Imaging

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This indicates slides for you to try out at your own convenience.

I will provide links to sample scripts and data used in the interactive section of the talk.

All the interactive sections are based on a subset of the 3C75 data set used in the casa polarization guide.

The 1.2 GB dataset utilized for this talk can be found at http://www.aoc.nrao.edu/~pjaganna/DRW_2021/

There is a script in that location for you to play with. Copy pasting into casa might have some formatting errors. So do keep that in mind.

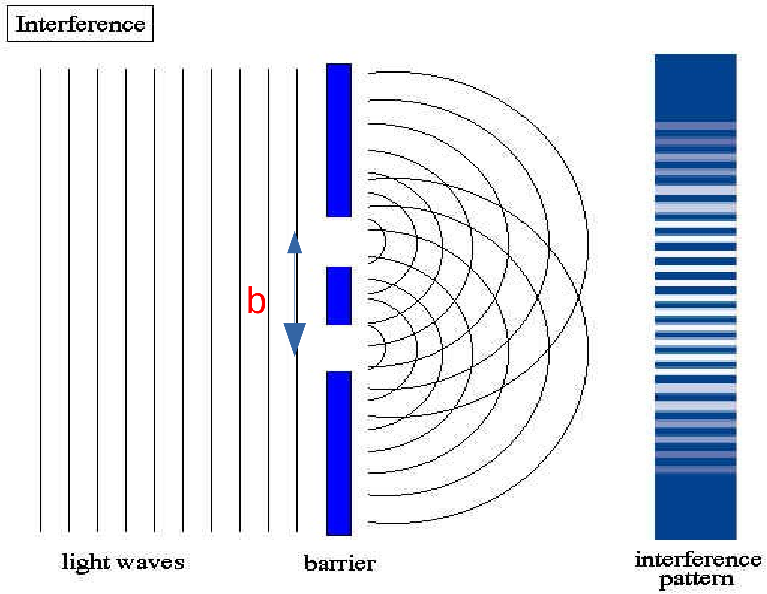
Overview

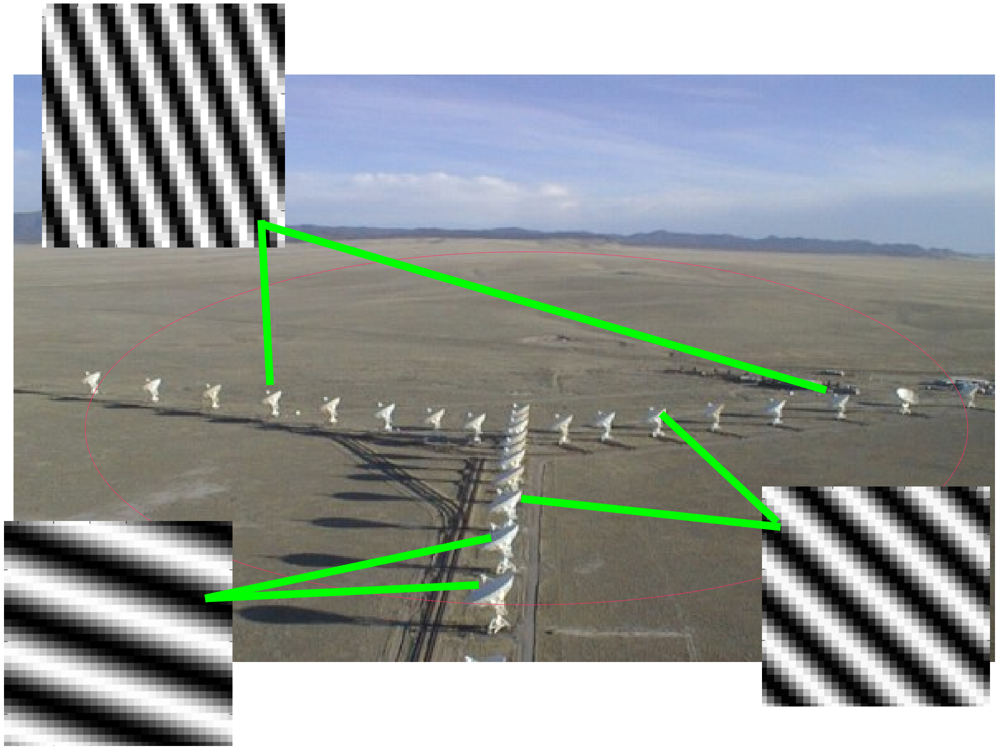
- Imaging Fundamentals
  - Van Cittert – Zernike theorem
  - Going from data to Images.
- tclean and how it maps to imaging fundamentals
- Wideband – multiscale continuum imaging
- Cube Imaging
- Interactive example to try out for yourself.

Interometry

- An interferometer measures the interference pattern of the sky per baseline.

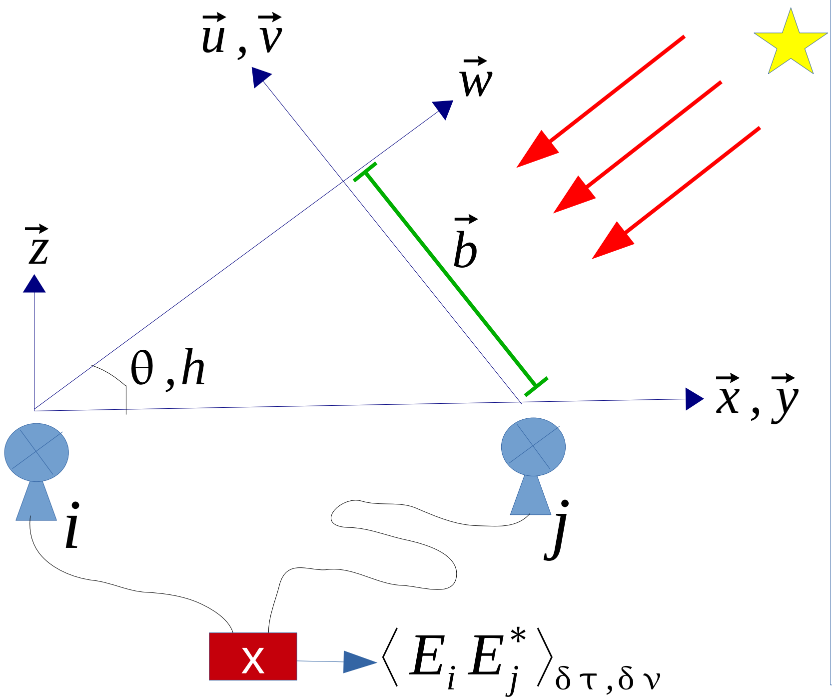
Young's double slit experiment



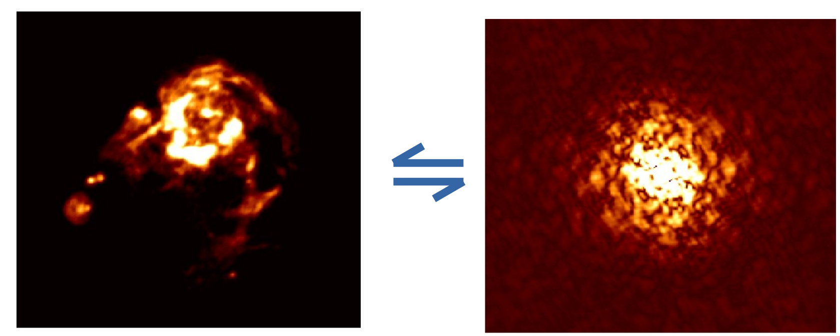


Parameters of a Fringe : Amplitude, Phase, Orientation, Wavelength

Van Cittert Zernike Theorem



Real | Imaginary



$I^{sky}(l,m)$

Sky Brightness (RA – DEC coordinates)

$V(u,v)$

Visibility Function (Spatial Freq. coordinates)

$$\langle E_i E_j^* \rangle \propto V_{ij}(u,v) = \iint I^{sky}(l,m)\, e^{2\pi i (ul+vm)}\, dl dm$$

Aperture Synthesis

- Measure as many baselines as possible ie. fill UV plane.

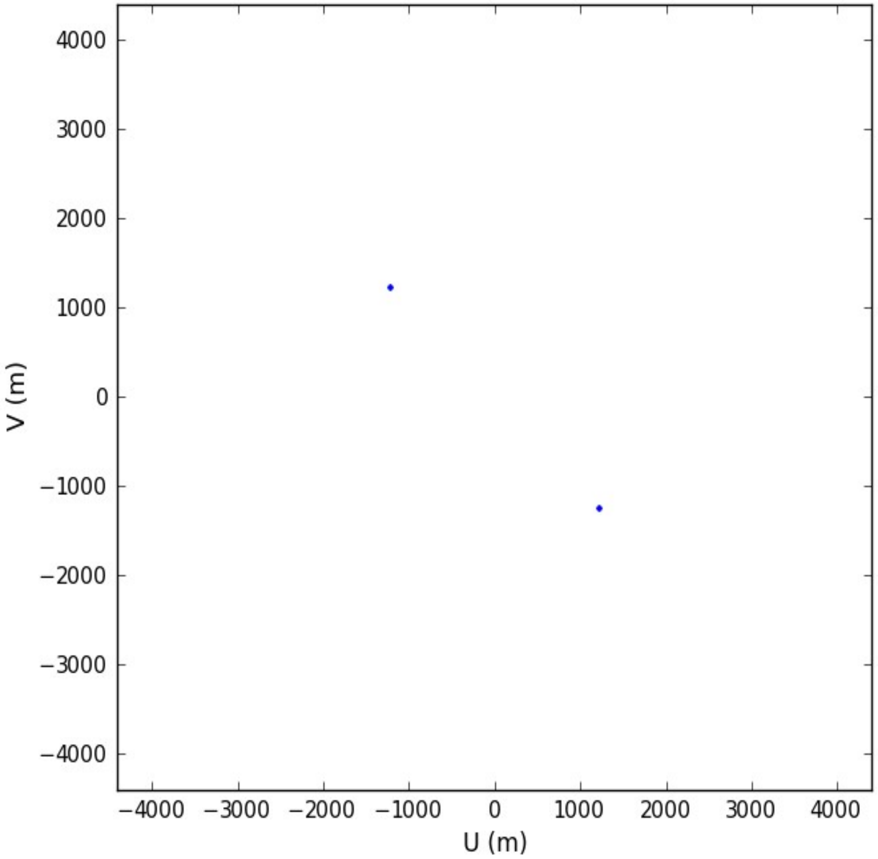
- VLA 27 antennas – 351 unique baseline

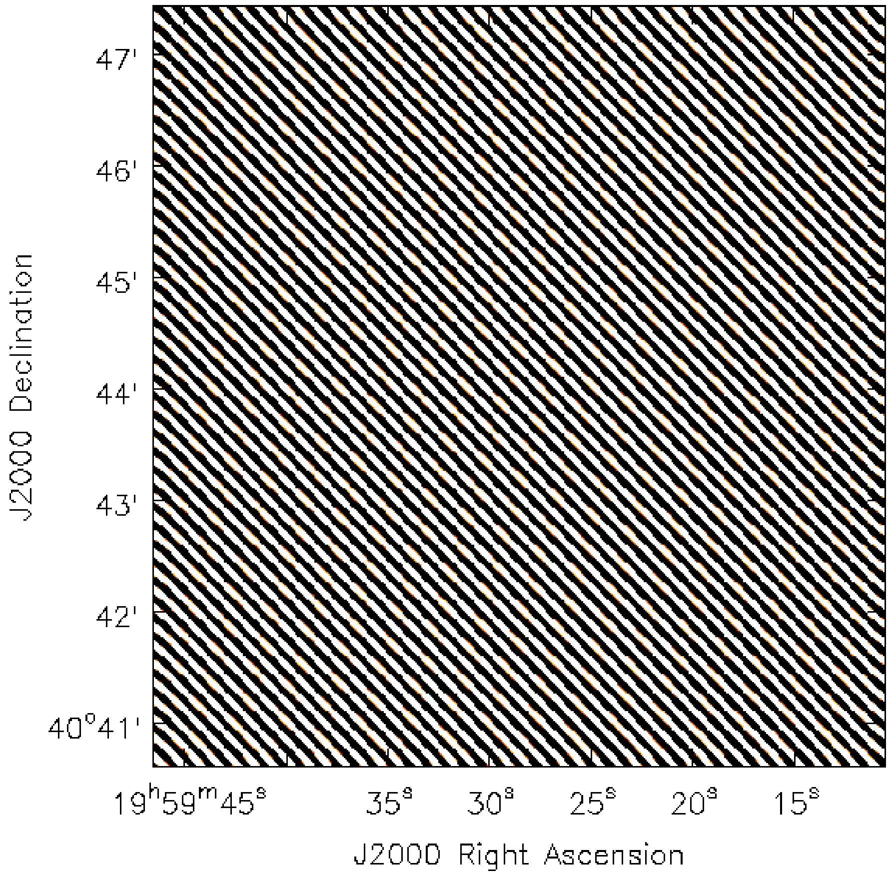
- Different Az-El corresponds to unique u,v for the same baseline – time dependence

