Hands on Tutorial: ALMA Imaging

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NRAO

Atacama Large Millimeter/submillimeter Array

Topics:

- Overview of MS for imaging
- Imaging primer
- Continuum imaging
- Self-Calibration
- Linecube imaging
- Automasking
- Pipeline imaging
- Data combination

https://casaguides.nrao.edu/index.php/ALMAguides

References

CASA documentation:
https://casa.nrao.edu/casadocs/casa-5.1.0/synthesis-imaging

Thompson, A.R., Moran, J.M., Swensen, G.W. 2017 "Interferometry and Synthesis in Radio Astronomy", 3rd edition (Springer)
http://www.springer.com/us/book/9783319444291

Perley, R.A., Schwab, F.R., Bridle, A.H. eds. 1989 ASP Conf. Series 6 "Synthesis Imaging in Radio Astronomy" (San Francisco: ASP)
www.aoc.nrao.edu/events/synthesis

IRAM Interferometry School proceedings
www.iram.fr/IRAMFR/IS/IS2008/archive.html

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Let's assume that your ALMA data has been successfully calibrated and delivered, and you restored the calibrated measurement set (MS) using the provided script.

Dataset:
ss_alma_data_v1p2.tar
tar –xvf ss_alma_data_v1p2.tar
cd working_data

Overview of MS for imaging

- Data column: “data” and “corrected” (additionally “model”)
- Data maybe flagged
- Contains calibrators and science targets
- Contains every spectral windows (not just for science spws)
- First step: understand the content of MS using **listobs**
- Check the data using **plotms**
- Can split using **split/mstransform** or merge using **concat**

sis14_twhya_calibrated_flagged.ms

- Pre-flagged and calibrated MS
- Has "data" and "model (null)"
- `listobs('sis14_twhya_calibrated_flagged.ms',listfile='listobs.txt')`

Chrome File Edit View History Bookmarks People Window Help   100%   Tue 12:05 PM iyoon

