Imaging in Practice

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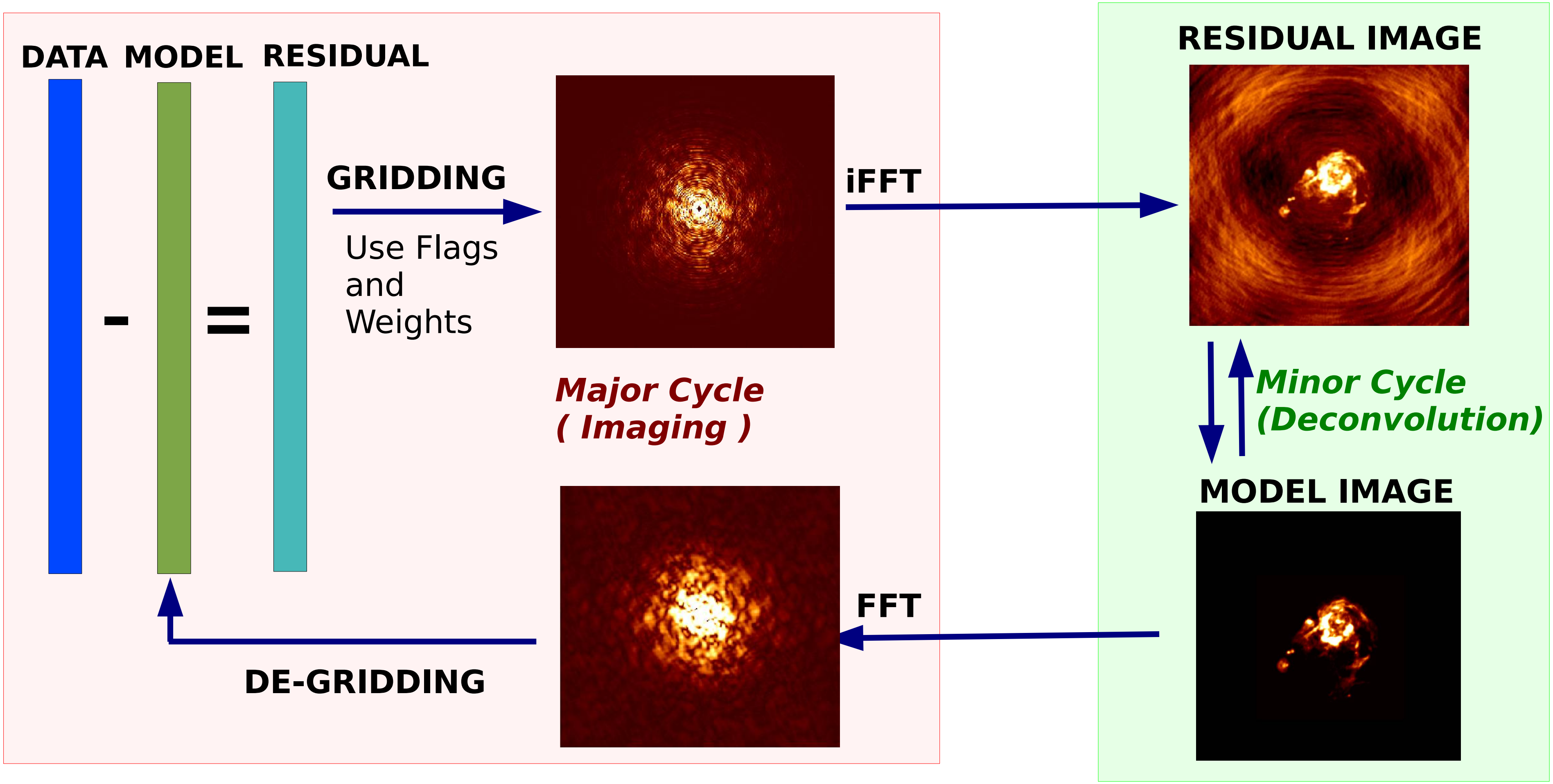
Overview

- Recap of Imaging
- *tclean* and how it maps to imaging in theory
- First step lets make a quick look image
- Wideband - multiscale continuum imaging
- Self-calibration
- Cube Imaging - Non-interactive
- Examples to be tried out later in the week.

Imaging - As an iterative chi square minimization



Courtesy - Urvashi 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.