- Different frequency of observation fills different for a given baseline – frequency dependence

Aperture Synthesis

Courtesy – U.Rau





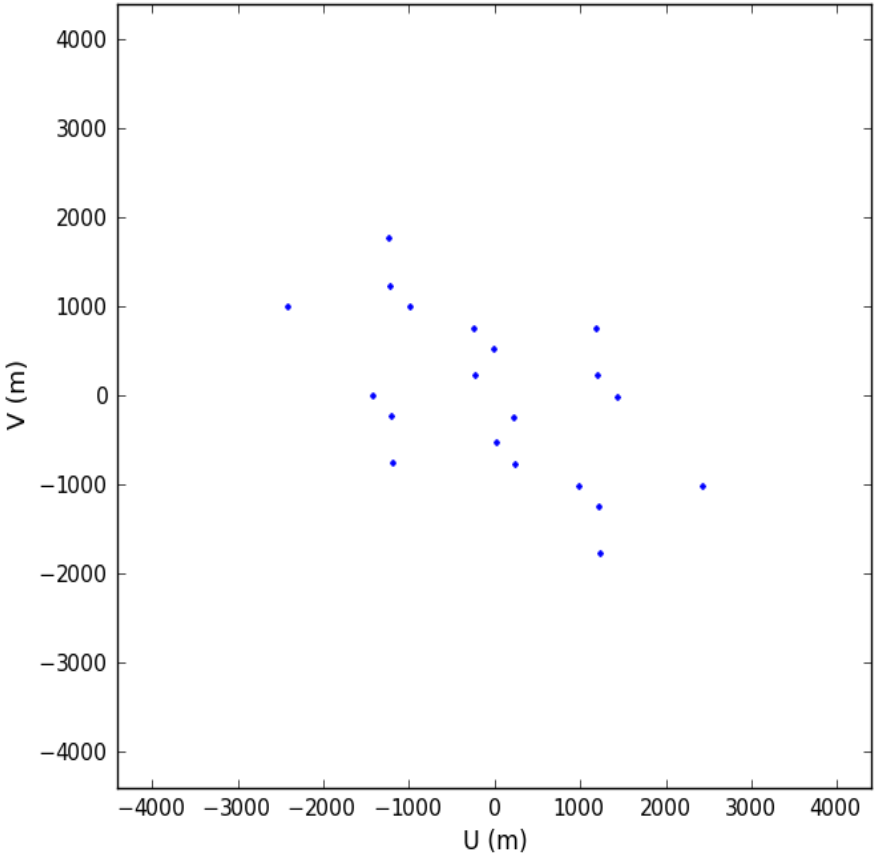
$S(u,v)$

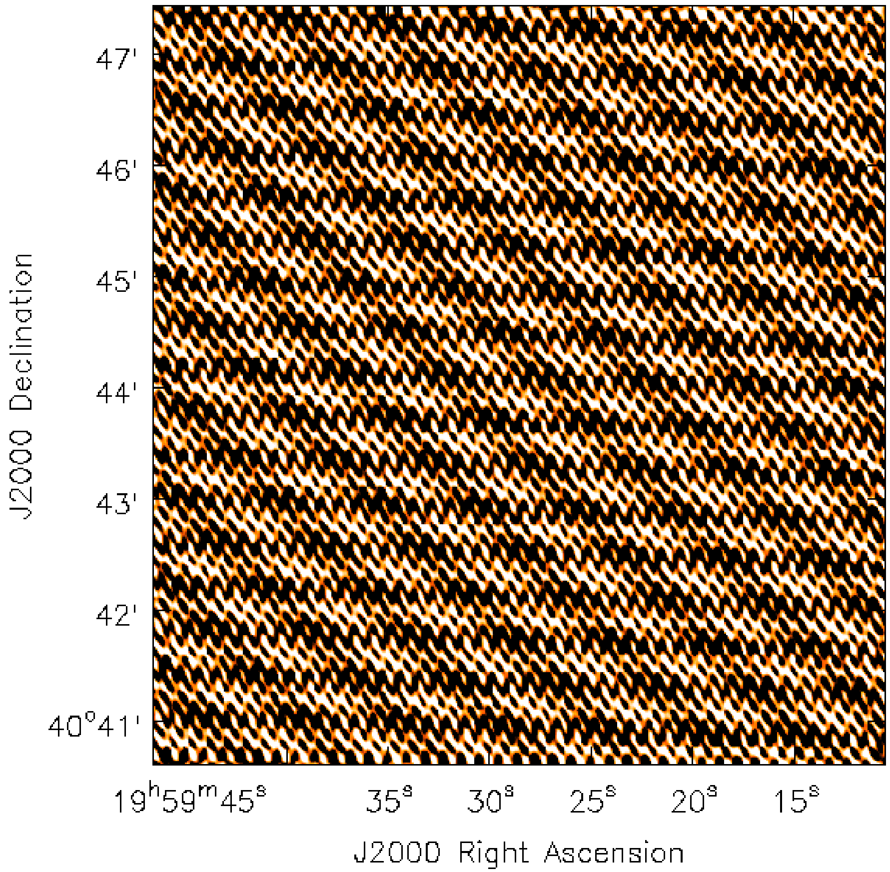
Image of the sky
using 2 antennas

$I^{obs}(l,m)$

Aperture Synthesis

Courtesy – U.Rau





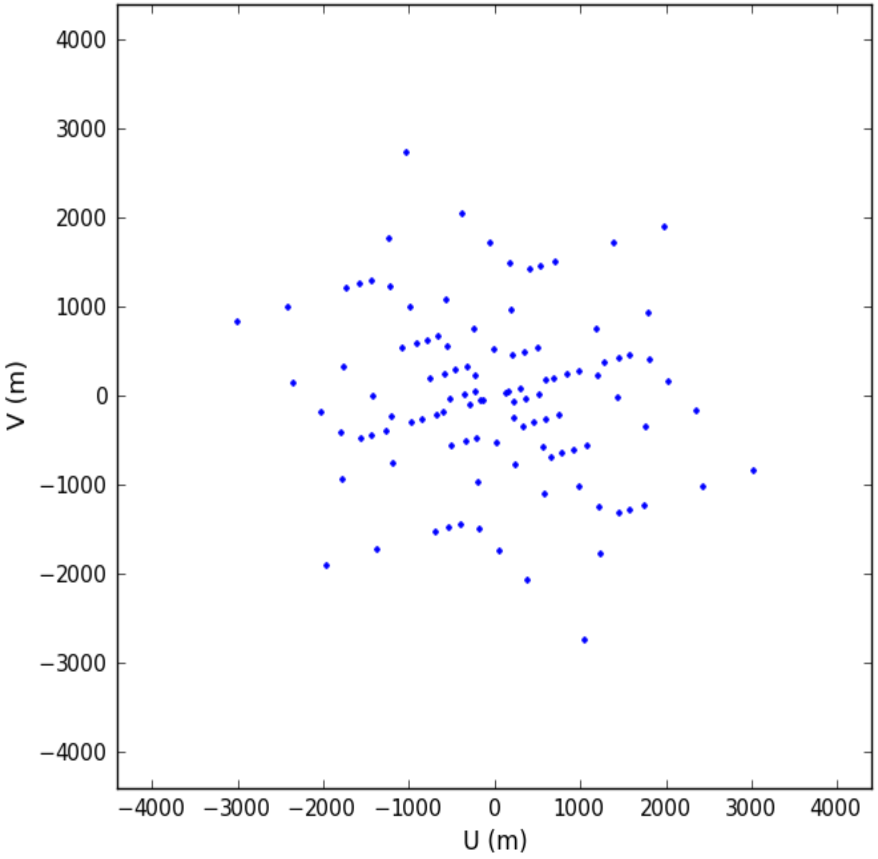
$S(u,v)$

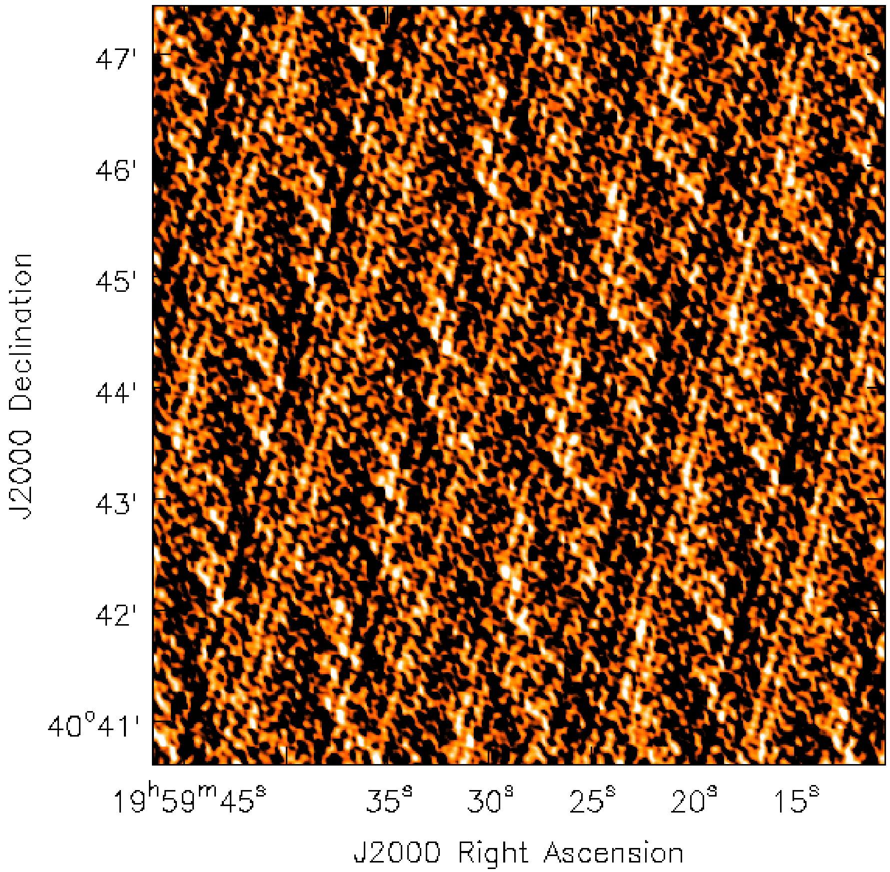
Image of the sky using 5 antennas

$I^{obs}(l,m)$

Aperture Synthesis

Courtesy – U.Rau





