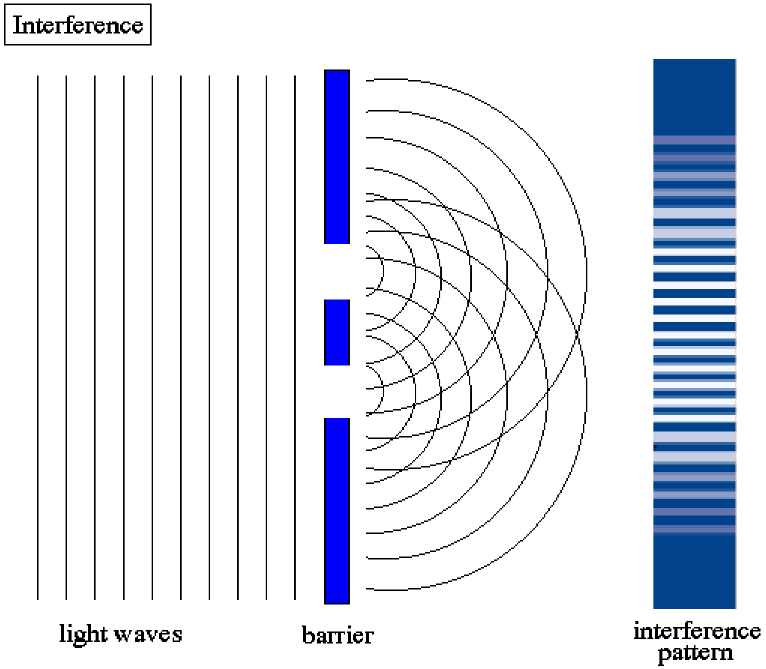
Comparison of the task to the algorithms.

Data files (1.25GB) for the demo along with a walkthrough script can be found at

http://www.aoc.nrao.edu/~pjaganna/DRW_2022/

Interferometry

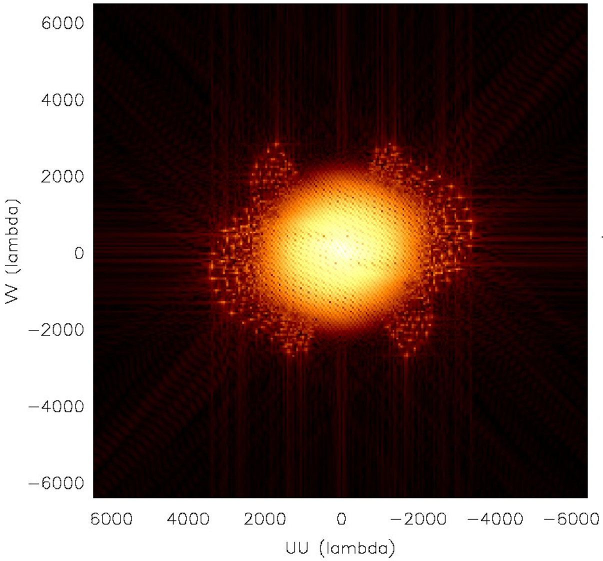
An interferometer is measuring the interference pattern of the sky per baseline.



Parameters : Amplitude, Phase, Orientation, Wavelength

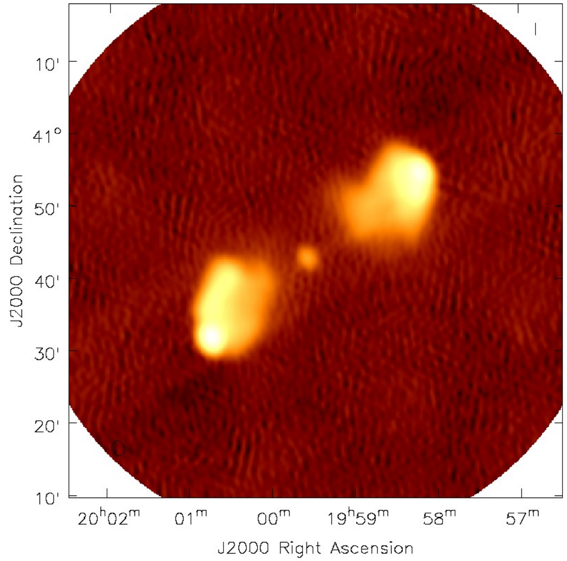
VanCittert - Zernike Theorem

The observed complex visibilities are related to the sky brightness distribution via the Fourier transform.



Visibilities (complex)

$$V(u,v) \leftrightharpoons I^{sky}(l,m)$$

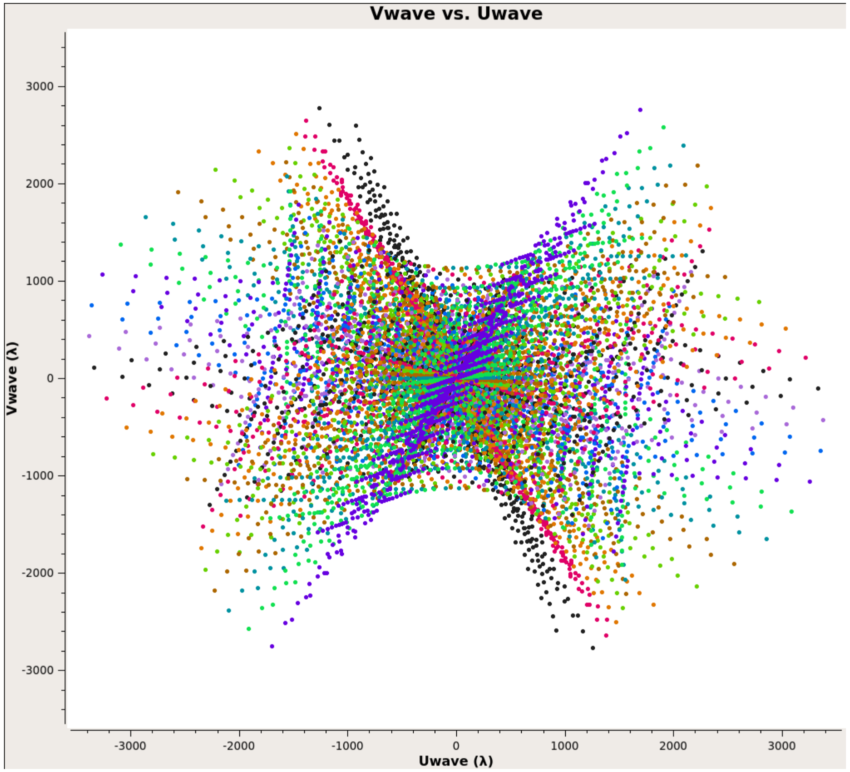


Sky Brightness (Real)

Aperture Synthesis

Fill in the UV plane however possible

- Instantaneous snapshot at the VLA has 351 baselines per channel per timestep per polarization.
- Different Az-El corresponds to different points in the UV plane - Time dependence
- Different Observing frequencies also fills in different tracks



Task *tclean*

This casa task takes calibrated visibilities in the measurement set and produces an image according to the parameters defined by the user.