Let us make our first image

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

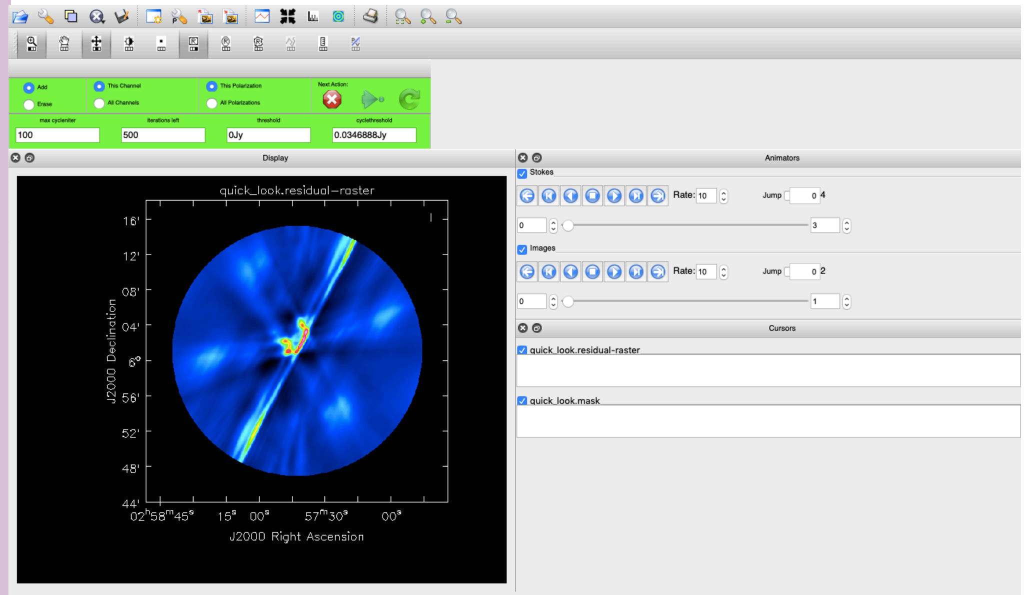
-“Hogbom” CLEAN of 500 iterations

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:
```

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

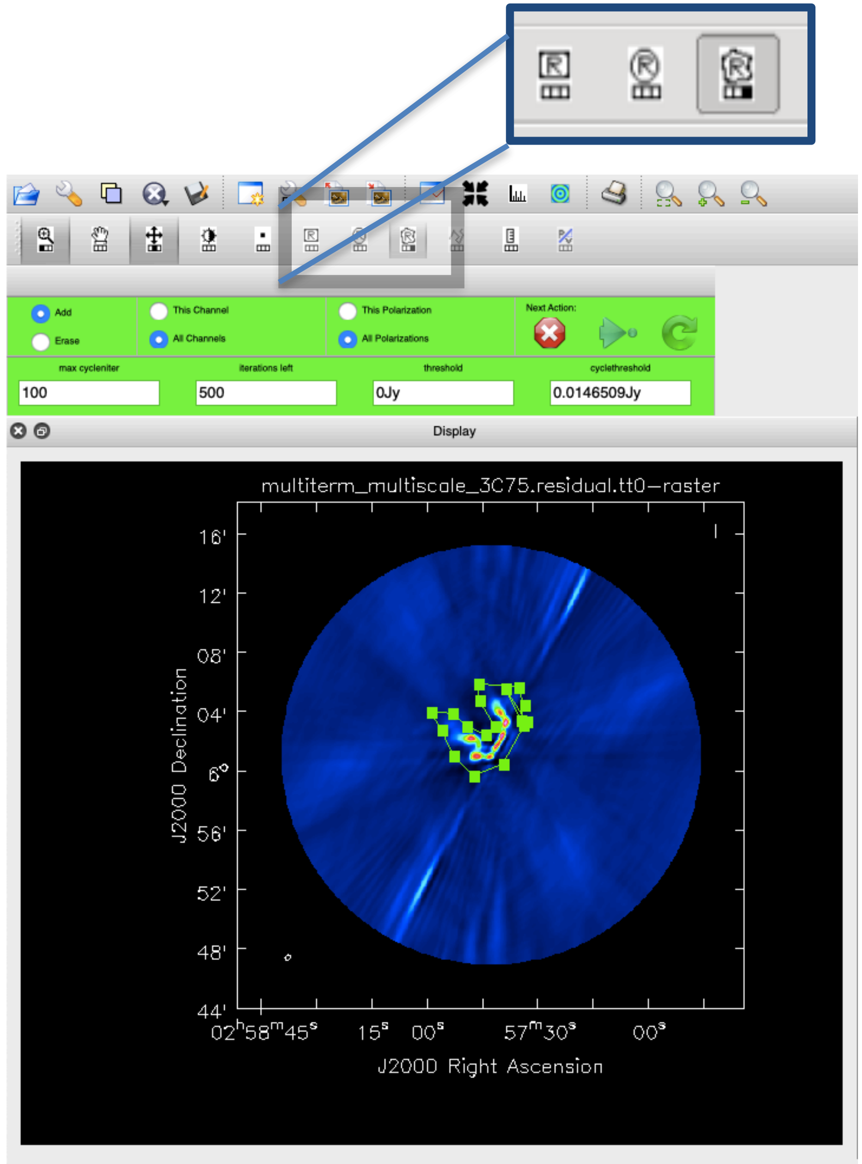
Double click inside to activate the mask and the buttons

Start the clean run

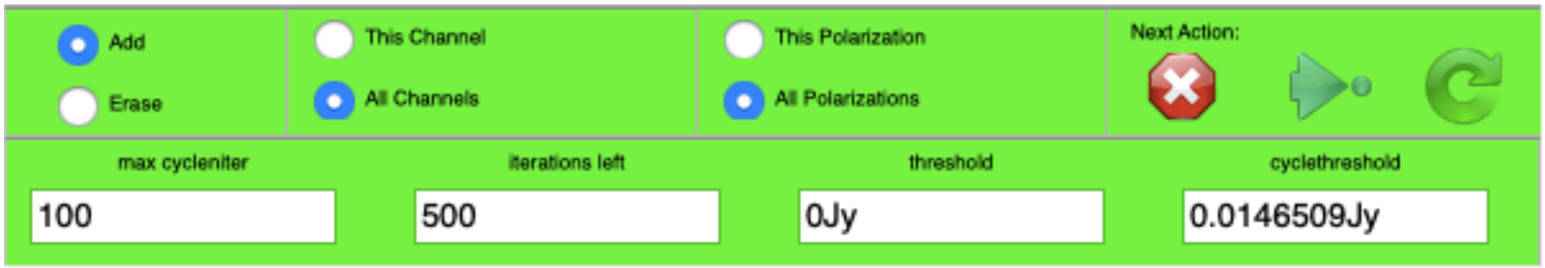
Adjust regions and continue

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 FOV
imagename.residual	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

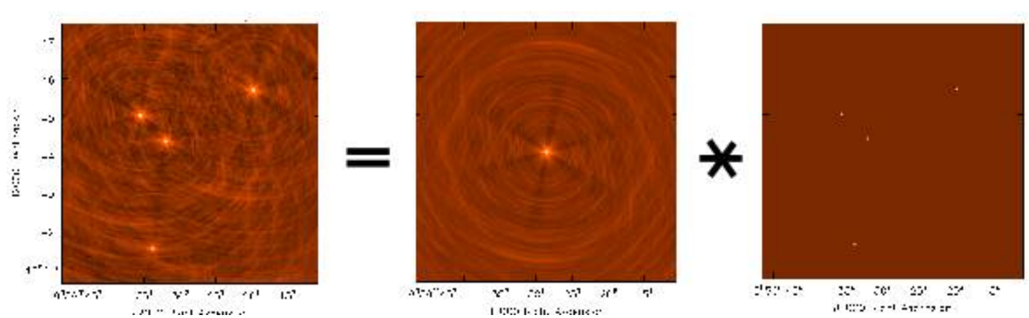
The specmode parameter is the place to inform the tclean task what kind of spectral behavior of your imaging run