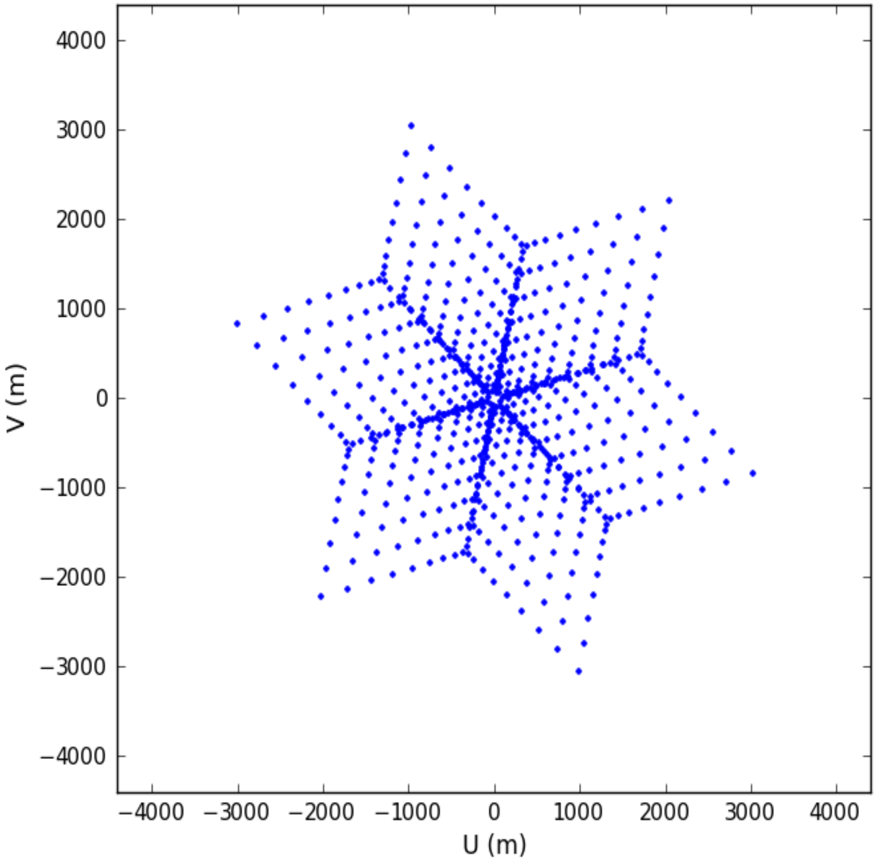
$S(u,v)$

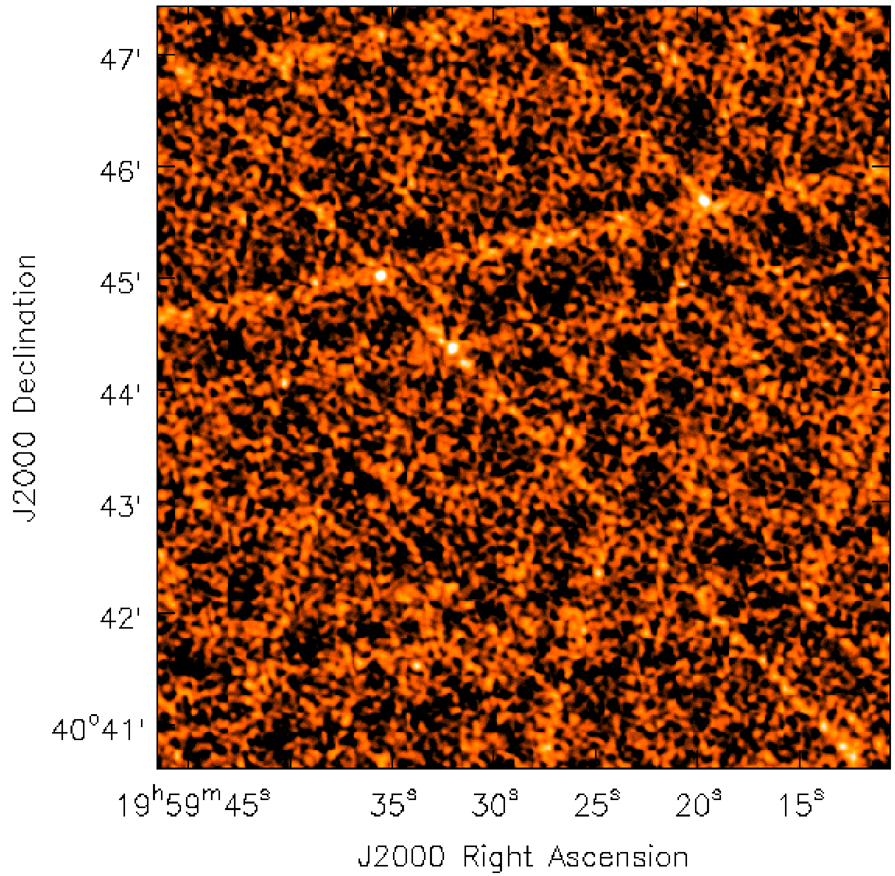
Image of the sky
using 11 antennas

$I^{obs}(l,m)$

Aperture Synthesis

Courtesy – U.Rau



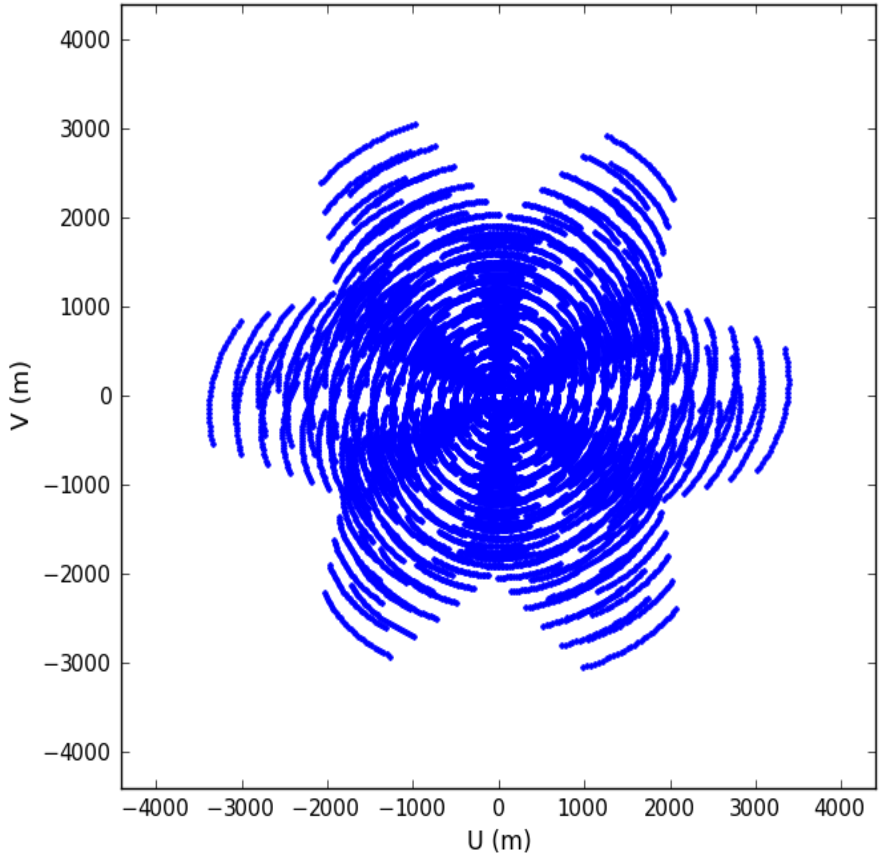


$S(u,v)$

Image of the sky
using 27 antennas

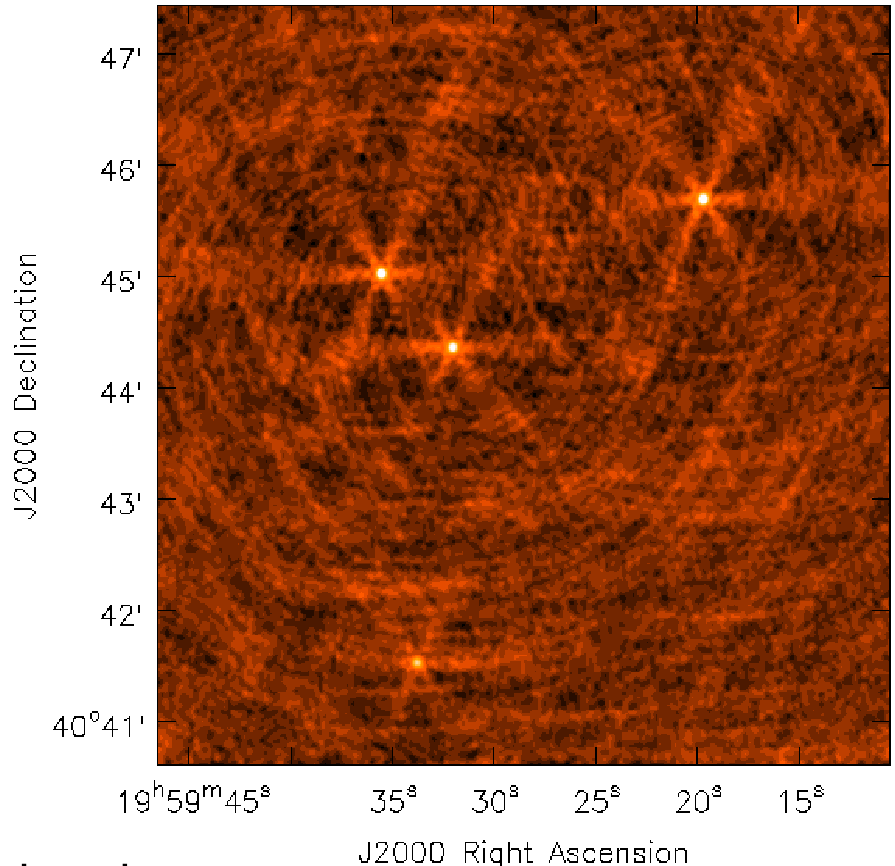
$I^{obs}(l,m)$

Aperture Synthesis



$$S(u,v)$$

Courtesy – U.Rau

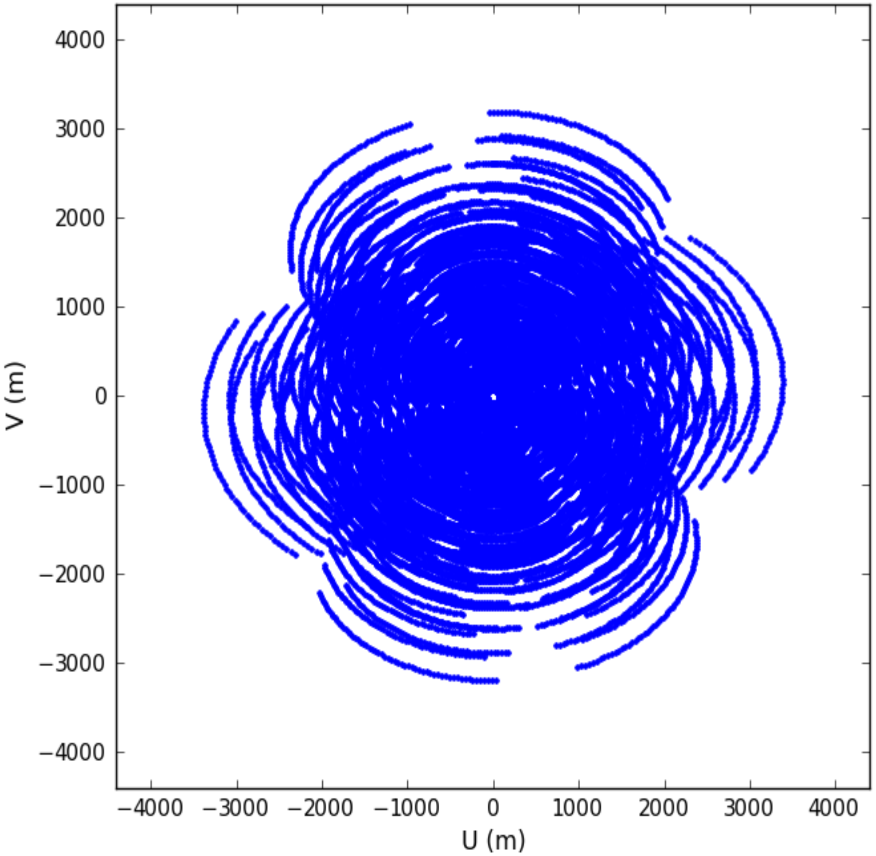


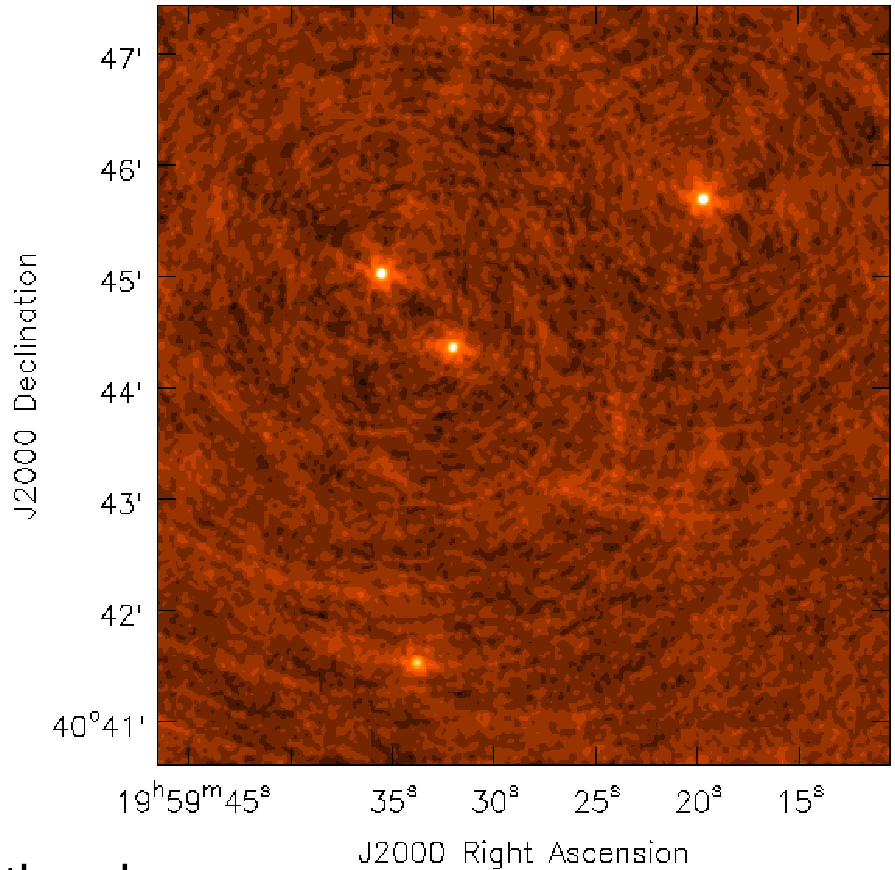
$$I^{obs}(l,m)$$

Image of the sky using 27 antennas over 2 hours.