Clean is an iterative chi square minimization algorithm split into major and minor cycles traditionally to perform imaging (data to image) and deconvolution (removing the imprint of the PSF)

Major cycles are in the data domain - called imaging.

Minor cycles are in the image domain - deconvolution.

This is the task where you will typically spend about 80% of your data reduction time. So it is an important task to master.

Task *tclean* - Products

imagename.psf	Point Spread Function
imagename.pb	Primary Beam of FoV
imagename.residual	Residual image
imagename.model	Model image - deconvolved components
imagename.image	Restored output image.
imagename.image.pbcor	Primary Beam corrected image - I/PB
imagename.mask	Deconvolution mask if specified.
imagename.sumwt	A single pixel image containing the sum of weights
imagename.weight	The visibility weight image.
imagename.XX.tt{0,1,2..}	Multi-term images of Taylor coefficients.

imagename.workdirectory Working directory with images created during a parallel run of tclean

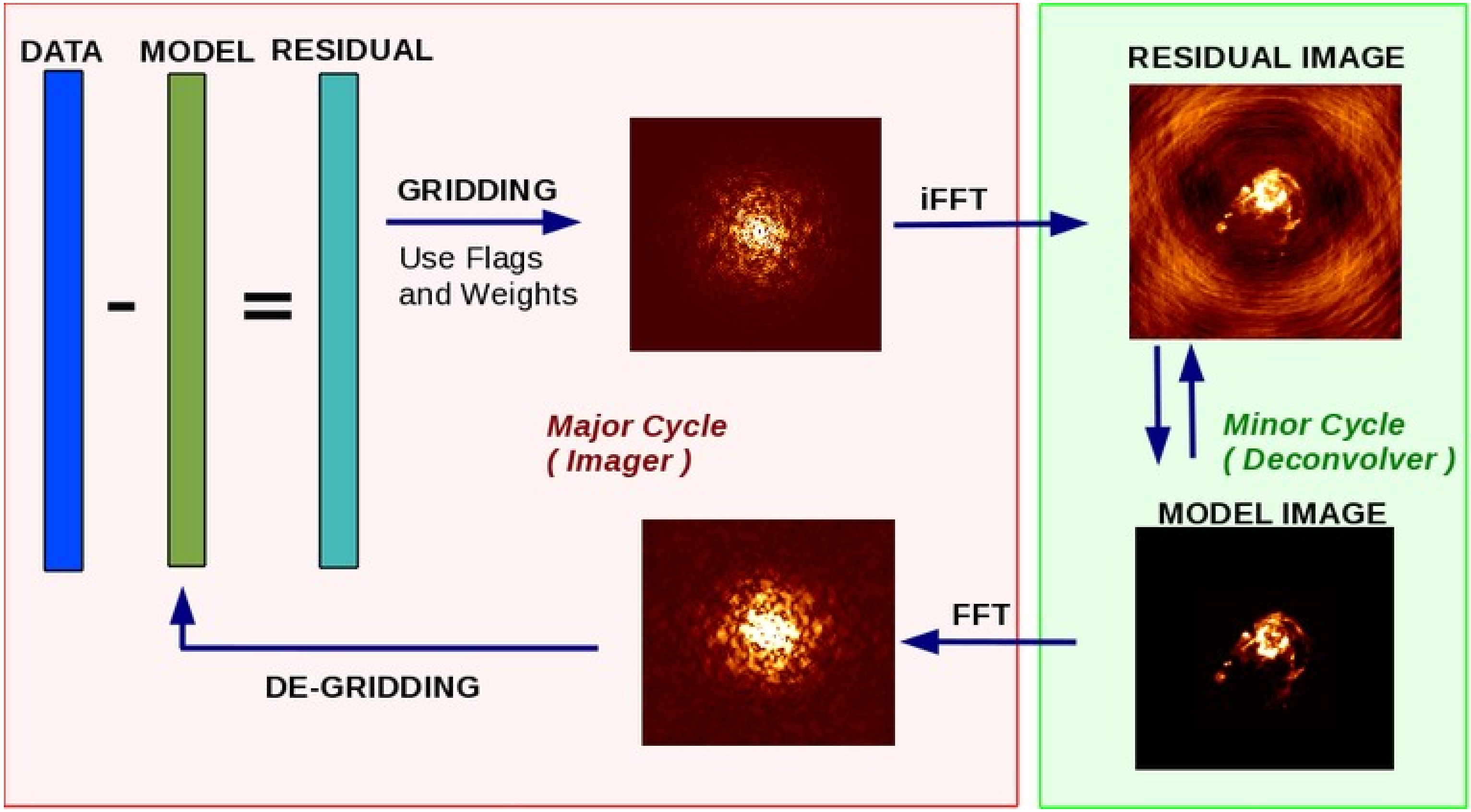
Task *tclean*

```
CASA <1>: 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                = []              # Cell size
phasecenter         = ''              # Phase center of the image
stokes              = 'I'             # Stokes Planes to make
projection          = 'SIN'           # Coordinate projection
startmodel          = ''              # Name of starting model image
```