Secure https://casaguides.nrao.edu/index.php/First_Look_at_Imaging

```
================================================================================
           MeasurementSet Name:  /users/rfriesen/casaguides/first_look_imaging/sis14_twhya_calibrated_flagged.ms      MS Version 2
================================================================================
   Observer: cqi     Project: uid://A002/X327408/X6f
Observation: ALMA
Computing scan and subscan properties...
Data records: 80563       Total elapsed time = 5647.68 seconds
   Observed from   19-Nov-2012/07:36:57.0   to   19-Nov-2012/09:11:04.7 (UTC)

   ObservationID = 0         ArrayID = 0
  Date        Timerange (UTC)          Scan  FldId FieldName             nRows     SpwIds   Average Interval(s)    ScanIntent
  19-Nov-2012/07:36:57.0 - 07:39:13.1     4      0 J0522-364                4200  [0]  [6.05]
[CALIBRATE_BANDPASS#ON_SOURCE,CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
              07:44:45.2 - 07:47:01.2     7      2 Ceres                    3800  [0]  [6.05]
[CALIBRATE_AMPLI#ON_SOURCE,CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
              07:52:42.0 - 07:53:47.6    10      3 J1037-295                1900  [0]  [6.05] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
              07:56:23.5 - 08:02:11.3    12      5 TW Hya                   8514  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              08:04:36.3 - 08:05:41.9    14      3 J1037-295                1900  [0]  [6.05] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
              08:08:09.6 - 08:13:57.3    16      5 TW Hya                  10360  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              08:16:20.6 - 08:17:26.2    18      3 J1037-295                2100  [0]  [6.05] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
              08:19:53.9 - 08:25:41.7    20      5 TW Hya                  10321  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              08:28:17.1 - 08:29:22.6    22      3 J1037-295                2100  [0]  [6.05] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
              08:32:00.5 - 08:37:48.2    24      5 TW Hya                  10324  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              08:40:11.9 - 08:41:17.4    26      3 J1037-295                2100  [0]  [6.05] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
              08:43:45.6 - 08:49:33.4    28      5 TW Hya                   9462  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              08:51:57.1 - 08:53:02.6    30      3 J1037-295                1900  [0]  [6.05] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
              08:58:12.0 - 09:00:28.1    33      6 3c279                    3402  [0]  [6.05]
[CALIBRATE_BANDPASS#ON_SOURCE,CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
              09:01:35.7 - 09:02:41.2    34      3 J1037-295                1900  [0]  [6.05] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
              09:05:15.6 - 09:07:31.6    36      5 TW Hya                   4180  [0]  [6.05] [OBSERVE_TARGET#ON_SOURCE]
              09:09:59.1 - 09:11:04.7    38      3 J1037-295                2100  [0]  [6.05] [CALIBRATE_PHASE#ON_SOURCE,CALIBRATE_WVR#ON_SOURCE]
           (nRows = Total number of rows per scan)
Fields: 5
  ID   Code Name                RA               Decl           Epoch   SrcId      nRows
  0    none J0522-364           05:22:57.984648 -36.27.30.85128 J2000   0           4200
  2    none Ceres               06:10:15.950590 +23.22.06.90668 J2000   2           3800
  3    none J1037-295           10:37:16.079736 -29.34.02.81316 J2000   3          16000
  5    none TW Hya              11:01:51.796000 -34.42.17.36600 J2000   4          53161
  6    none 3c279               12:56:11.166576 -05.47.21.52464 J2000   5           3402
Spectral Windows:  (1 unique spectral windows and 1 unique polarization setups)
  SpwID  Name                           #Chans   Frame   Ch0(MHz)  ChanWid(kHz)  TotBW(kHz) CtrFreq(MHz) BBC Num  Corrs
  0      ALMA_RB_07#BB_2#SW-01#FULL_RES    384   TOPO  372533.086       610.352    234375.0 372649.9688        2  XX  YY
Sources: 5
  ID   Name                SpwId RestFreq(MHz)  SysVel(km/s)
  0    J0522-364           0     -              -
  1    Ceres               0     -              -
  2    J1037-295           0     -              -
  3    TW Hya              0     -              -
  4    3c279               0     -              -
Antennas: 21:
  ID   Name  Station   Diam.    Long.         Lat.                Offset from array center (m)                ITRF Geocentric coordinates (m)
                                                                     East         North     Elevation               x               y               z
  1    DA42  A050      12.0 m   -067.45.16.2  -22.53.29.3        43.0352      -744.9713       21.6702  2225079.880016 -5440041.377534 -2481724.598031
  2    DA44  A068      12.0 m   -067.45.20.6  -22.53.25.7       -82.4232      -631.7828       23.5810  2224981.097784 -5440131.250387 -2481621.066374
  3    DA45  A070      12.0 m   -067.45.11.9  -22.53.29.3       166.1833      -743.4934       19.8811  2225193.450167 -5439993.764157 -2481722.540534
```

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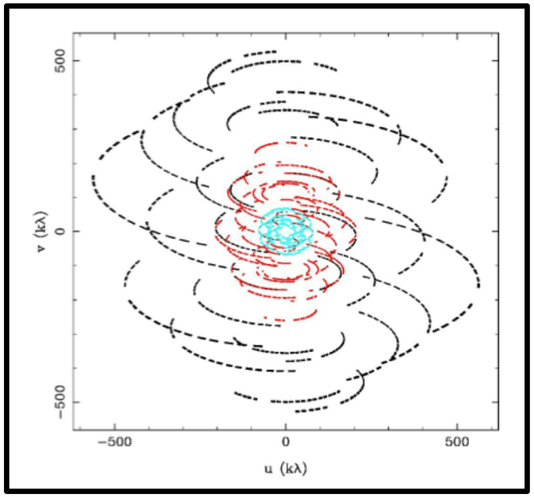
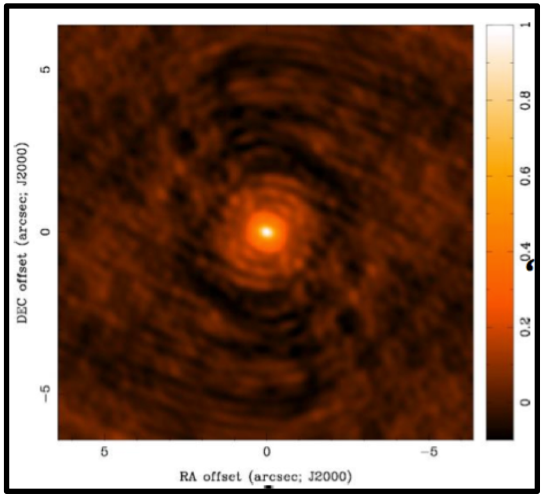
The interferometry imaging