Aperture Synthesis

Courtesy – U.Rau





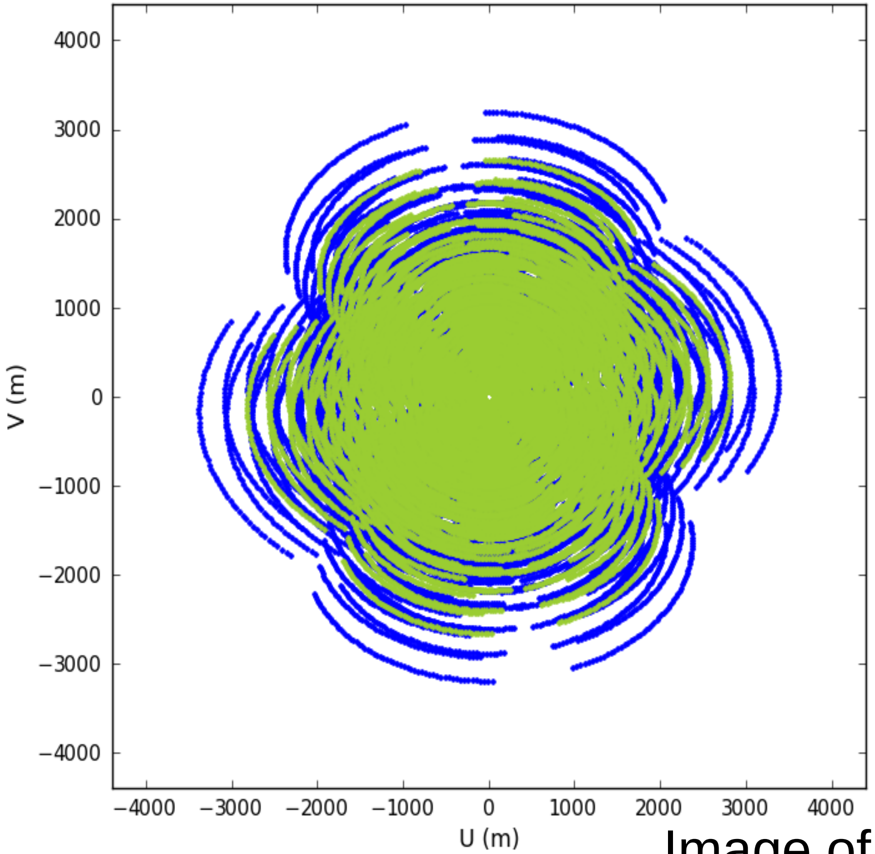
$S(u,v)$

Image of the sky using 27 antennas over 4 hours

$I^{obs}(l,m)$

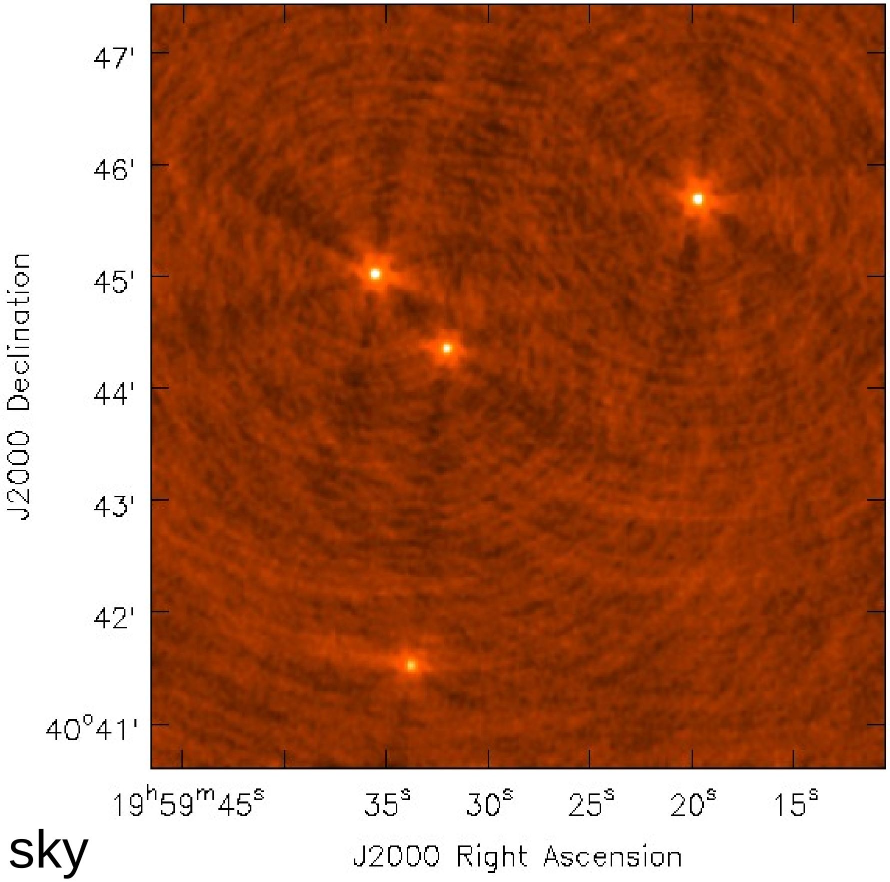
Aperture Synthesis

Courtesy – U.Rau



$S(u,v)$

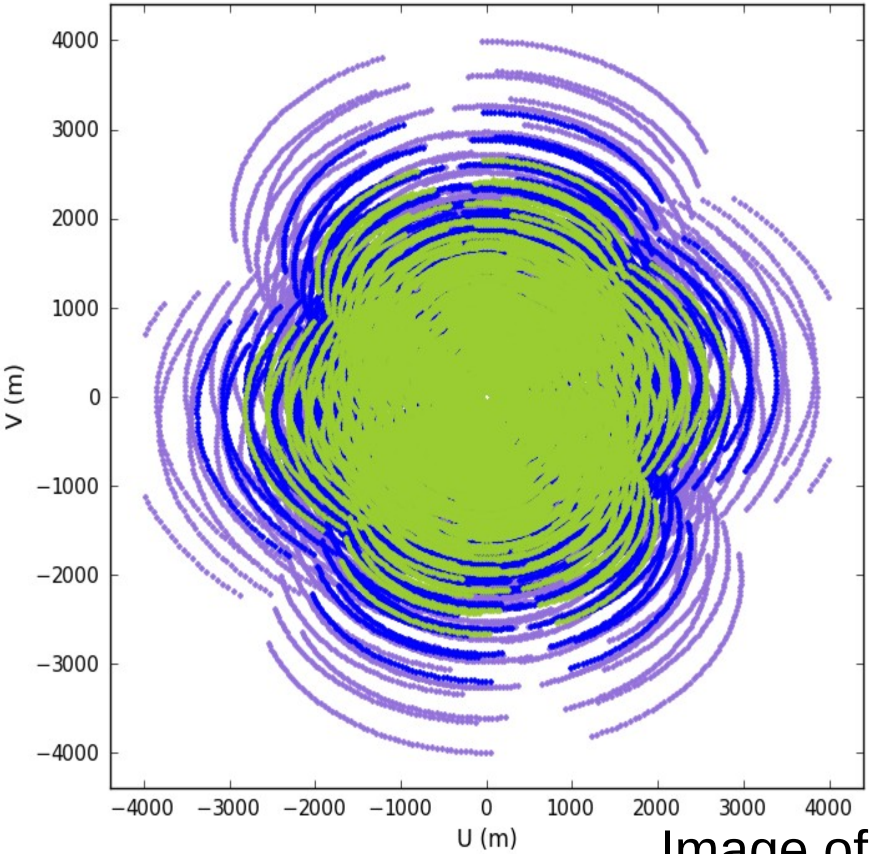
Image of the sky
using 27 antennas over 4
hours across 2 spw