- 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

Point Source CLEAN

- Sky model is a set of delta functions.
- deconvolver = “hogbom” - uses PSF of same size throughout image. Is the imager default.
- deconvolver = “clark” - uses patch of PSF and an intermediate model subtraction on the gridded visbilities.



CASA task *tclean* - Deconvolution

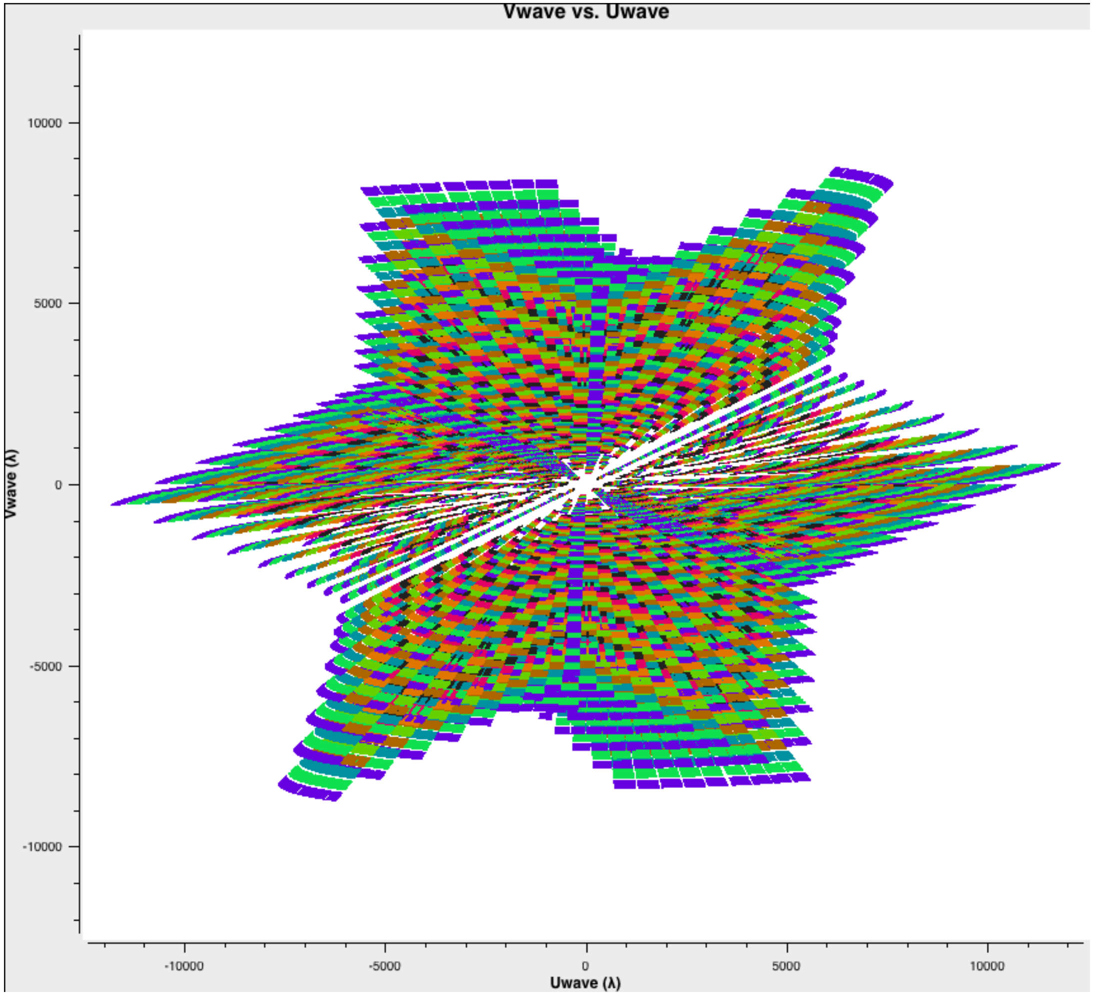
Multi-Term CLEAN : Joint deconvolution of sky model using a set of basis function.

- 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.

UV coverage

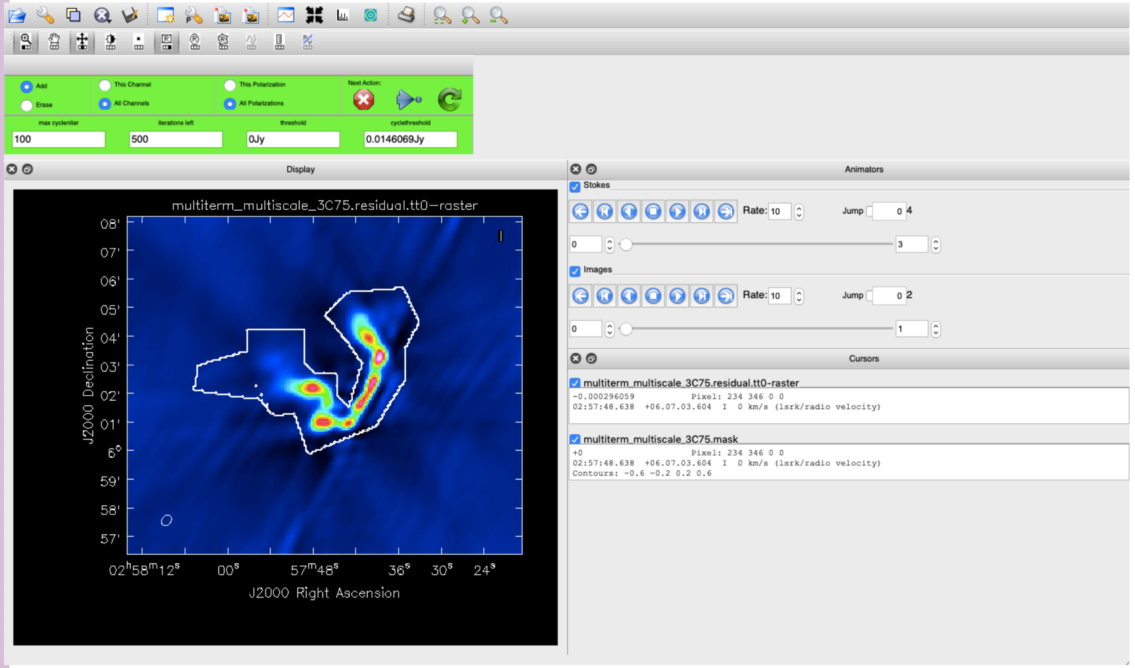
The data are wide-band.

So our deconvolution algorithm must account for the broadband nature of the psf and the sky model.



Multi-term Multi-scale CLEAN