S(u,v)

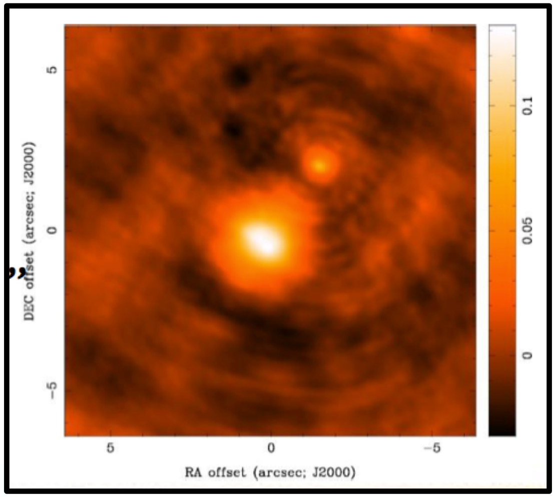


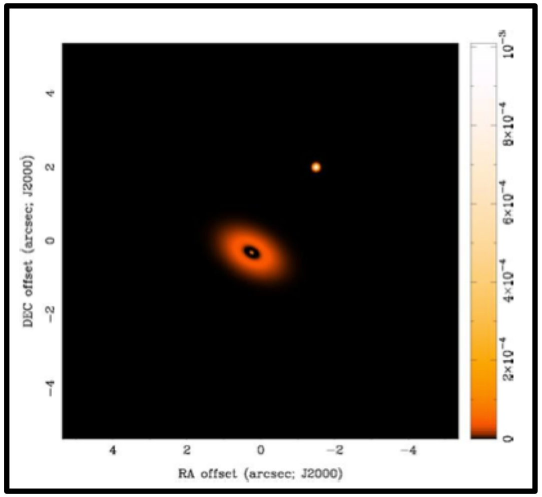
FT

s(l,m)
"Dirty Beam"



*** (Convolution)**





T_D(l,m)
"observed image"

T(l,m)

Making an Image: clean

Assumption: Image T(l,m) is a collection of point sources

Steps to Clean:

Initialize: set residual map to dirty image and empty "clean component list"

1. Start by identifying the highest peak in the residual map as a point source
2. Subtract a fraction of this peak from the residual map using a scaled dirty beam: s(l,m) x gain
3. Add this point source location and amplitude to the "clean component list"
4. Go back to step 1 (complete an iteration) unless stopping criterion reached

Stopping Criteria? Usually max(residual map within clean mask) < multiple of rms noise