Task *tclean*

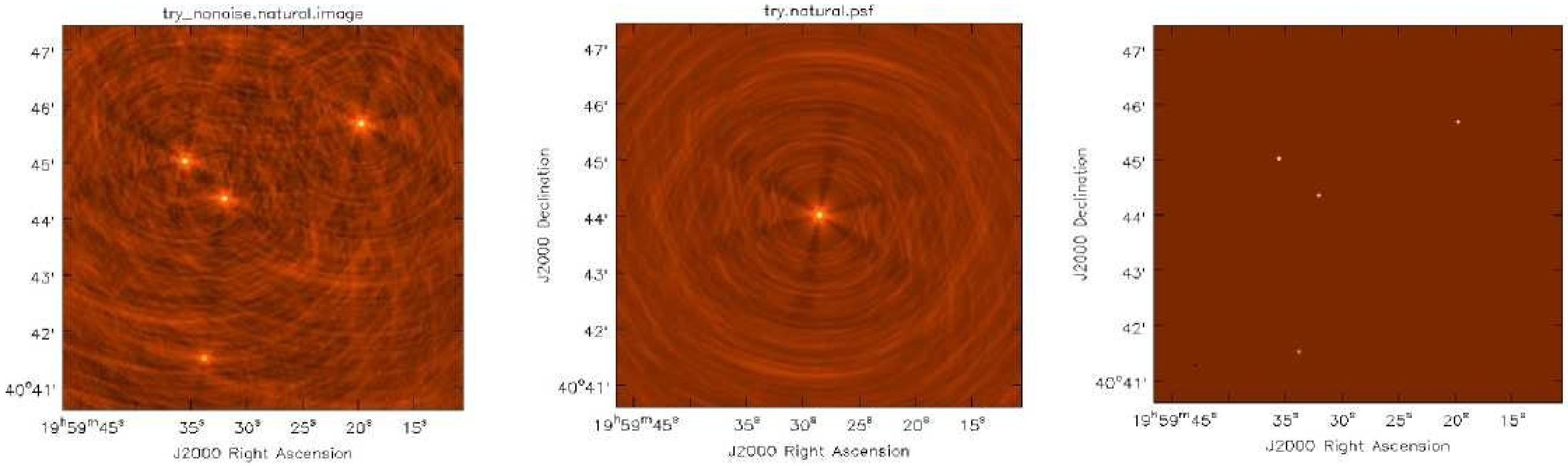
```
specmode            = 'mfs'         # Spectral definition mode (mfs,cube,cubedata, cubesource)
   reffreq          = ''            # Reference frequency
gridder             = 'standard'    # Gridding options (standard, wproject, widefield, mosaic, awproject)
   vptable          = ''            # Name of Voltage Pattern table
   pblimit          = 0.2           # PB gain level at which to cut off normalizations
deconvolver         = 'hogbom'      # Minor cycle algorithm (hogbom,clark,multiscale,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, briggsabs[experimental], briggsbwtaper[experimental])
   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, 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
fastnoise           = True          # True: use the faster (old) noise calculation. False: use the new improved noise calculations
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
   psfcutoff        = 0.35          # All pixels in the main lobe of the PSF above psfcutoff are used to fit a Gaussian beam (the Clean beam).
parallel            = False         # Run major cycles in parallel
```

Imaging as a minimization problem



Deconvolution

$$I^{obs}(l,m) = I^{PSF}(l,m) * I^{sky}(l,m)$$



Hogbom CLEAN

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

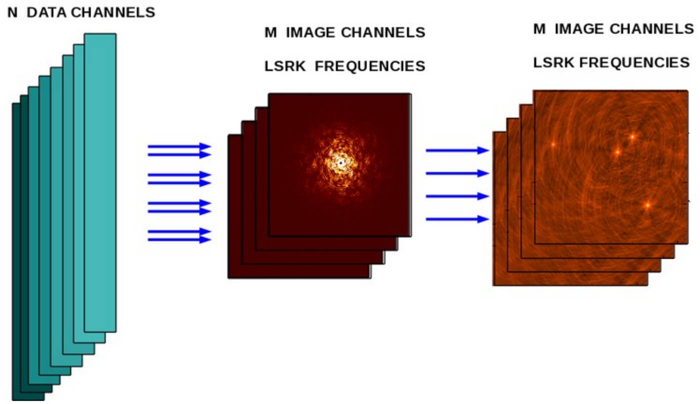
from the dirty image - a scaled/shifted copy of the PSF

Repeat steps (2), (3), (4) until a stopping criterion is reached.

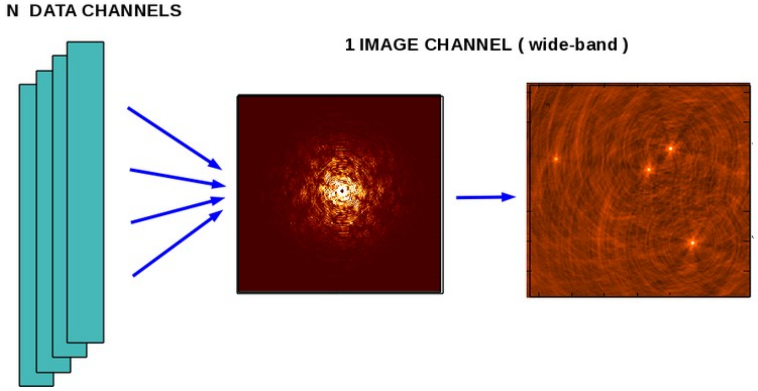
(5) Restore : Smooth the model with a ’clean beam’ and

add residuals

Mapping Data to Images - I



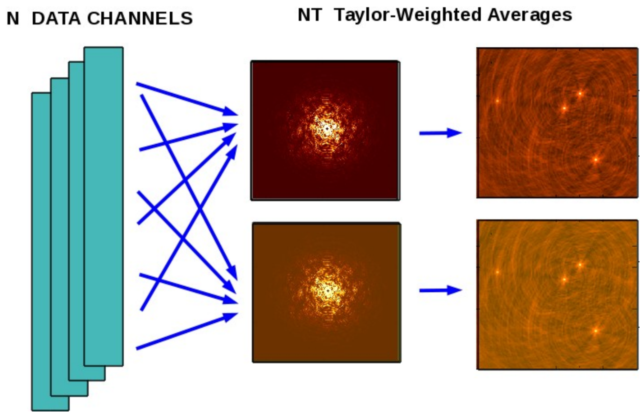
Cube Imaging
specmode='cube'
specmode='cubedata'