```
# 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()
```

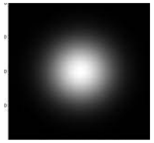


CASA task *tclean* - Gridders

Gridding - Data domain operation.

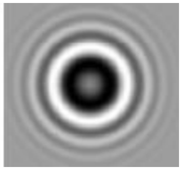
Accumulate weighted visibility on a regular grid

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



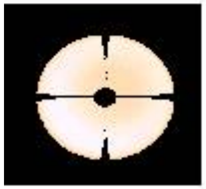
- Standard gridding - Prolate Spheroidal .

  gridder = ‘standard’



- W-Projection - Fresnel Kernel

  gridder = ‘wproject’



- A-Projection - Aperture Illumination Function

  gridder = ‘awproject’

- Mosaic - Phase gradient + standard gridding + pbmodels

  gridder = ‘mosaic’

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”

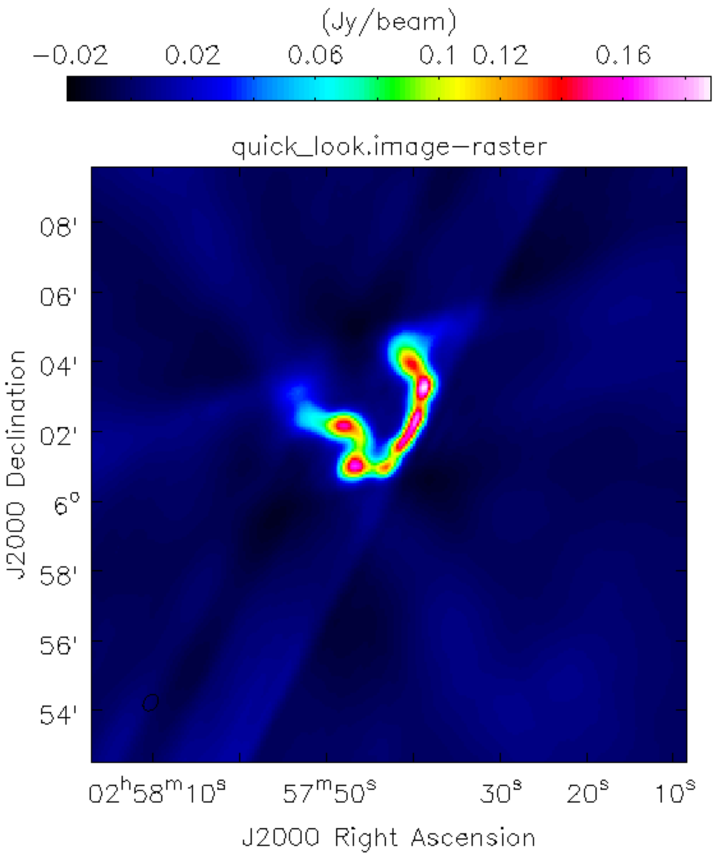
- UV-Taper - Emphasize larger scales in the data. uvtaper(subparam)

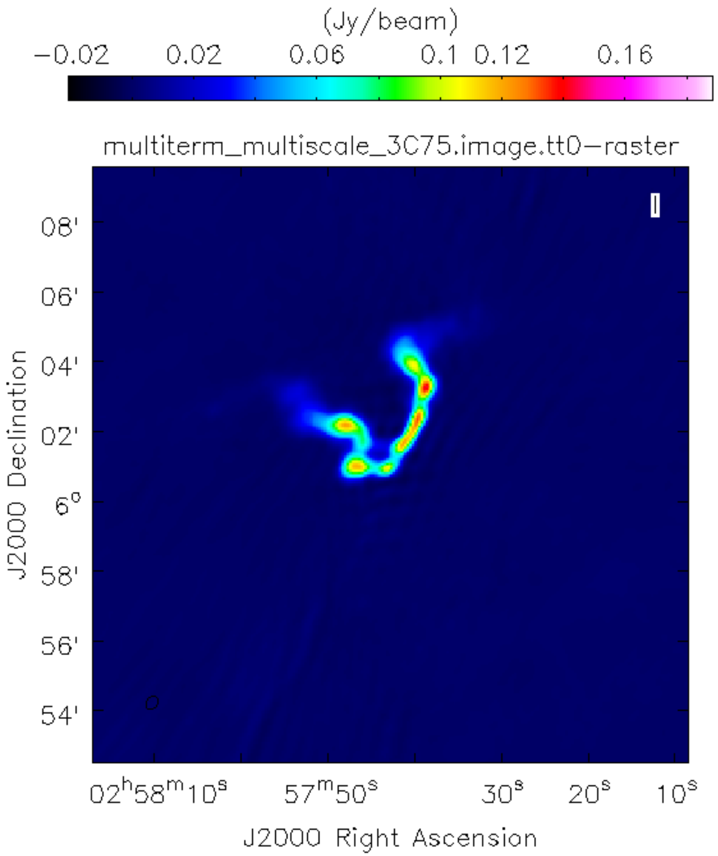
CASA task *tclean* - Runtime and Memory

Imaging runtime and memory are dependent on the following parameters.

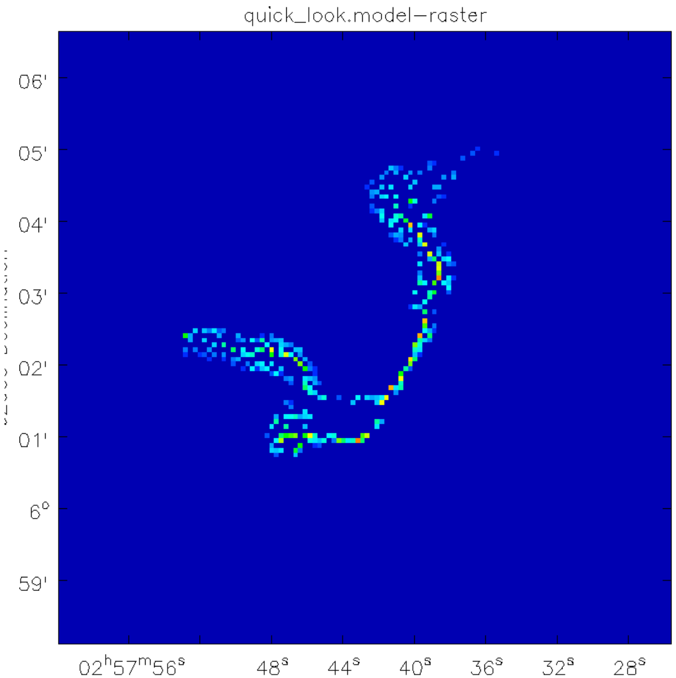