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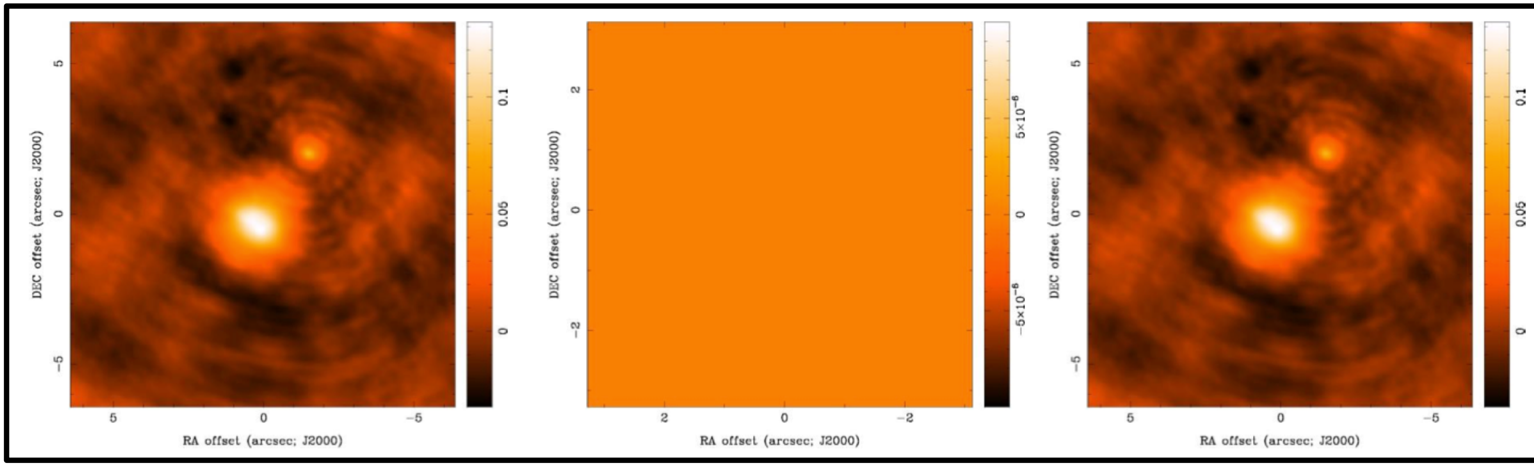
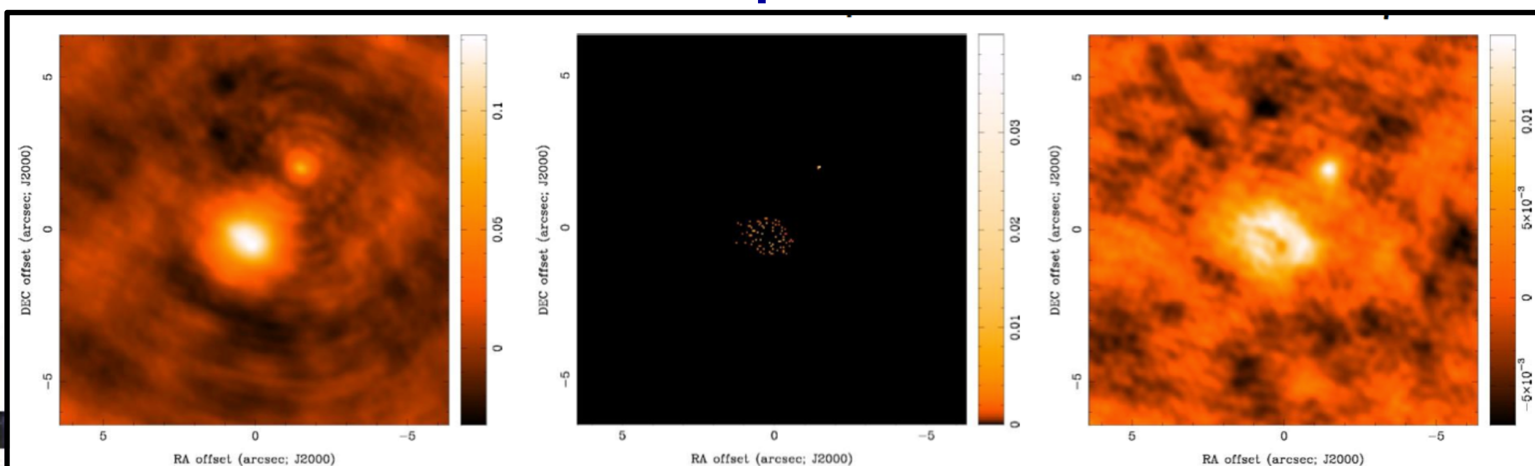
Making an Image

$T_D(l,m)$ "Dirty Image" | **0 Clean Components** | **Residual Map**



100 Clean Components



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Iteractive process: major/minor cycle