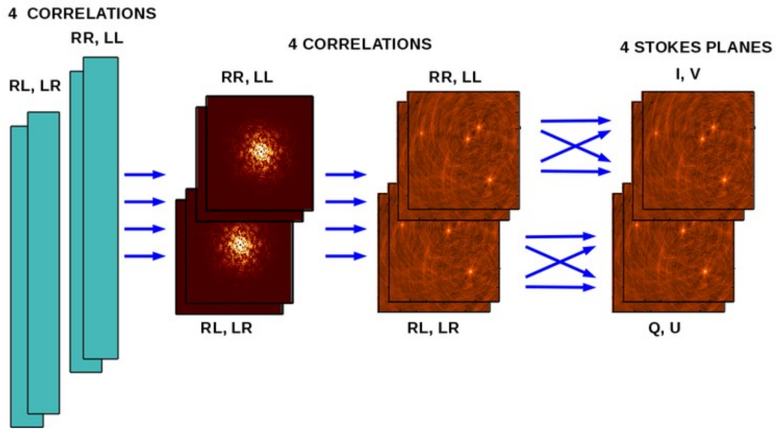
Continuum Imaging
specmode='mfs'

- specmode = 'mfs' - Continuum imaging. All channels on a single uv grid to produce an output image containing only one channel.
- specmode = 'cube' - Mapping relevant visibilities onto a set of image channels based on the frequency resolution of the output image in velocity space in the choice of reference frame.
- specmode = 'cubedata' Mapping relevant visibilities on a set of image channels but a direct mapping not requiring a regrid in velocity space.

Mapping Data to Images - II



Continuum Imaging
deconvolver = ‘mtmfs’
nterms = 2



Polarimetric Continuum Imaging
stokes = ‘IQUV’

Imaging in Practice - I

Step1 : Define image size, cell size and imagename

- 3 to 5 pixels across the psf for cell size.
- FoV that spans the full PB given cell size.
- https://science.nrao.edu/facilities/vla/docs/manuals/oss/performance/resolution

Step2 : Pick a gridding algorithm and data weighting

- “standard” gridder
- “briggs” weighting

Step 3: Run iterative deconvolution

- “hogbom” deconvolver
- niter=200 iterations.

Imaging in Practice - II

Iteration control & stopping criterion

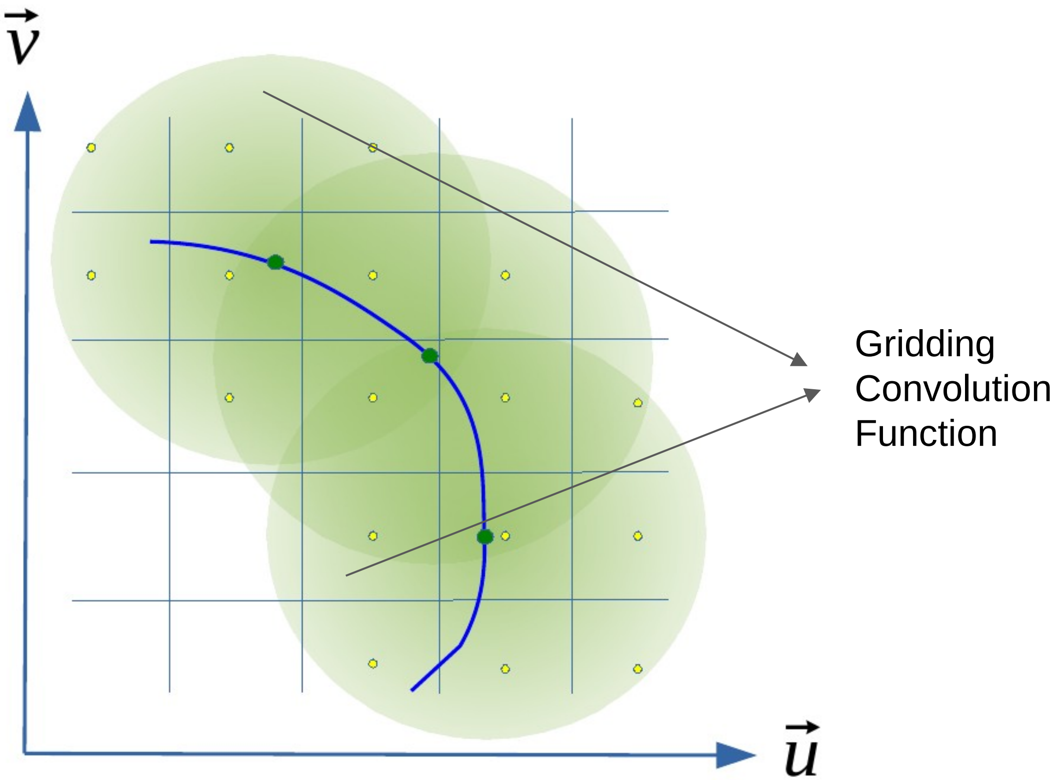
- ‘niter’ - Maximum number of deconvolution iterations to perform
- ‘threshold’ - Limit in flux density beyond which CLEANing will stop.
- ‘nsigma’ - A computed limit based on the imaging sensitivity