- Image size : Scales as the square of number of pixels. It is optimal for speed to choose FFTW preferred values.(factors of 2,3,5,7)
- Data size : Scales linearly with the data size that needs to be imaged.
- Gridding : Scales as function of the algorithm and the corresponding convolution function size. 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.

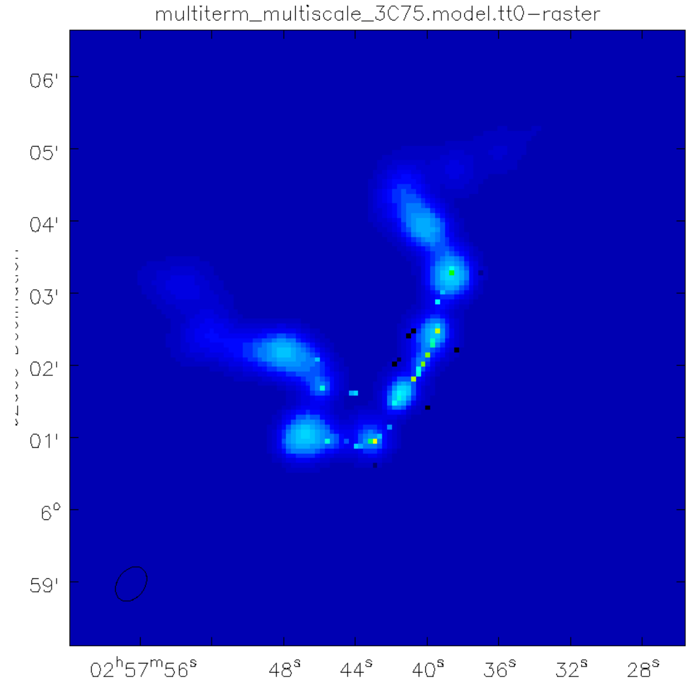
Comparison of quick look vs MTMFS





Comparison of quick look vs MTMFS





Self Calibration

Self - Calibration

Use the current best estimate to derive new gain solutions.

Step 1 : predict model image into model column

Step 2 : Run gaincal (phase only)

Apply gain solutions

Step 2 : Run applycal

Image to update model - Repeat until satisfied.

Step 4: Run tclean to produce an updated image.

Multi-term Multi-scale CLEAN - Self Calibration

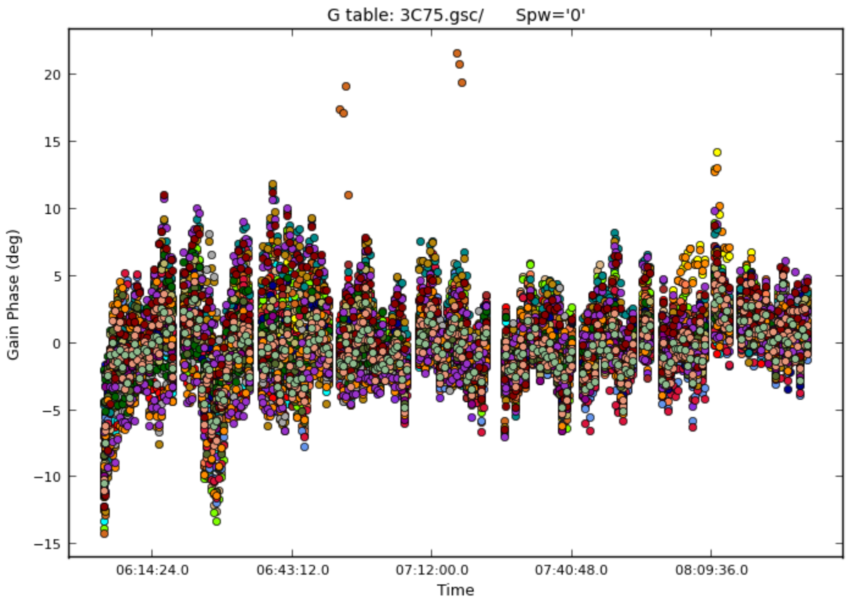
```
# In CASA
default (tclean)
tget (tclean)
niter=0
savemodel='modelcolumn'
calcres=False
calcpsf=False
go()