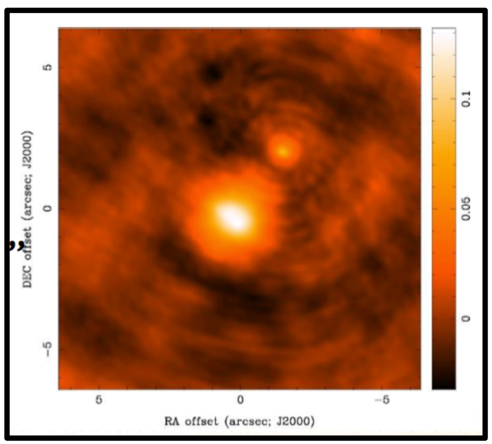
- **Major cycle: data / model comparison in Fourier space, gridding for iFFT to convert into image space**
- **Minor cycle: building clean component in image space using deconvolution algorithm**
- **Combination of major/minor cycle controls clean procedure**

Making an Image

1. Make a model image with all point sources from the "clean component list"
2. Convolve point sources with an elliptical Gaussian, fit to the main lobe of the dirty beam ("clean beam")
3. Add residual map of noise and source structure below the set threshold

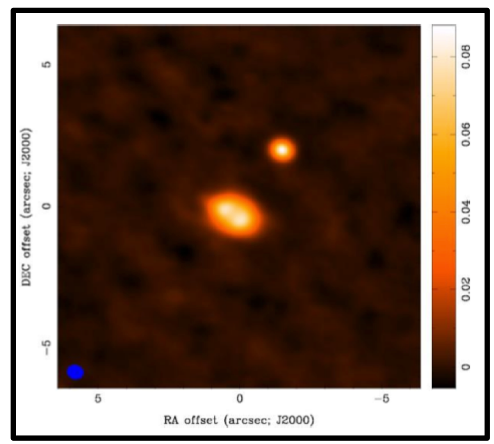
Result: A final "restored image" that is an estimate of the true sky brightness T(l,m)

Units of the restored image are (mostly) Jy per clean beam area = intensity



T_D(l,m)
"Dirty Image"

Clean →



T(l,m)
"Restored Image"

Inspect data and identify line free channels

```
# In CASA
plotms(vis='sis14_twhya_calibrated_flagged.ms',
xaxis='channel', yaxis='amp', field='5', avgspw=False,
avgtime='1e9', avgscan=True, avgbaseline=True,
showgui = True)
```

Split target for continuum imaging

```
# In CASA
flagdata(vis='sis14_twhya_calibrated_flagged.ms',
   mode= 'manual', spw='0:225~270')

split(vis='sis14_twhya_calibrated_flagged.ms',
      field='5', width='8',
      outputvis='sys14_twhya_smoothed_cont.ms',
      datacolumn='data')

listobs('sis14_twhya_smoothed_cont.ms')
```

Making a continuum image

```
# In CASA
os.system('rm -rf twhya_cont.*’)

tclean(vis=‘sis14_twhya_smoothed_cont.ms’,
   imagename='twhya_cont’,
   field='0', spw=’’, specmode=‘cont’,
   gridder='standard', deconvolver='hogbom’,
   imsize=[250,250], cell=['0.08arcsec’],
   weighting='briggs', robust=0.5,
   threshold='0mJy', niter=5000, pbcor=True,
   interactive=True)
```