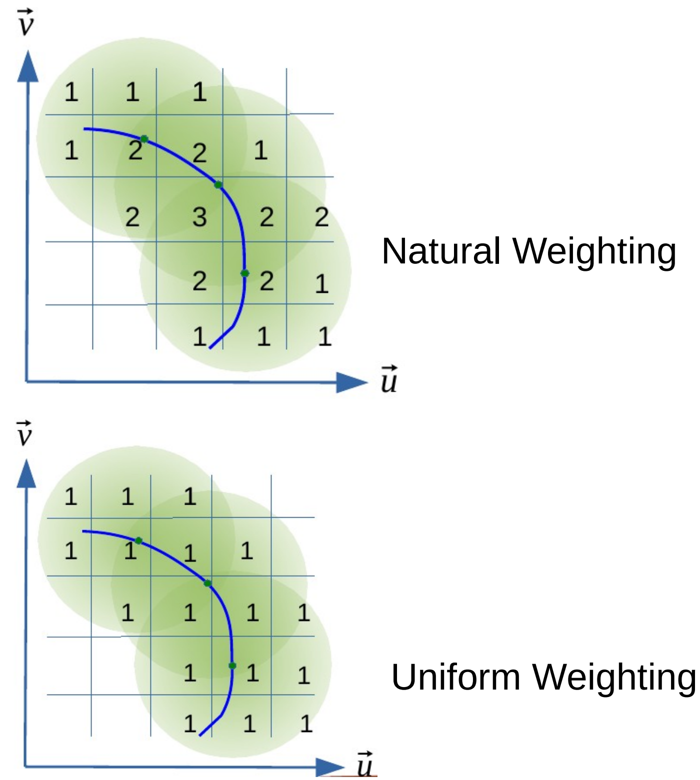
Masking

- Only needed when deconvolving complex structure
- Extended emission or a mixture of extended and compact emission

Masks can be drawn interactively, can also be supplied as a boolean image at the start of tclean.

Gridding & Weighting



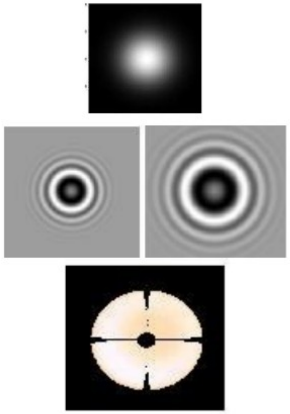


Convolutional Resampling of visibilities onto the centers of the uv grid cells.

Task *tclean* - Gridders

Gridding - Data domain operation of convolutional resampling of visibilities onto the centres of the uv cells.

Choice of an appropriate kernel can help correct for several direction dependent and instrumental effects.



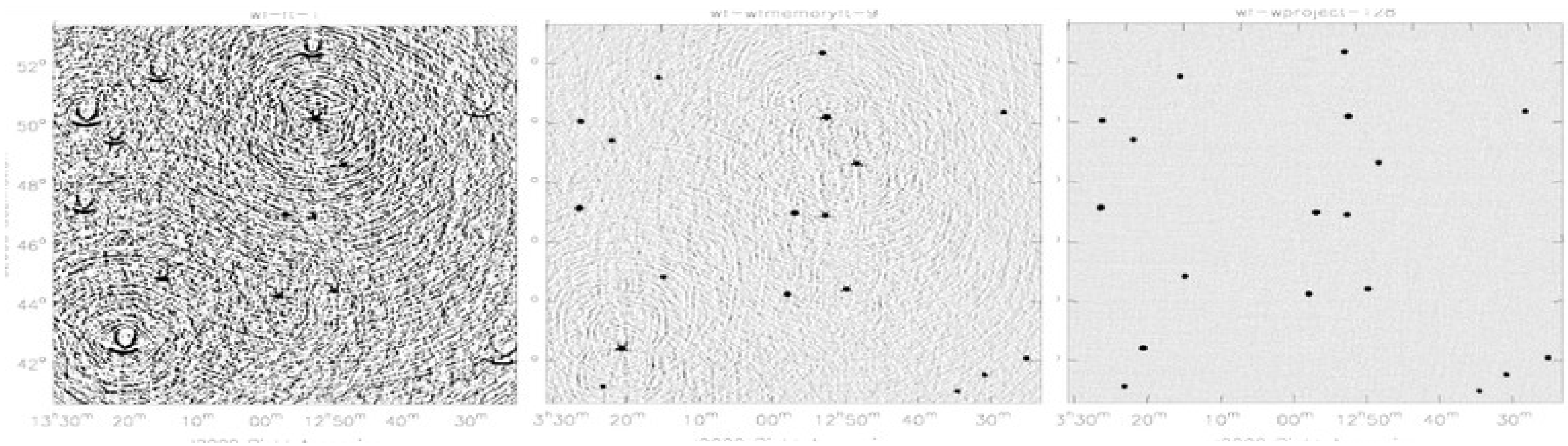
- Standard gridder - Prolate spheroidal function
  - gridder = ‘standard’
- W-Projection gridder - Frenel kernel
  - gridder = ‘wproject’
- A-Projection gridder - Aperture illumination function
  - gridder = ‘awproject’
- Mosaic gridder - Phase gradient + standard gridder + pbmodels
  - gridder = ‘mosaic’