# In CASA

gaincal(vis='3C75.ms',
caltable='3C75.gsc', solint='30s',
calmode='p')
```

Step 1 : predict model image into model column

Step 2 : Run gaincal (phase only)

Multi-term Multi-scale CLEAN - Self Calibration

```
# In CASA

plotms(vis="3C75.gsc/",xaxis="time",yaxis="phase",coloraxis="antenna1",iteraxis="spw")
```

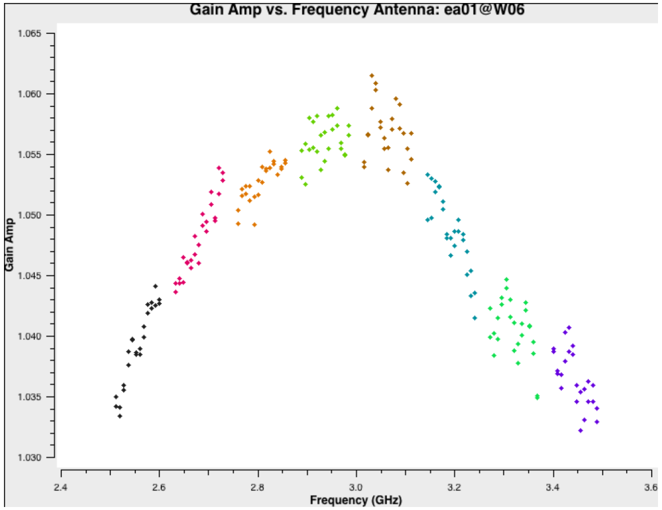


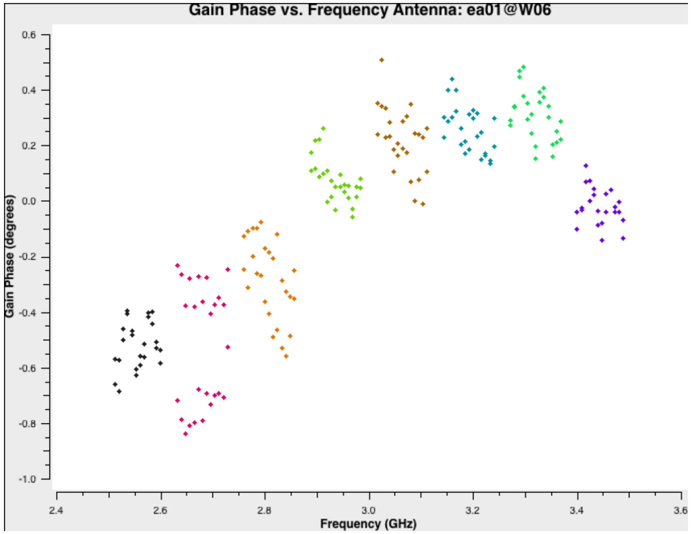

```
# In CASA

applycal('3C75.ms/',
gaintable=['3C75.gsc/'],
applymode='calflagstrict')
```

Step 3 : Apply the gain calibrations.

Optional - Bandpass SelfCalibration

```
# In CASA

bandpass(vis='3C75.ms',
caltable='3C75.scbp',
solint='inf',
gaintable=['3C75.gsc'])

plotms(vis="3C75.scbp/",xaxis="freq",yaxis="amp",coloraxis="spw",iteraxis="antenna")