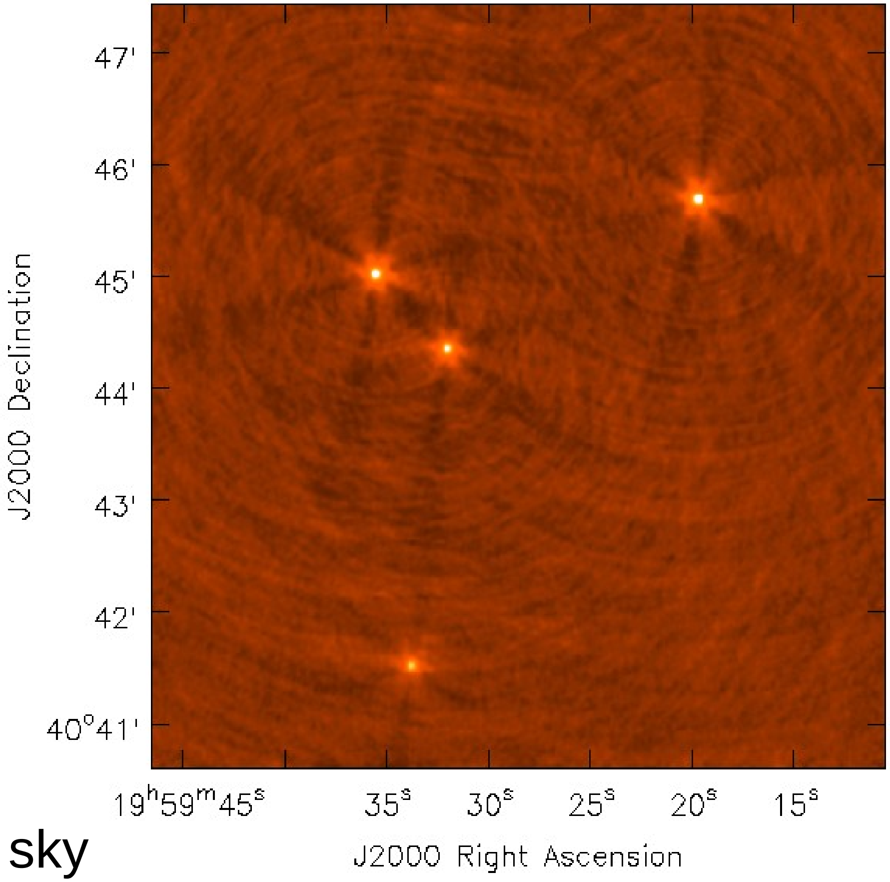


$I^{obs}(l,m)$

Aperture Synthesis

Courtesy – U.Rau





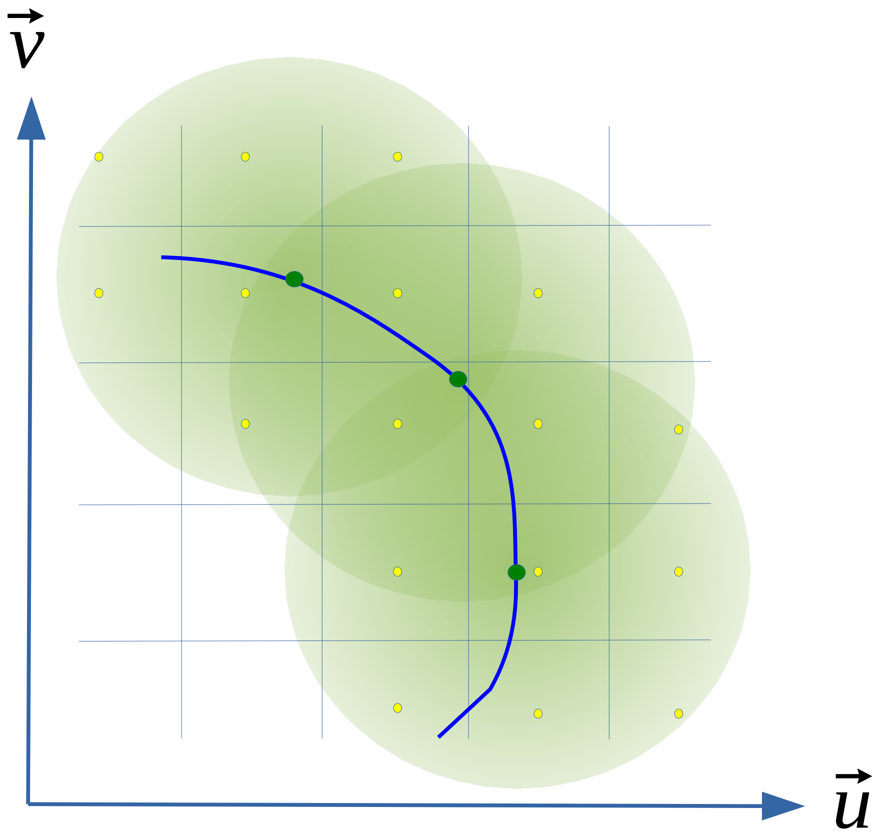
$S(u,v)$

Image of the sky
using 27 antennas over 4
hours across 8 spw

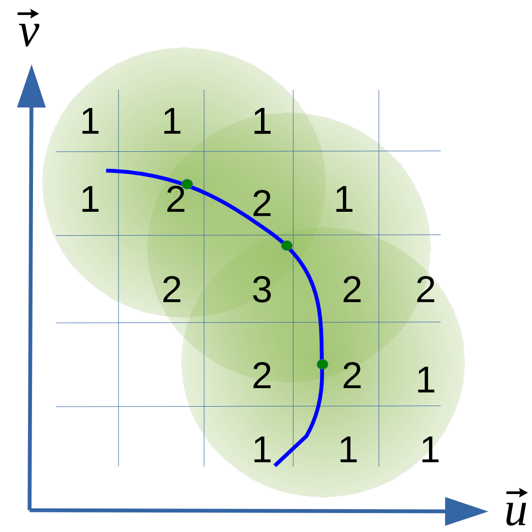
$I^{obs}(l,m)$

Gridding & Weighting

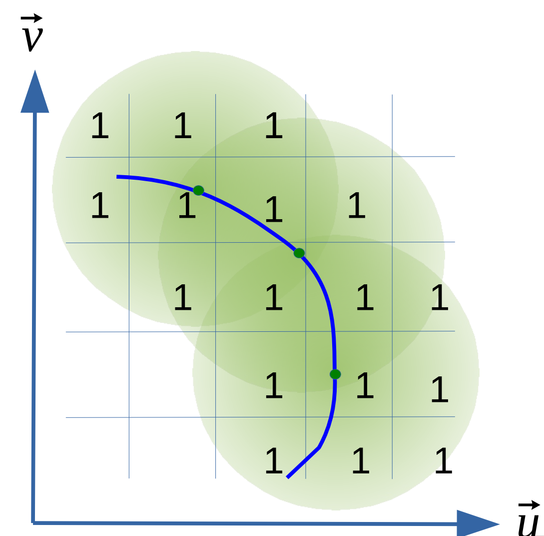
Courtesy – U.Rau



Gridding – Convolutional Resampling



Natural Weights



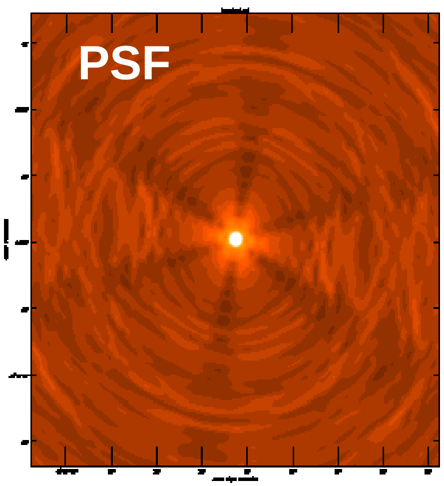
Uniform Weights

Weighting

Courtesy – U.Rau

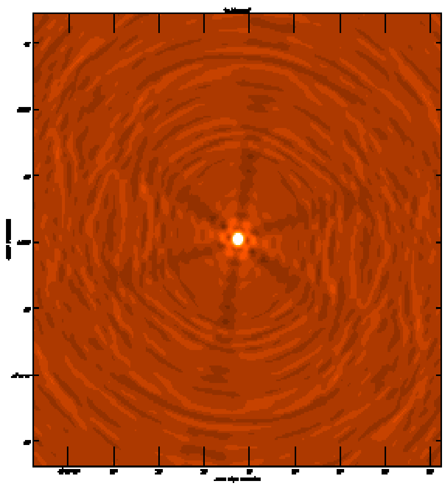
Natural

Bm : 5.6 arcsec
0.1 sidelobe



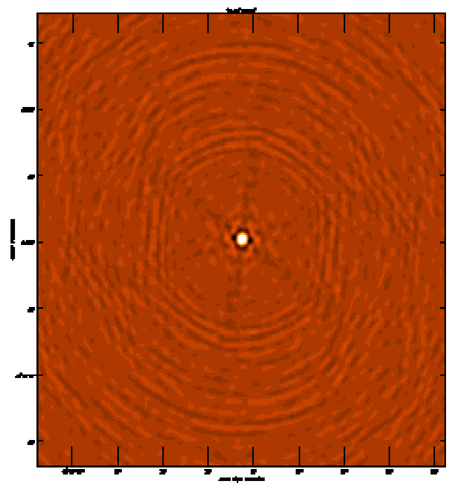
Robust 0.7

Bm : 4.0 arcsec
0.05 sidelobe



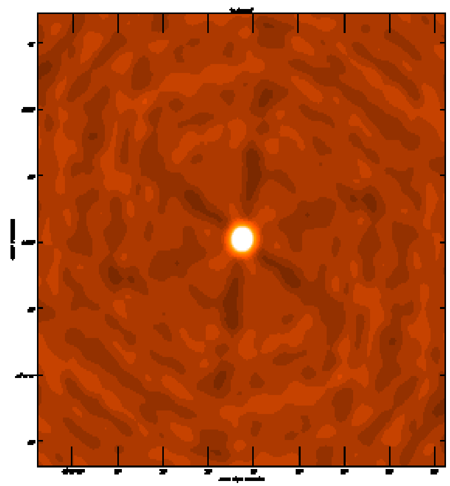
Uniform

Bm : 3.2 arcsec
+0.03,-0.08 sidelobe



Tapered Uniform

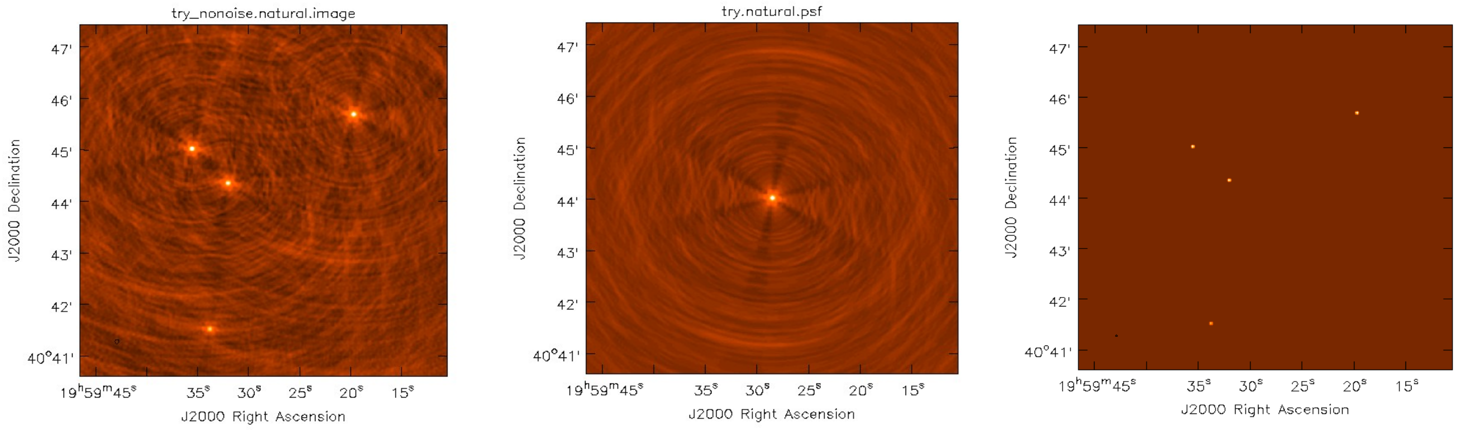
Bm : 8.0arcsec
0.01 sidelobe



Deconvolution

Courtesy – U.Rau

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



Deconvolution – Hogbom CLEAN

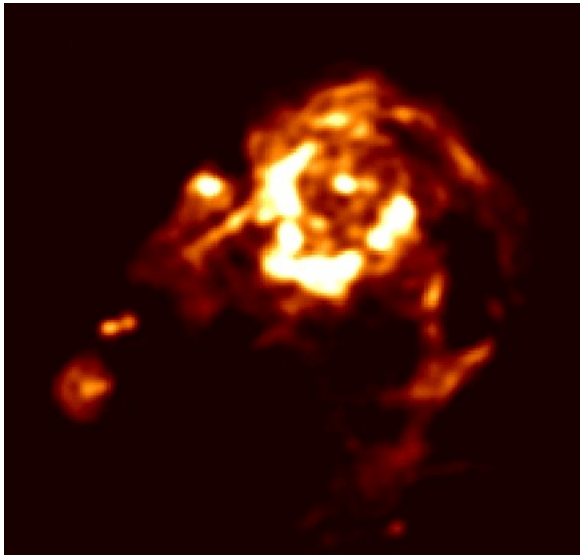
Sky Model : List of delta-functions

- (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.

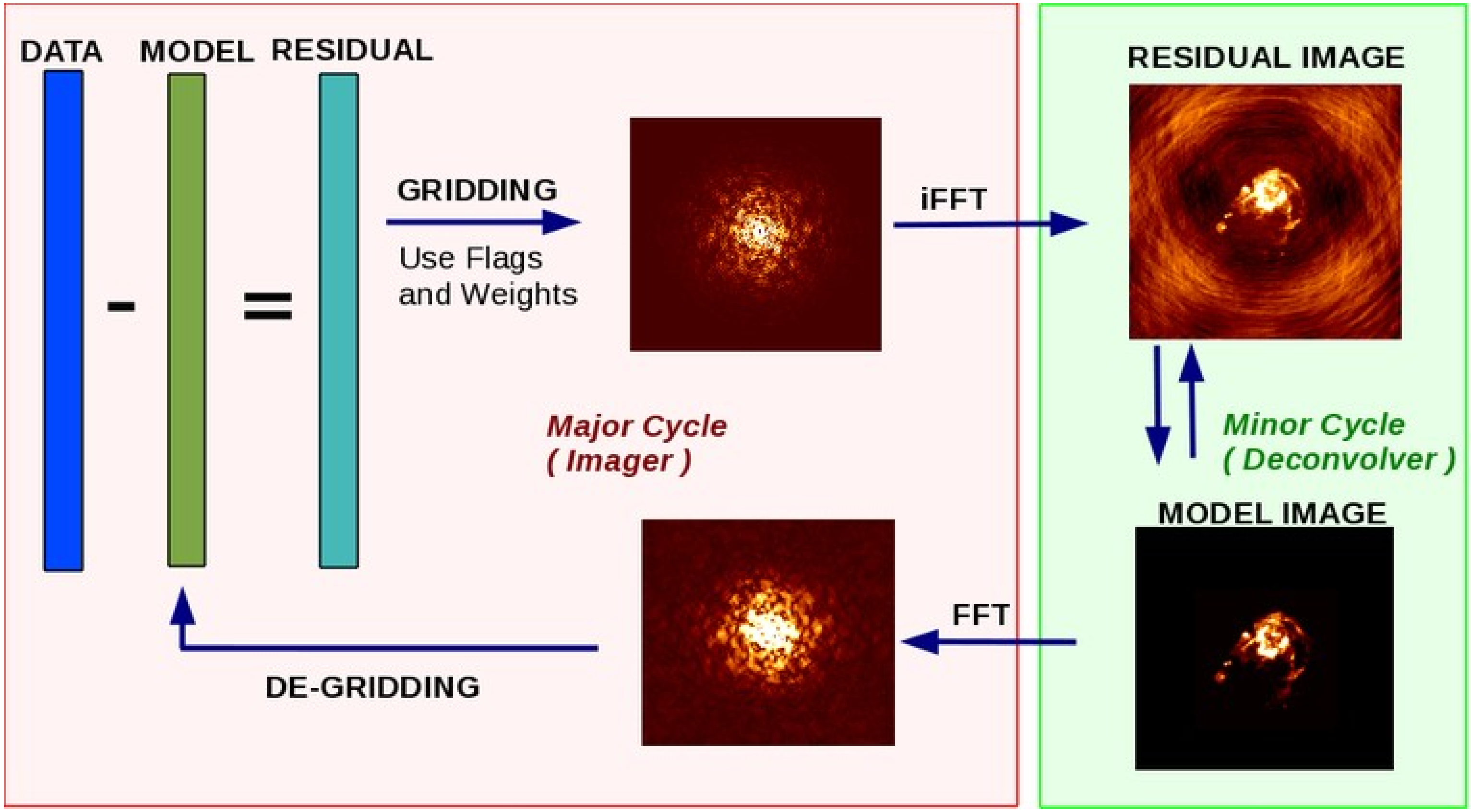
- (5) Restore : Smooth the model with a 'clean beam' and add residuals

Deconvolution – Multiscale CLEAN



- A scale-sensitive algorithm
- (1) Choose a set of scale sizes
- (2) Calculate dirty/residual images
  smoothed to several scales (basis functions)
- – Normalize by the relative sum-of-weights
  (instrument's sensitivity to each scale)
- (3) Find the peak across all scales, update a single multi-scale model as well as all residual images (using information about coupling between scales)
- Iterate, similar to Classic CLEAN, and restore at the end.