Widefield Imaging - W projection

$$V^{obs}(u,v) = \iint S(l,m)I(l,m)e^{2\pi i(ul+vm)}dl\,dm$$

$$V^{obs}(u,v) = \iint S(l,m)I(l,m)e^{2\pi i(ul+vm+w(n-1))}dl\,dm\,dn$$

2D Imaging | Facet Imaging | W-Projection



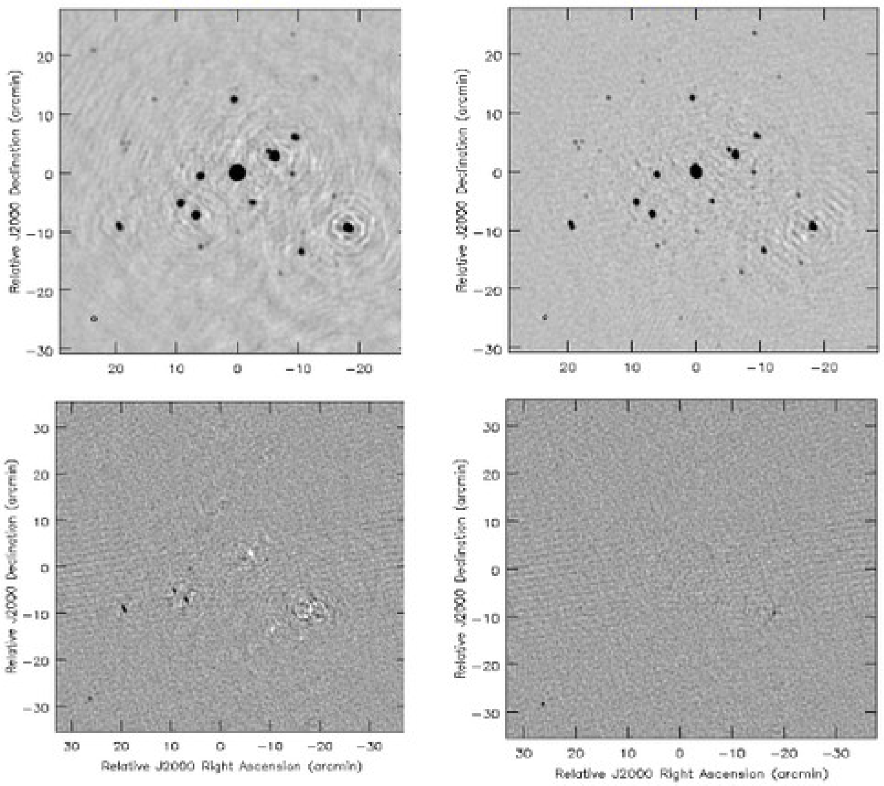
Widefield Imaging - A Projection

Before

After

Stokes I

Artifacts around all sources away from the pointing center



Stokes I

Artifacts removed or reduced within the main lobe

Stokes V

Artificial signals around bright sources due to beam squint

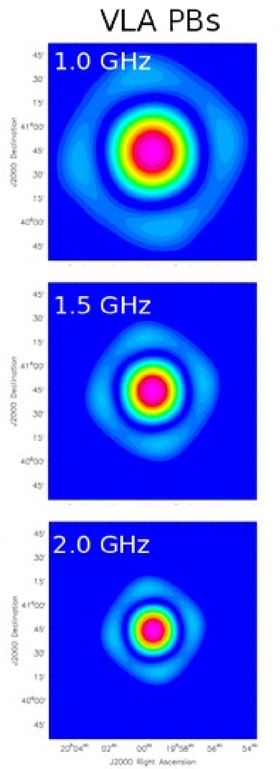
Stokes V

Instrumental Stokes V removed within the main lobe

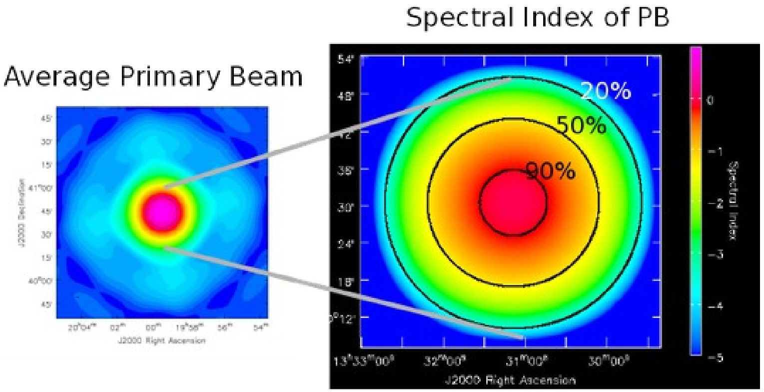
Widefield Wideband Imaging - AW Projection

The wide bandwidth of the VLA bands implies that the PB changes significantly in-band.

In addition VLA is alt-az mounted and has time variations in the PB due to field rotation



$$\alpha_{app} = \alpha_{source} + \alpha_{PB}$$



$$I^{obs}(l,m) \approx I^{PSF}(l,m) * [P^{sky}(l,m) . I^{sky}(l,m)]$$

Mapping Data to Images - III

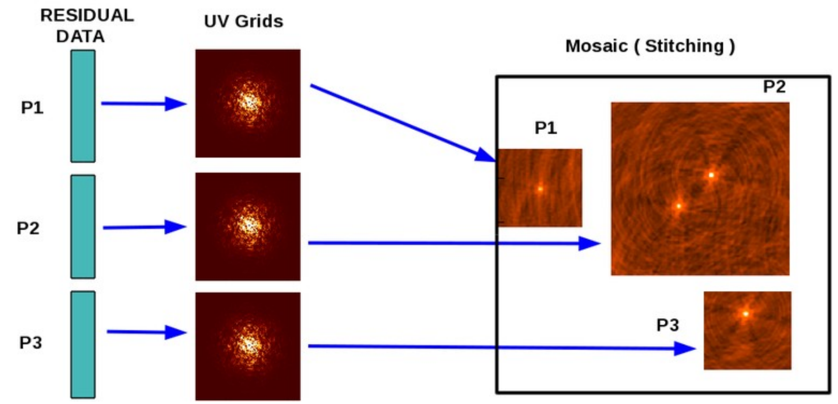
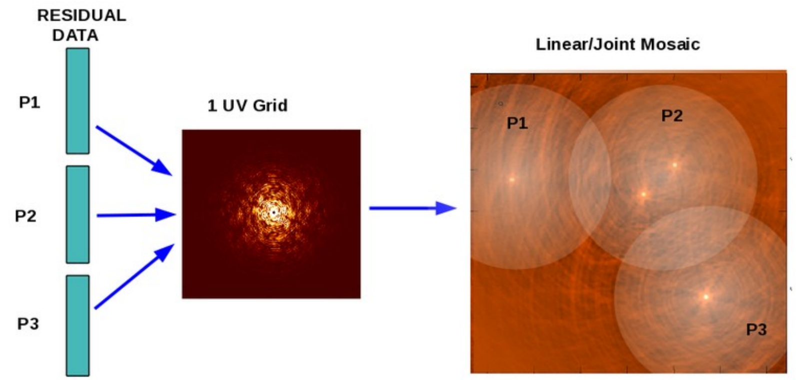
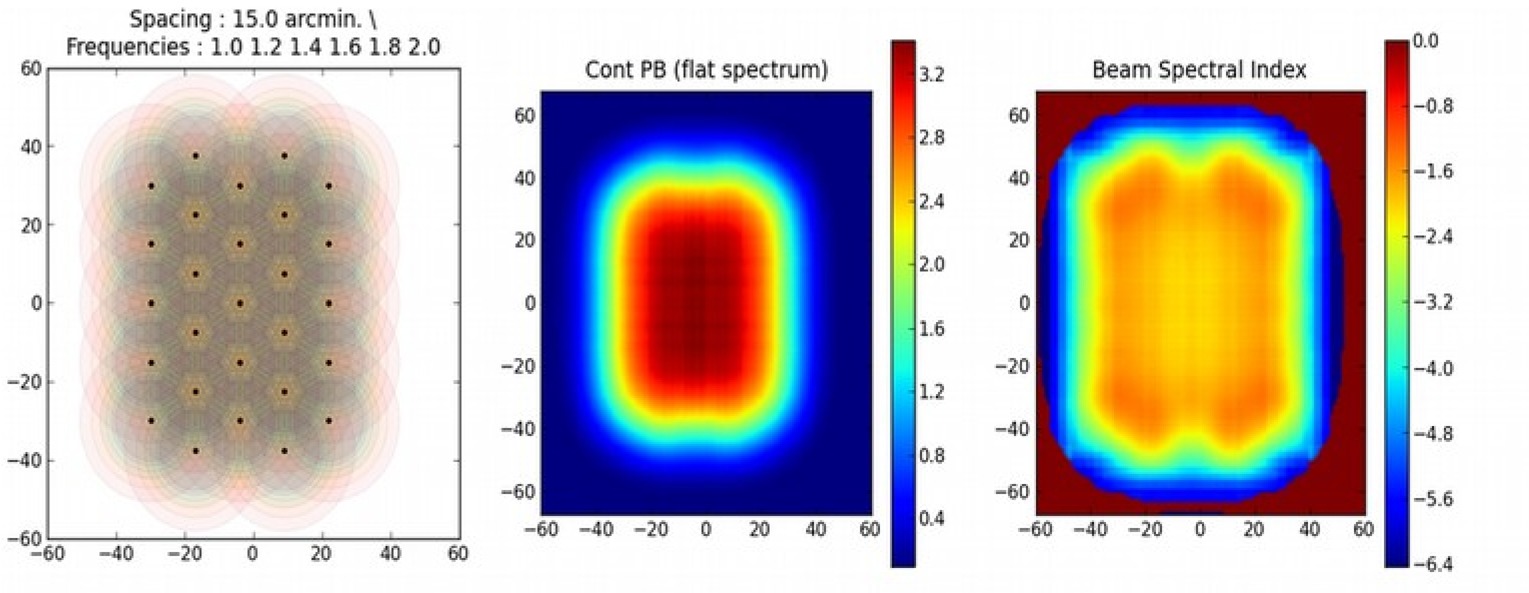