plotms(vis="3C75.scbp/",xaxis="freq",yaxis="phase",coloraxis="spw",iteraxis="antenna")
```

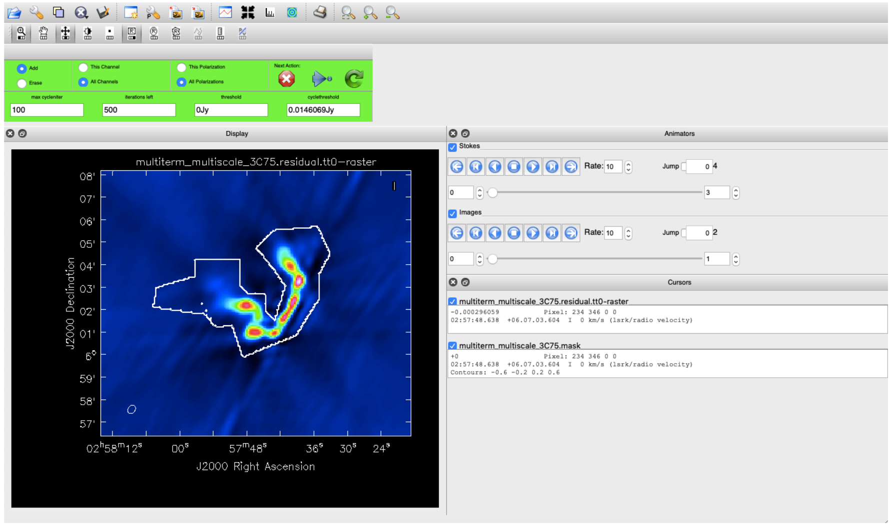




Multi-term Multi-scale CLEAN - Self Calibration

```
# In CASA
default (tclean)
inp(tclean)
vis = “3C75.ms”
datacolumn = ‘data’
imagename =
‘multiterm_multiscale_3C75_sc1’
cell = 4.0
imsize = 512
stokes = ‘IQUV’
pblimit = 0.01
deconvolver = ‘mtmfs’
nterms = 3
scales = [0,5,10]
weighting = ‘briggs’
niter = 700
interactive = True
go()
```

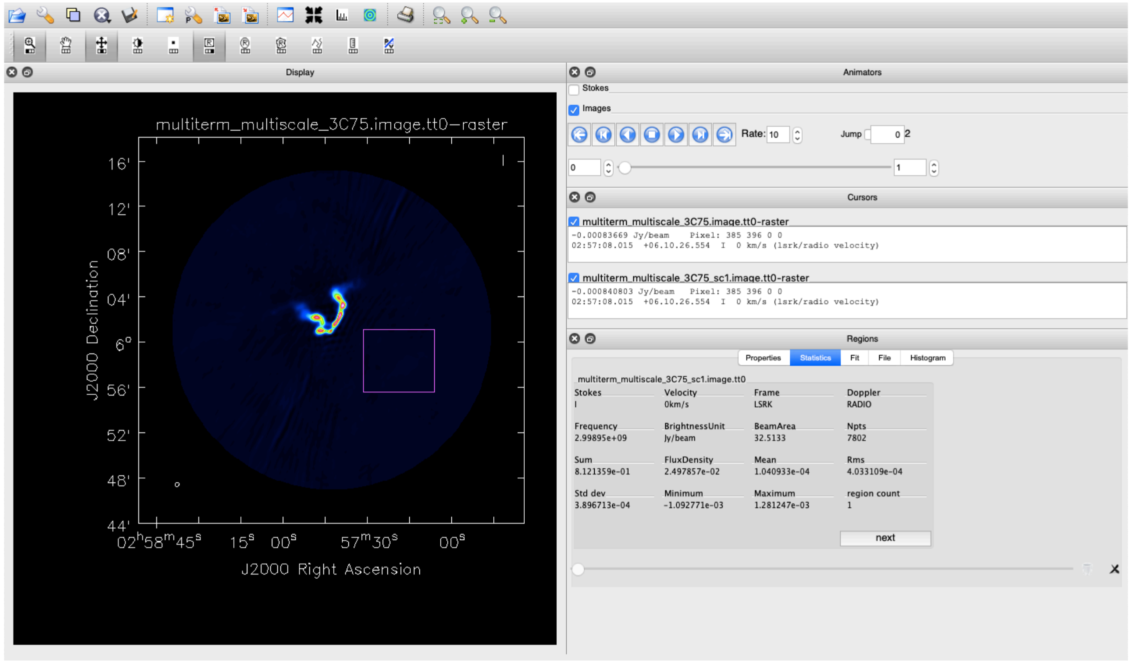
Step 3 : Re-image



Did the image get better ?

Measures of goodness for an image

- Improved R.M.S (400μJy from 430μJy)
- Reduction in artifacts (8 % reduction in the negatives artifacts)

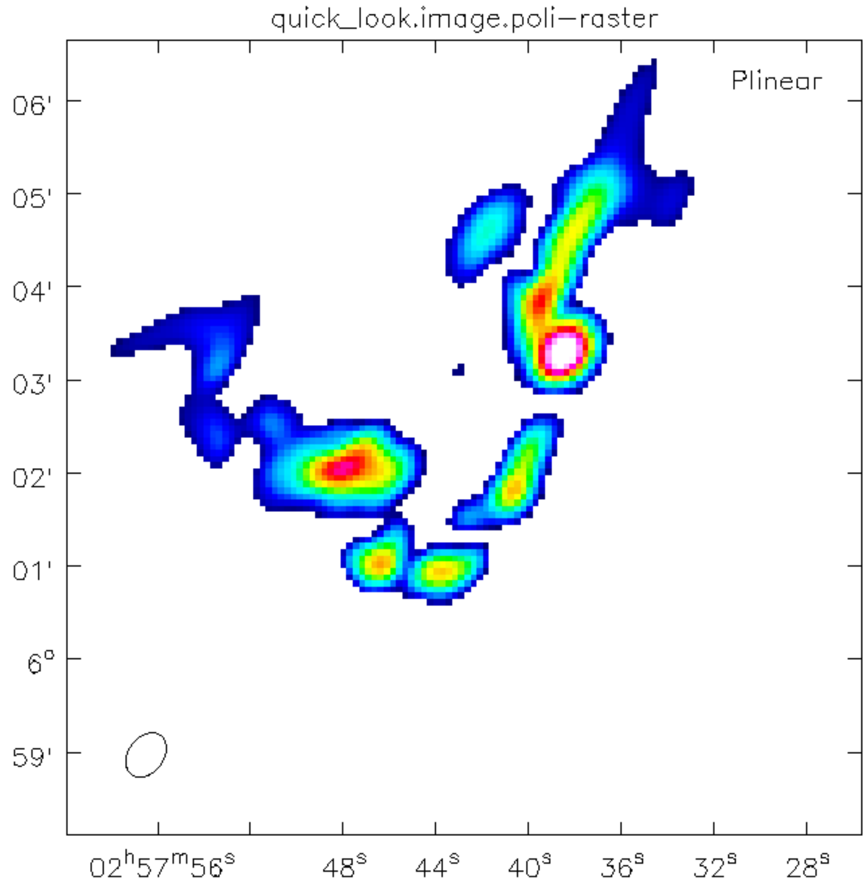


Step 4 : Repeat For varying solution intervals, while mindful of signal to noise.

Image Analysis - Polarimetry