Imaging as a Chi-square Minimization



Courtesy – U.Rau

CASA task *tclean*

- This CASA command takes calibrated visibilities in your measurement set (or list of measurement sets) and produces an image according to the user defined parameters
- Clean is an iterative chi-square minimization process split into major and minor cycles traditionally to perform imaging and deconvolution.
  - Major cycles are in the visibility data domain - Imaging
  - Minor cycles are in the image domain - Deconvolution
- Task where you will spend ~ 80 % of time in data reduction.

Task tclean interface

```
CASA <1>: 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
startmodel          =         ''        #  Name of starting model image
```

- The box in red is the data - selection portion. It defines the selection of data that is passed to the task to produce an image. This includes **data selection** such as field, **spectral window, antennas, scan, observation ids, scan intents.**
- The box in blue is the image definition. It defines the parameters of the image being produced. Some important parameters are the **image name, imsize and cell-size**.

Task tclean interface

```
gridder             = 'standard'        #  Gridding options (standard, wproject, widefield, mosaic, awproject)
     vptable        =         ''        #  Name of Voltage Pattern table
     pblimit        =       0.01        #  PB gain level at which to cut off normalizations

deconvolver         =    'mtmfs'        #  Minor cycle algorithm (hogbom,clark,multiscale,mtmfs,mem,clarkstokes)
     scales         = [0, 5, 10, 20]    #  List of scale sizes (in pixels) for multi-scale algorithms
     nterms         =          3        #  Number of Taylor coefficients in the spectral model
     smallscalebias =        0.0        #  Biases the scale selection when using multi-scale or mtmfs deconvolvers

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           =   'briggs'        #  Weighting scheme (natural,uniform,briggs, briggsabs[experimental])
     robust         =        0.5        #  Robustness parameter
     npixels        =          0        #  Number of pixels to determine uv-cell size
     uvtaper        =         []        #  uv-taper on outer baselines in uv-plane
```

- The parameters in red are the major cycle parameters.
    - The gridding algorithm.
    - The weighting scheme for visbilities.
- The parameter in green define the minor cycle algorithm chosen to perform image deconvolution.
- The parameters in blue shows the operations that a user can perform at image restoration.

Task tclean interface

```
niter            =       2000        #  Maximum number of iterations
     gain            =        0.1        #  Loop gain
     threshold       =        0.0        #  Stopping threshold
     nsigma          =        0.0        #  Multiplicative factor for rms-based threshold stopping
     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     =       True        #  Modify masks and parameters at runtime

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.
restart          =       True        #  True : Re-use existing images. False : Increment imagename
savemodel        = 'modelcolumn'     #  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
```

- The parameters in green are the deconvolution iteration control. Allows control on number iterations of deconvolution performed by the minor cycle algorithms chosen. In addition to allowing for type and choice of deconvolution masks.
- The parameters in blue are some extra parameters that allow for the easier control of restarting imaging runs and for saving the model data back to the measurement set.

Whats in the measurement set ?

```
…8   …ms::summary  ================================================================================
…8   …s::summary+            MeasurementSet Name:  /Users/pjaganna/Data/DRW_3C75.ms      MS Version 2
…8   …s::summary+  ================================================================================
…8   …s::summary+     Observer: Dr. Emmanuel Momjian     Project: uid://evla/pdb/35621723
…8   …s::summary+  Observation: EVLA
…8   …Properties   Computing scan and subscan properties...
…8   …ms::summary  Data records: 1137240       Total elapsed time = 8760 seconds
…8   …s::summary+     Observed from   04-Oct-2018/06:04:00.0   to   04-Oct-2018/08:30:00.0 (UTC)
…8   …ms::summary
…8   …s::summary+     ObservationID = 0         ArrayID = 0
…8   …s::summary+    Date        Timerange (UTC)          Scan  FldId FieldName             nRows     SpwIds   Average Interval(s)    ScanIntent
…8   …s::summary+    04-Oct-2018/06:04:00.0 - 06:18:45.0     8      0 3C75                  126360  [0,1,2,3,4,5,6,7]  [19.7, 19.7, 19.7, 19.7, 19.7, 19.7, 19.7, 19.7]
…8   …s::summary+                06:20:15.0 - 06:35:05.0    10      0 3C75                  126360  [0,1,2,3,4,5,6,7]  [19.7, 19.7, 19.7, 19.7, 19.7, 19.7, 19.7, 19.7]
…8   …s::summary+                06:36:25.0 - 06:51:20.0    12      0 3C75                  126360  [0,1,2,3,4,5,6,7]  [19.9, 19.9, 19.9, 19.9, 19.9, 19.9, 19.9, 19.9]
…8   …s::summary+                06:52:35.0 - 07:07:30.0    14      0 3C75                  126360  [0,1,2,3,4,5,6,7]  [19.9, 19.9, 19.9, 19.9, 19.9, 19.9, 19.9, 19.9]
…8   …s::summary+                07:08:50.0 - 07:23:40.0    16      0 3C75                  126360  [0,1,2,3,4,5,6,7]  [19.8, 19.8, 19.8, 19.8, 19.8, 19.8, 19.8, 19.8]
…8   …s::summary+                07:26:30.0 - 07:41:25.0    18      0 3C75                  126360  [0,1,2,3,4,5,6,7]  [19.9, 19.9, 19.9, 19.9, 19.9, 19.9, 19.9, 19.9]
…8   …s::summary+                07:42:45.0 - 07:57:35.0    20      0 3C75                  126360  [0,1,2,3,4,5,6,7]  [19.7, 19.7, 19.7, 19.7, 19.7, 19.7, 19.7, 19.7]
…8   …s::summary+                07:58:55.0 - 08:13:50.0    22      0 3C75                  126360  [0,1,2,3,4,5,6,7]  [19.9, 19.9, 19.9, 19.9, 19.9, 19.9, 19.9, 19.9]
…8   …s::summary+                08:15:10.0 - 08:30:00.0    24      0 3C75                  126360  [0,1,2,3,4,5,6,7]  [19.7, 19.7, 19.7, 19.7, 19.7, 19.7, 19.7, 19.7]
…8   …ms::summary           (nRows = Total number of rows per scan)
…8   …ms::summary  Fields: 1
…8   …s::summary+    ID   Code Name              RA               Decl           Epoch   SrcId      nRows
…8   …s::summary+    0    NONE 3C75             02:57:42.630000 +06.01.04.80000 J2000   0        1137240
…8   …ms::summary  Spectral Windows:  (8 unique spectral windows and 1 unique polarization setups)
…8   …s::summary+    SpwID  Name           #Chans   Frame   Ch0(MHz)  ChanWid(kHz)  TotBW(kHz) CtrFreq(MHz) BBC Num  Corrs
…8   …s::summary+    0      EVLA_S#A0C0#2     13    TOPO    2503.000      8000.000    104000.0   2551.0000       12  RR  RL  LR  LL
…8   …s::summary+    1      EVLA_S#A0C0#3     13    TOPO    2631.000      8000.000    104000.0   2679.0000       12  RR  RL  LR  LL
…8   …s::summary+    2      EVLA_S#A0C0#4     13    TOPO    2759.000      8000.000    104000.0   2807.0000       12  RR  RL  LR  LL
…8   …s::summary+    3      EVLA_S#A0C0#5     13    TOPO    2887.000      8000.000    104000.0   2935.0000       12  RR  RL  LR  LL
…8   …s::summary+    4      EVLA_S#A0C0#6     13    TOPO    3015.000      8000.000    104000.0   3063.0000       12  RR  RL  LR  LL
…8   …s::summary+    5      EVLA_S#A0C0#7     13    TOPO    3143.000      8000.000    104000.0   3191.0000       12  RR  RL  LR  LL
…8   …s::summary+    6      EVLA_S#A0C0#8     13    TOPO    3271.000      8000.000    104000.0   3319.0000       12  RR  RL  LR  LL
…8   …s::summary+    7      EVLA_S#A0C0#9     13    TOPO    3399.000      8000.000    104000.0   3447.0000       12  RR  RL  LR  LL
…8   …ms::summary  Sources: 8
…8   …s::summary+    ID   Name                SpwId RestFreq(MHz)  SysVel(km/s)
…8   …s::summary+    0    3C75                0     -              -
…8   …s::summary+    0    3C75                1     -              -
…8   …s::summary+    0    3C75                2     -              -
…8   …s::summary+    0    3C75                3     -              -
…8   …s::summary+    0    3C75                4     -              -
…8   …s::summary+    0    3C75                5     -              -
…8   …s::summary+    0    3C75                6     -              -
…8   …s::summary+    0    3C75                7     -              -
…8   …ms::summary  Antennas: 27:
```

Basic Imaging

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” gridding

-“briggs” weighting

Step3 : Run iterative deconvolution

-“Hogbom” CLEAN of 500 iterations

Imaging Controls

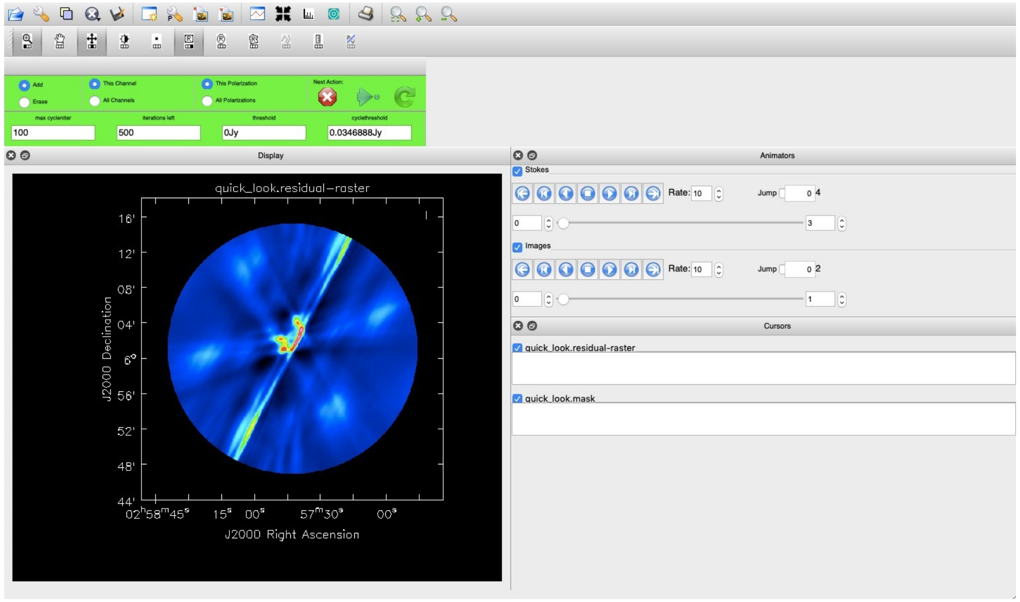
- Iteration and Stopping criterion
  - ‘niter’ : Maximum number of deconvolution iterations
  - ‘threshold’ : Limit in flux density to stop CLEANing

- Masking
  - Only need masks when deconvolving complex structure.
  - Extended emission
  - In the presence of spiky artifacts around your source.

Draw interactive masks or supply masks. Can also generate with automasking.