Image Plane Mosaic Imaging



Joint UV Mosaic Imaging
gridder = ‘mosaic’
gridder = ‘awproject’

Widefield Imaging - Mosaicking



Mosaic Pattern

Mosaic PB Sensitivity

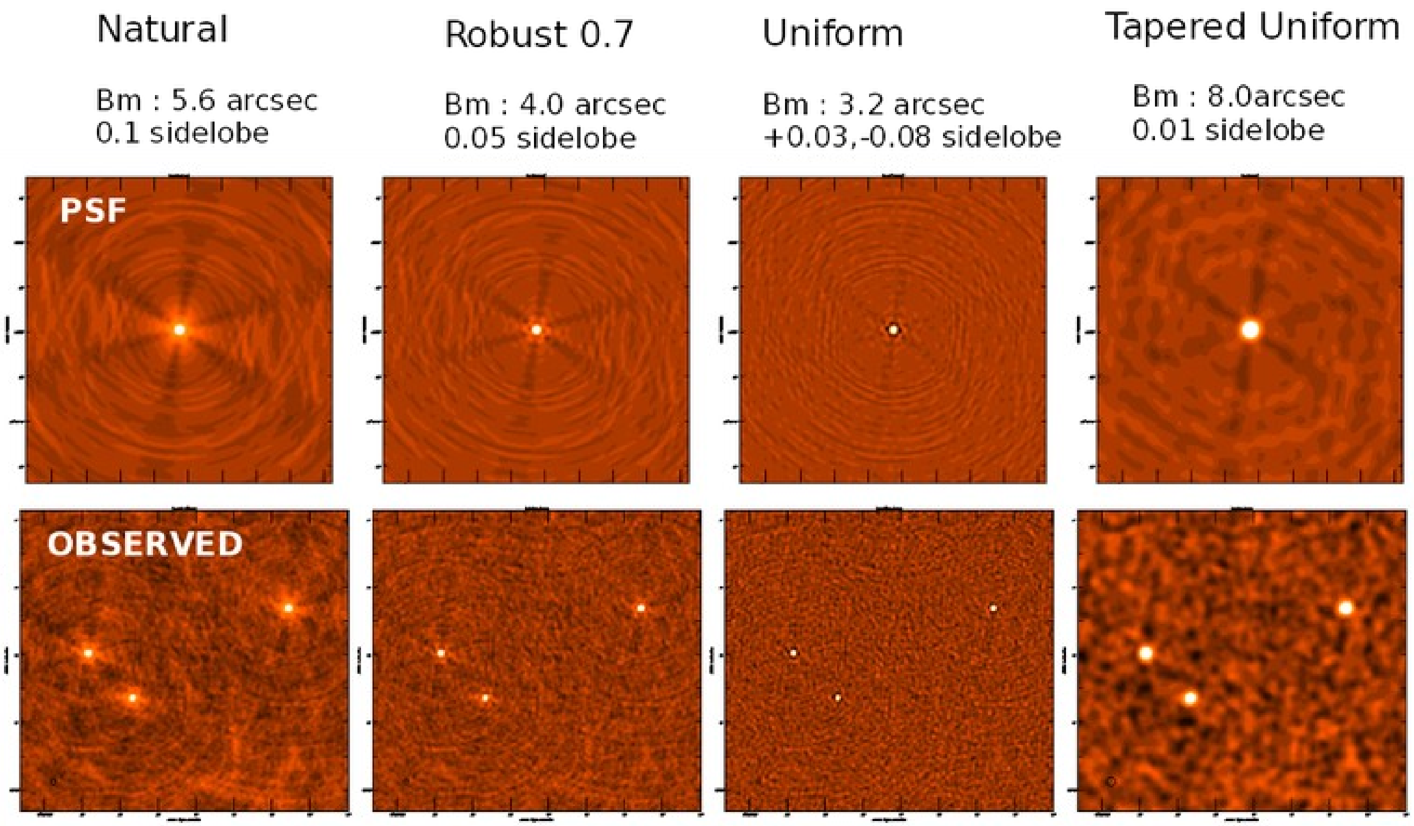
Mosaic PB
alpha

Task *tclean* - Weighting

The gridded visibilties can be weighted differently to alter the sensitivity and the resolution of the psf.