```
# In CASA
immath(“quick_look.image",expr="IM0",stokes='Q',outfile='quick_look.image.Q')

immath("quick_look.image",expr="IM0",stokes='U',outfile='quick_look.image.U')

immath(imagename=["quick_look.image.Q",
"quick_look.image.U"],mode="poli", outfile = "quick_look.image.poli", sigma =
"3mJy/beam")

immath(imagename=["quick_look.image.Q",
"quick_look.image.U"],mode="pola", outfile = “quick_look.image.pola")

viewer (‘quick_look.imagepoli’)
```

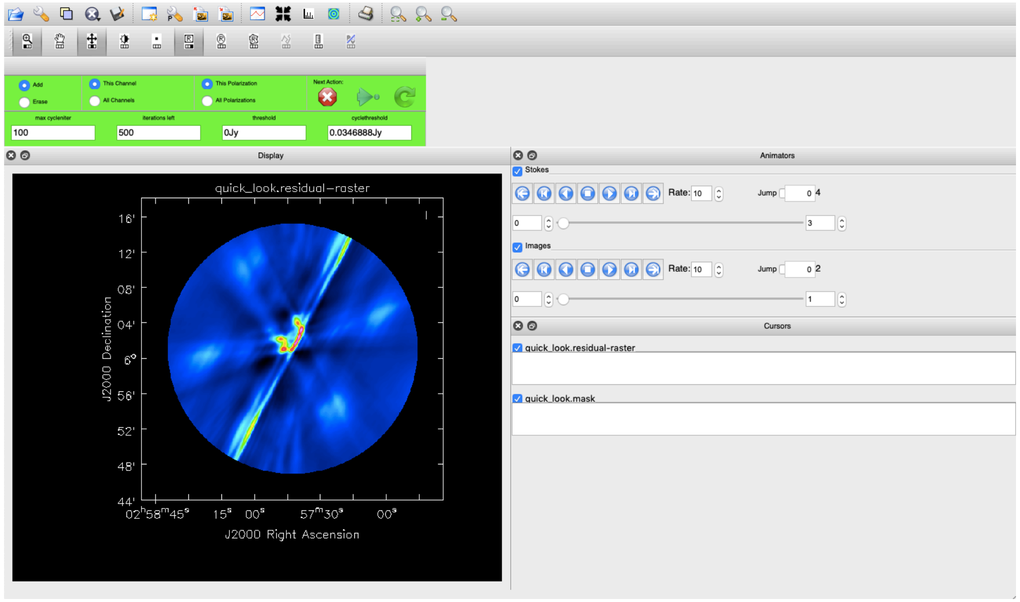
Image Analysis - Polarimetry



For more - checkout
The polarization casa guide

Cube CLEAN

```
# In CASA
default (tclean)
inp(tclean)
vis = “3C75.ms”
datacolumn = ‘data’
imagename = ‘cube_3C75’
cell = 4.0
imsize = 512
stokes = ‘IQUV’
specmode=‘cubedata’
width=13
pblimit = 0.01
deconvolver = ‘multiscale’
scales = [0,5,10]
weighting = ‘briggs’
niter = 500
interactive = True
go()
```



Summary

- The choice of the algorithm is important
    - Gridder & weighting
    - Deconvolve
- Pick the algorithm or tool that suits your needs
- Self-calibrate to improve your imaging if needed.
- A very detailed imaging casaguide is available here
  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.

Cube CLEAN

```
default (tclean)
inp(tclean)
vis='IRC10216.contsub'
spw='0:7~58'
imagename='IRC10216_HC3
N.cube'
imsize=300
cell=['0.4arcsec']
specmode='cube'
outframe='LSRK'
restfreq='36.39232GHz'
perchanweightdensity=True
pblimit=-0.0001
weighting='briggs'
robust=0
niter=100000
threshold='3.0mJy'
interactive=True
go()
```

https://casaguides.nrao.edu/index.php/VLA_high_frequency_Spectral_Line_tutorial_-_IRC%2B10216-CASA5.5.0

Wideband AWProjection

```
# In CASA
default (tclean)
inp(tclean)
vis = “3C75.ms”
datacolumn = ‘data’
imagename = ‘awp_multiscale_3C75’
cell = 4.0
imsize = 512
stokes = ‘IQUV’
gridder = ‘awproject’
wbawp=True
conjbeams=True
rotatepastep=5.0
pblimit = 0.01
deconvolver = ‘multiscale’
scales = [0,5,10]
weighting = ‘briggs’
niter = 500
interactive = True
go()
```

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