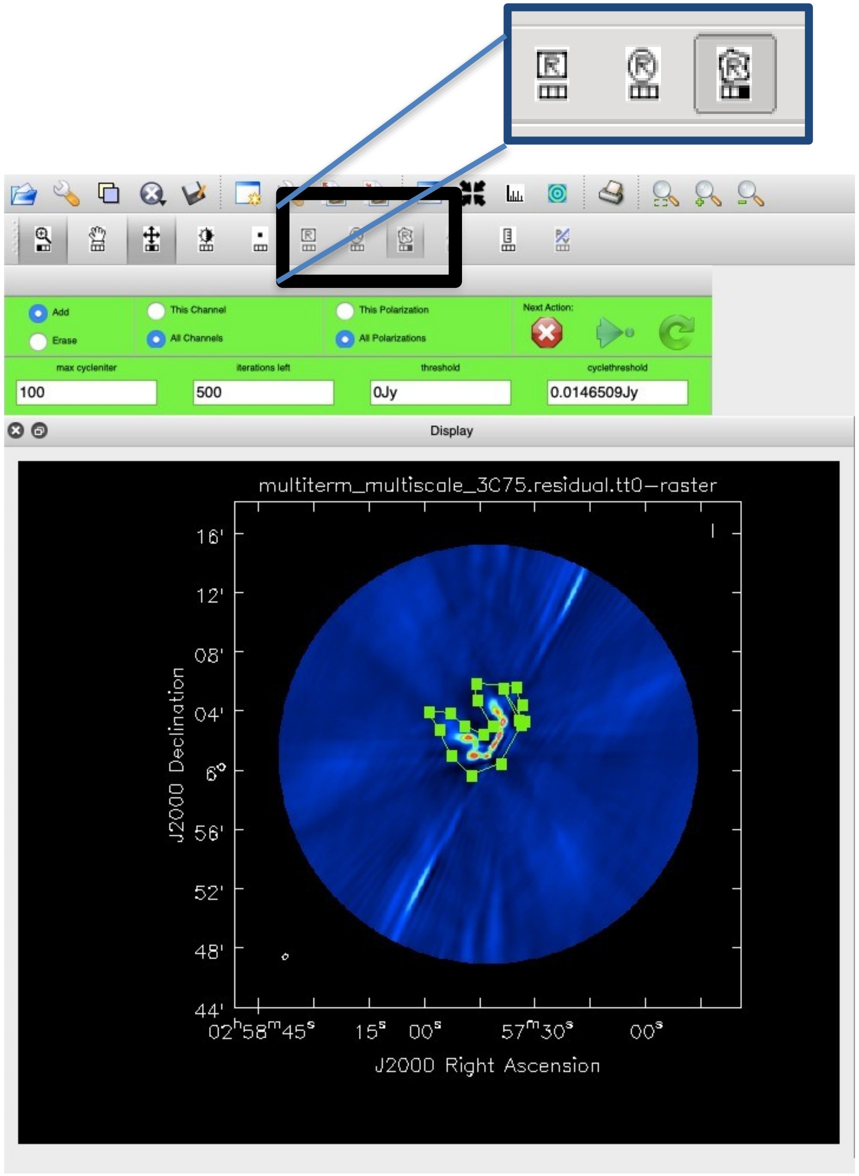
Commands for your first image

```
# In CASA
default (tclean)
inp()
vis = “3C75.ms”
datacolumn = ‘data’
imagename = ‘quick_look’
cell = 4.0 # “4.0 arcsec”
imsize = 512
stokes = ‘IQUV’
pblimit = 0.01
niter = 500
interactive = True
go()
```



Standard gridder and deconvolution using the hogbom clean algorithm are the defaults and so are not set.

Task *tclean*



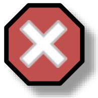
Interactive =True

Double click inside to activate the mask and the buttons

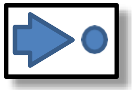
Start the clean run

Adjust regions and continue

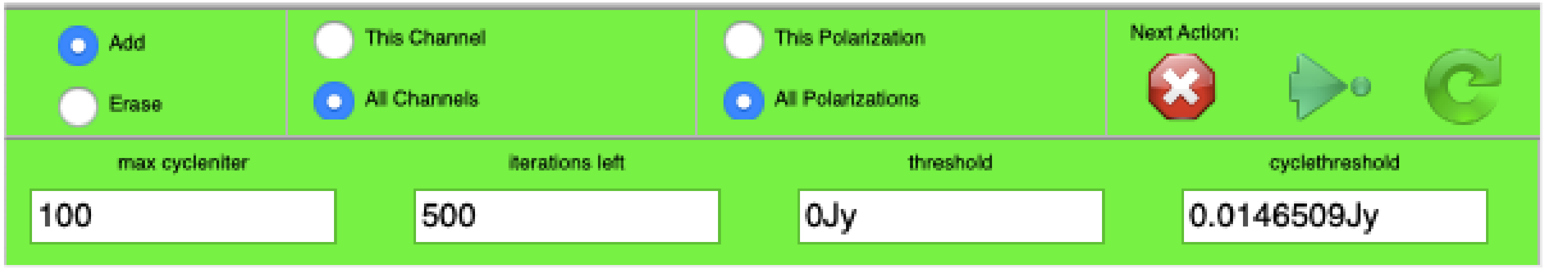
Stop interactive clean



If mask is not to be updated, let it continue until iterations are done



Task *tclean*



- Iterations controls are available in interactive mode on the panel.
- Make sure to select all channels and all polarization if you want the same mask to be applied everywhere.
- Ask to continue, cancel or proceed to return after the next update.

CASA task *tclean* - Output Images

imagename.psf	Point spread function.
imagename.pb	Primary Beam or
imagename.residual	FOV Residual Image
imagename.model	Model Image post deconvolution
imagename.image	Restored output image
imagename.image.pbcor	Primary beam gain corrected image . I/PB
imagename.mask	Mask used for deconvolution
imagename.sumwt	A single pixel image containing sum of weights
imagename.weight	An image containing PB-square
imagename.XX.{tt0,tt1,tt2}	Multi-term images of the Taylor coefficients.
imagename.workdirectory	Working directory for a parallel run.

CASA task *tclean* - spectral mode

The specmode parameter is the place to inform the tclean task what kind of spectral behavior of your imaging run

- mfs : Multi frequency synthesis or continuum imaging. Resulting image contains only one spectral axis. Allows for multi-term options within the deconvolver. i.e nterms >1
- cube : N data channels are mapped to the user specified image channels with binning and interpolation options. User can define channel, frequency, velocity. Gridding and imaging is done natively in LSRK.
- cubedata : Direct mapping of channels to images according to the width and output channels required. No internal LSRK conversion

CASA task *tclean* - Deconvolution

Multi-Term CLEAN : Joint deconvolution of sky model using a set of basis function.

- deconvolver = “multiscale” : Sky modeled using a 2D gaussian basis (circular basis convolved with psf).
- deconvolver = “mtmfs”: Wide-band sky is expanded as a Taylor polynomial with respect of frequency. Allows you to derive the frequency dependence of the sky model in additional to its spatial scales. Defined by nterms and the scales parameter.

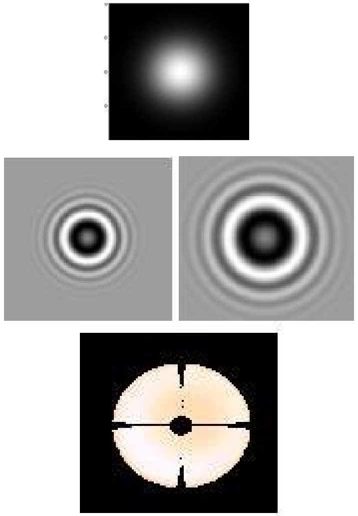
CASA task *tclean* - Gridders

Gridding - Data domain operation.

Accumulate weighted visibility on a regular grid

Appropriate gridding kernel allows for the correction of variety of wide-field and instrumental effects.

- Standard gridding - Prolate Spheroidal . gridder = 'standard'
- W-Projection - Fresnel Kernel gridder = 'wproject'
- A-Projection - Aperture Illumination Function gridder = 'awproject'
- Mosaic - Phase gradient + standard gridding + pbmodels gridder = 'mosaic'



Widefield imaging

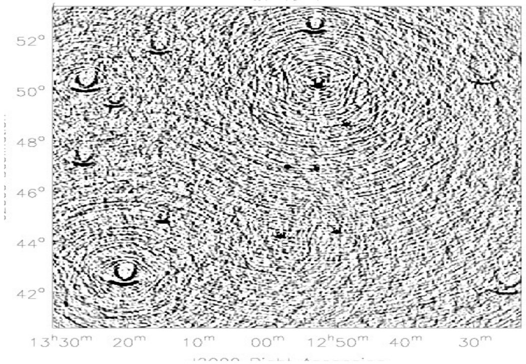
$$V^{obs}(u,v) = S(u,v) \iint I(l,m)\, e^{2\pi i (ul+vm)}\, dl\, dm$$

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

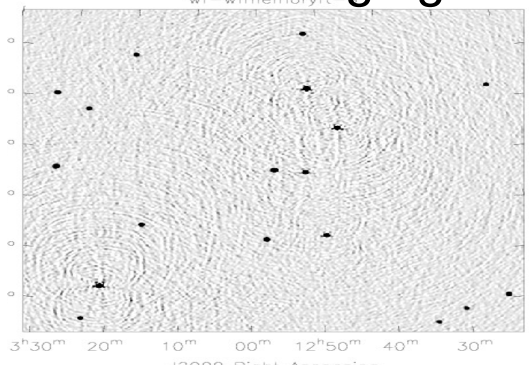
The ' w ' of a baseline can be large, away from the image phase center

The ' n ' for a source can be large, away from the image phase center

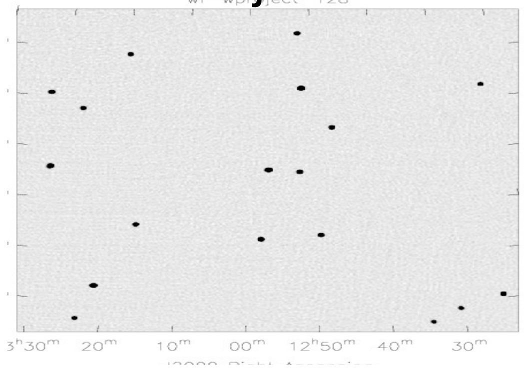
2D Imaging



Facet Imaging



W-Projection



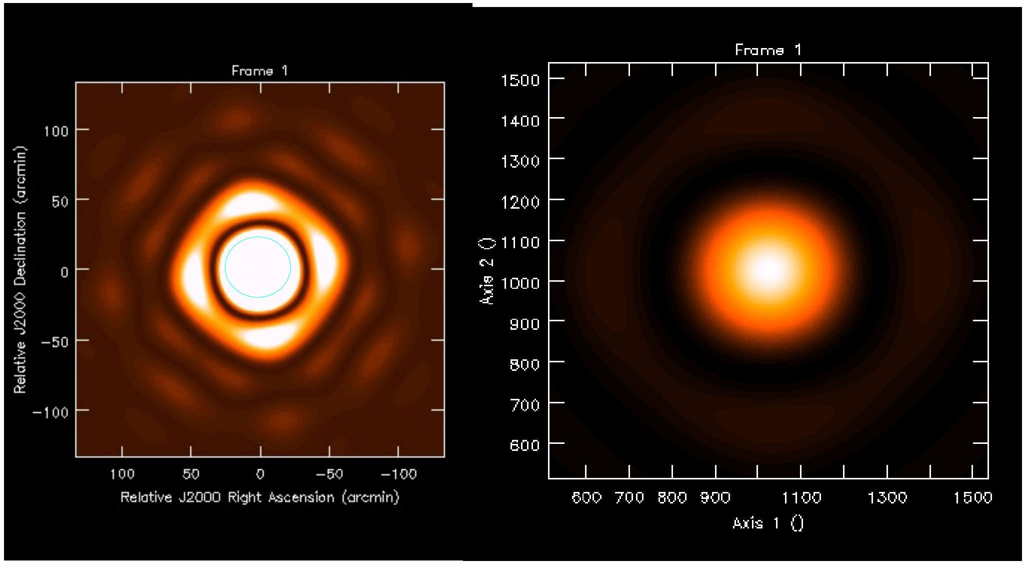
Courtesy – S.Bhatnagar

Widefield imaging

Each antenna has a limited field of view => Primary Beam (gain) pattern

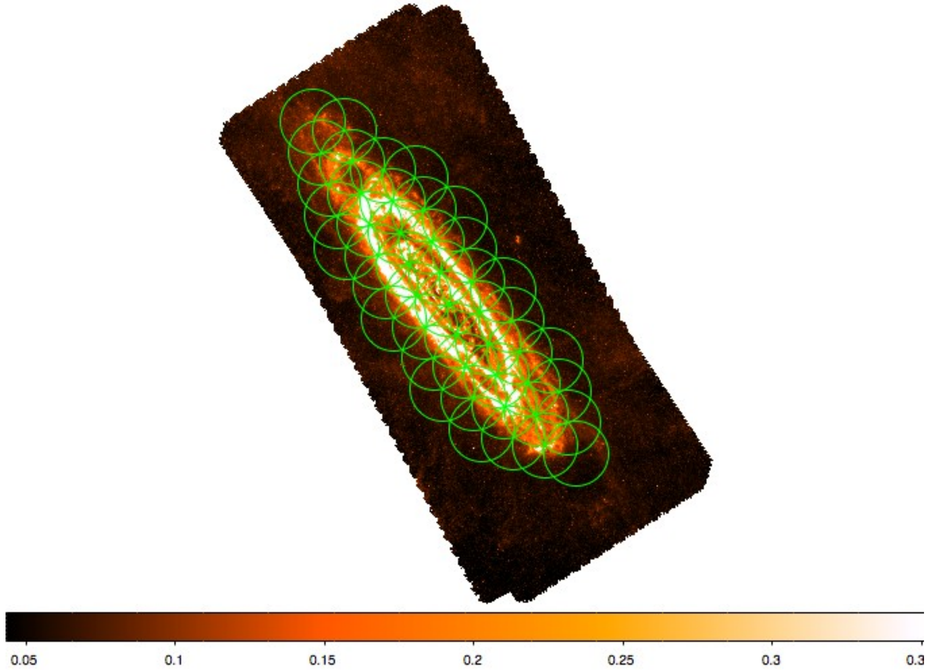
=> Sky is multiplied by PB, the antenna forward gain at the time of sampling

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



Courtesy – S.Bhatnagar

Widefield imaging - Mosaciking



When imaging objects spanning multiple FoV. An overlapped pointing pattern or mosaic is utilized.