- Natural Weighting - Maximal sensitivity, wider psf, more sensitive to extended structure. **weighting = ‘natural’**
- Uniform Weighting - Reduced sensitivity, narrower psf, favors point sources. **weighting = ‘uniform’**
- Briggs (Robust) Weighting - Smoothly varying function between natural and uniform weighting. **weighting = ‘briggs’, robust = -2 to 2**
- UV Taper - Emphasize larger scales in the data. **uvtaper = []**

Weighting


Natural
Bm : 5.6 arcsec
0.1 sidelobe
Robust 0.7
Bm : 4.0 arcsec
0.05 sidelobe
Uniform
Bm : 3.2 arcsec
+0.03,-0.08 sidelobe
Tapered Uniform
Bm : 8.0arcsec
0.01 sidelobe
PSF
OBSERVED

Task *tclean* - Deconvolver

deconvolver = 'hogbom' - Favors point sources, sky modelled as delta functions.

deconvolver = 'clark' - Favors point sources, sky modelled as delta functions, uses a small patch of psf rather than the whole.

deconvolver = 'multiscale' - Sky is modelled using a series of 2D gaussian basis. Circular basis functions convolved with a psf. Defined by **scales** parameter.

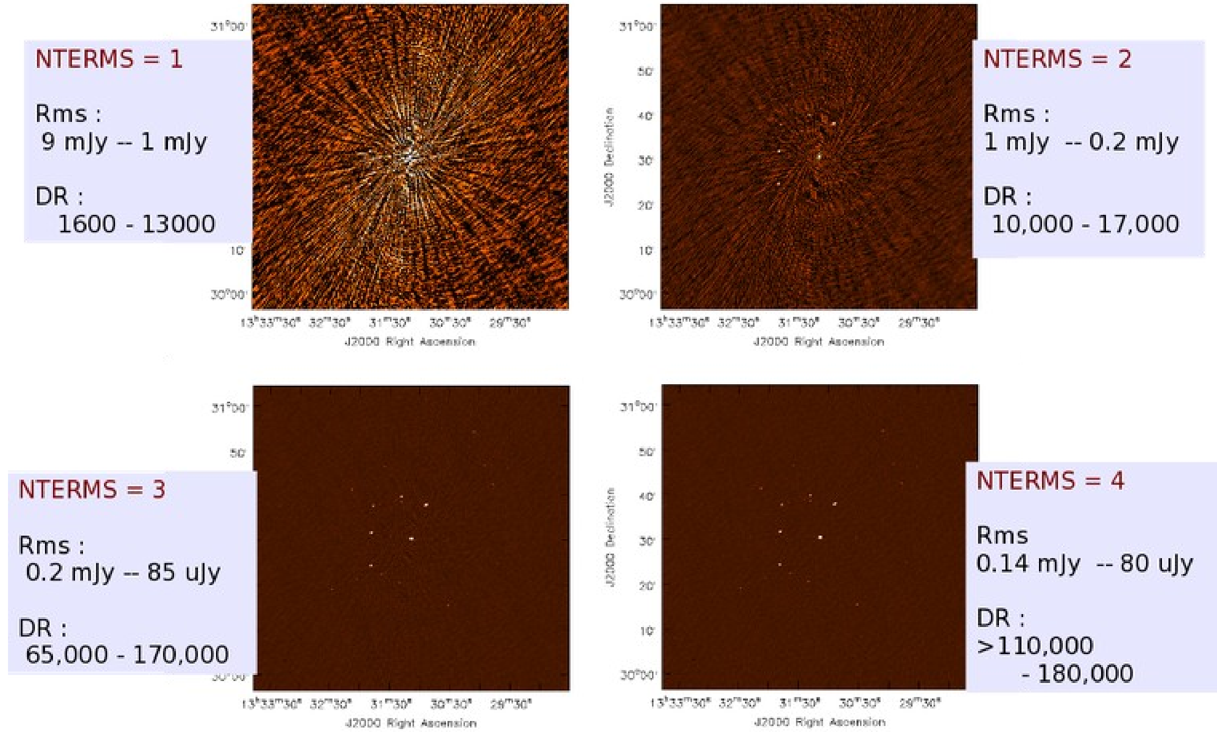
deconvolver = 'multiterm' - Wideband sky is modelled as Taylor polynomials across frequency. Allows you to discover the frequency dependence of the sky model in addition to its spatial scales. Defined by **nterms** and **scales** parameters

deconvolver = 'aasp' - Sky is modelled as a series of 2D gaussians but the number of gaussians needed and their size is automatically determined.

Wideband Imaging

Do the sources of interest in your field have significant spectral structure across the observed bandwidth ?

Are you dynamic range limited and your source still displays spokes ?



Task *tclean* - Runtime & Memory

Image size - Scales as the square of number of pixels.

Data size - Scales linearly as the number of visibilities

Gridding - Scales as a function of the algorithm and the corresponding convolution function size 3x3 for standard gridder to up to 200x200 for w-projection.

Deconvolver - MSClean and MTMFS require multiple scales or multiple terms to be gridded and held in memory so is significantly slower than hogbom or clark.

Iteration Control - The frequency of major cycles and sensitivity based stopping criterion

Hardware - Serial vs Parallel execution. OpenMP enabled ? RAM/core. Number of cores utilized overall.

Summary

Choice of algorithm is very important

- Gridder & weighting
- Deconvolution

Pick the algorithm/tool that is appropriate for your science.

Self-calibrate your images if needed. (Steve's talk)

A detailed imaging guide is available here
https://casaguides.nrao.edu/index.php?title=VLA_CASA_Imaging-CASA6.2.0

If your image looks weird ask yourself the following questions

- Is my cell size correct ?
- Am I imaging all the emission in the field ?
- Is my algorithm appropriate for the data being reduced.