Two kinds of mosaicking options are possible – linear mosaic, joint mosaic.

Linear mosaic : Image each pointing separately and combine the images in the image plane to prodce a map.

Joint mosaic : Utilize the gridder to grid all the data from all the pointings onto a single grid for imaging.

Currently join mosaics are supported by Mosaic and AW-Projection gridders.

CASA task *tclean* - Weighting

The gridded visibilities can be weighted to alter sensitivity and resolution.

- Natural weighting - Highest sensitivity, wider psf, more extended structure. weighting = “natural”

- Uniform weighting - Reduced sensitivity, narrower psf, favors point sources. weighting = “uniform”

- Briggs (robust) - Smoothly vary between natural and uniform. weighting = “briggs”

- UV-Taper - Emphasize larger scales in the data. uvtaper(subparam)

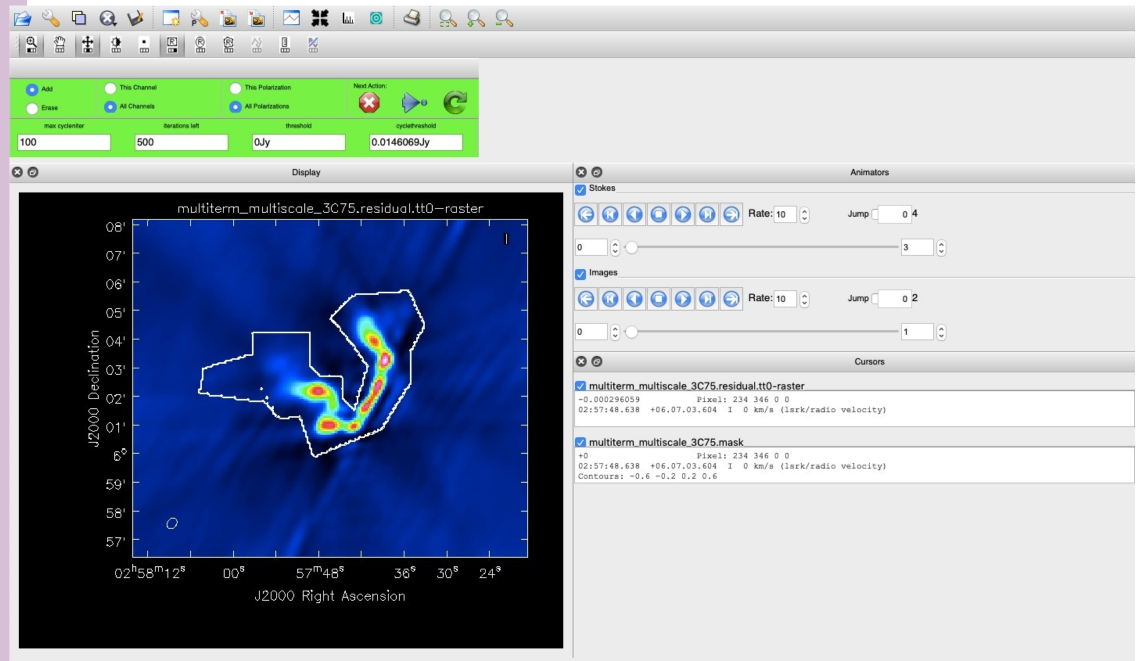
CASA task *tclean* - Runtime and Memory

Imaging runtime and memory are dependent on the following parameters.

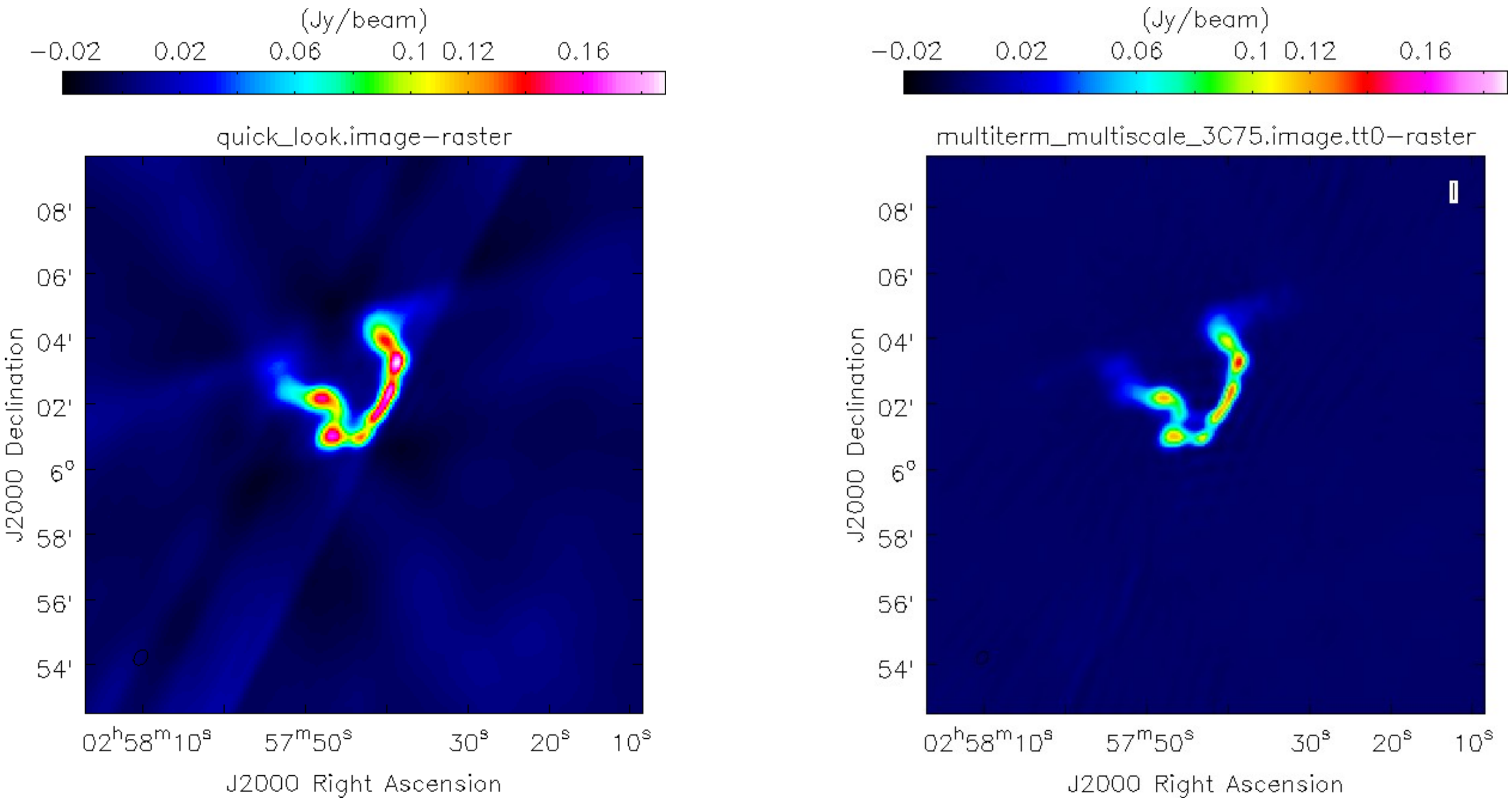
- Image size : Scales as the square of number of pixels. It is optimal for speed to choose FFTW preferred values.(factors of 2,3,5,7)
- Data size : Scales linearly with the data size that needs to be imaged.
- Gridding : Scales as function of the algorithm and the corresponding convolution function size. 3x3 for standard to up to 200x200 for w-projection.
- Deconvolver : MS-Clean and MTMFS require multiple scales or multiple terms and their corresponding images to be gridded and held in memory so significantly slower than hogbom or clark clean.
- Iteration Control : The frequency of major cycles, the right choice of deconvolution algorithm given your sky structure.
- Hardware : Serial vs parallel run. Is OpenMP enabled ? core, RAM/core. Number of cores utilized if run in parallel.

MTMFS imaging

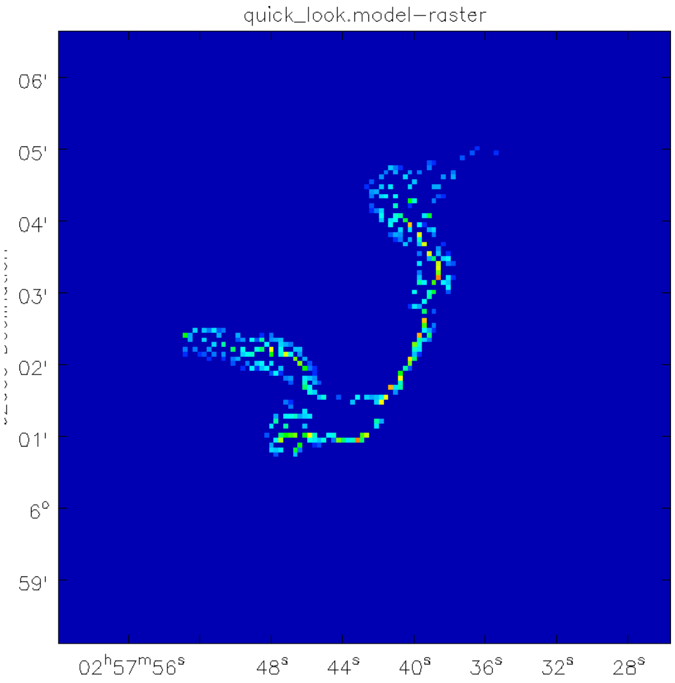
```
# In CASA
default (tclean)
inp()
vis = “3C75.ms”
datacolumn = ‘data’
imagename =
‘multiterm_multiscale_3C75’
cell = 4.0
imsize = 512
stokes = ‘I’
pblimit = 0.01
deconvolver = ‘mtmfs’
nterms = 3
scales = [0,5,10]
weighting = ‘briggs’
niter = 500
interactive = True
go()
```

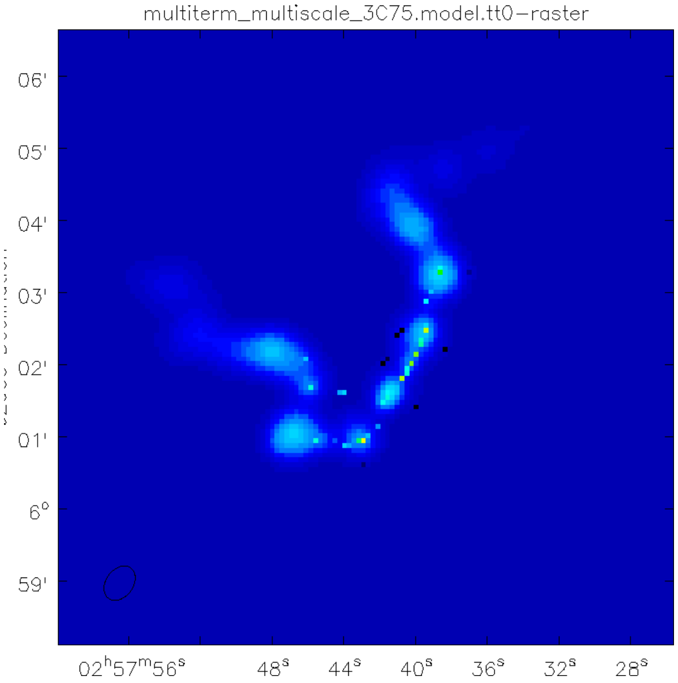


Choice of the algorithm matters - hogbom vs MTMFS



Choice of the algorithm matters - hogbom vs MTMFS





Summary

- The choice of your algorithm is very important

    Gridder & weighting

    Deconvolution
- Pick the algorithm or tool that suits your needs
- Self-calibrate to improve your imaging if needed.

- A very detailed imaging casaguide is available at
  https://casaguides.nrao.edu/index.php/VLA_CASA_Imaging-CASA5.5.0

- If your image looks weird start by asking yourself the questions

    Is my cell size correct?

    Am I imaging everything in my field ?

    Is my algorithm appropriate for the data being used?

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