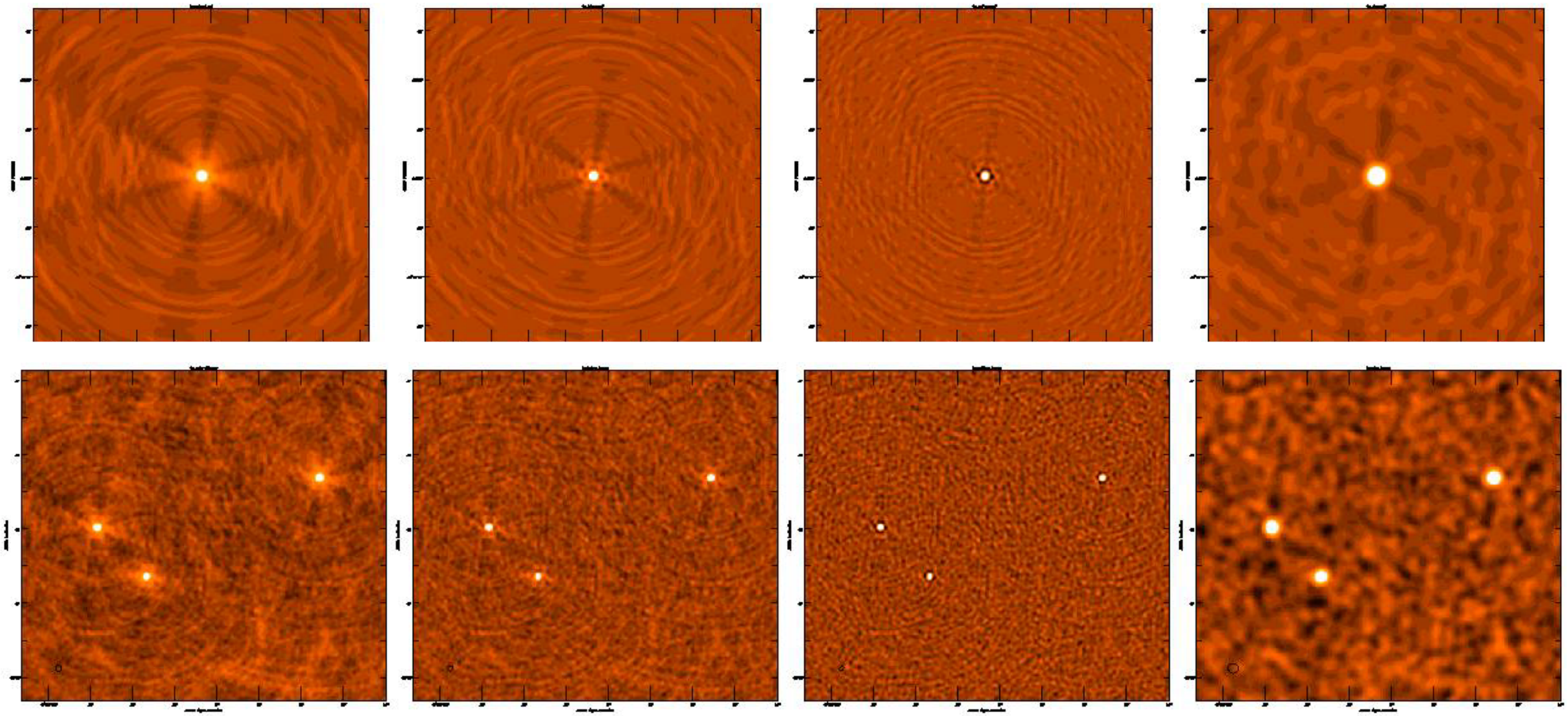
tclean parameters:

specmode=['mfs','cont','cube']
gridder=['standard','mosaic']
deconvolver=['hogbom','clark','multiscale','mtmfs']
weighting=['briggs','natural','uniform']
robust=0.5
threshold='0mJy'
niter=5000
phasecenter=[field id or coordinate]
cycleniter=100
uvtaper=['1arcsec']
usemask=['user','pb','auto-multithresh']

For more details, CASA documentation
https://casa.nrao.edu/casadocs/
Choose version, then click Global Task List from the Directory
Find tclean task and then click
There are tabs: description, parameters,changelog and examples

tclean parameters (robust):

Natural	Robust 0.7	Uniform	Uniform taper
Bm: 5.6arcsec	Bm: 4.0arcsec	Bm: 3.2arcsec	Bm: 8.0arcsec
0.1 sidelobe	0.05 sidelobe	0.03 sidelobe	0.01 sidelobe



by courtesy of Urvashi Rau

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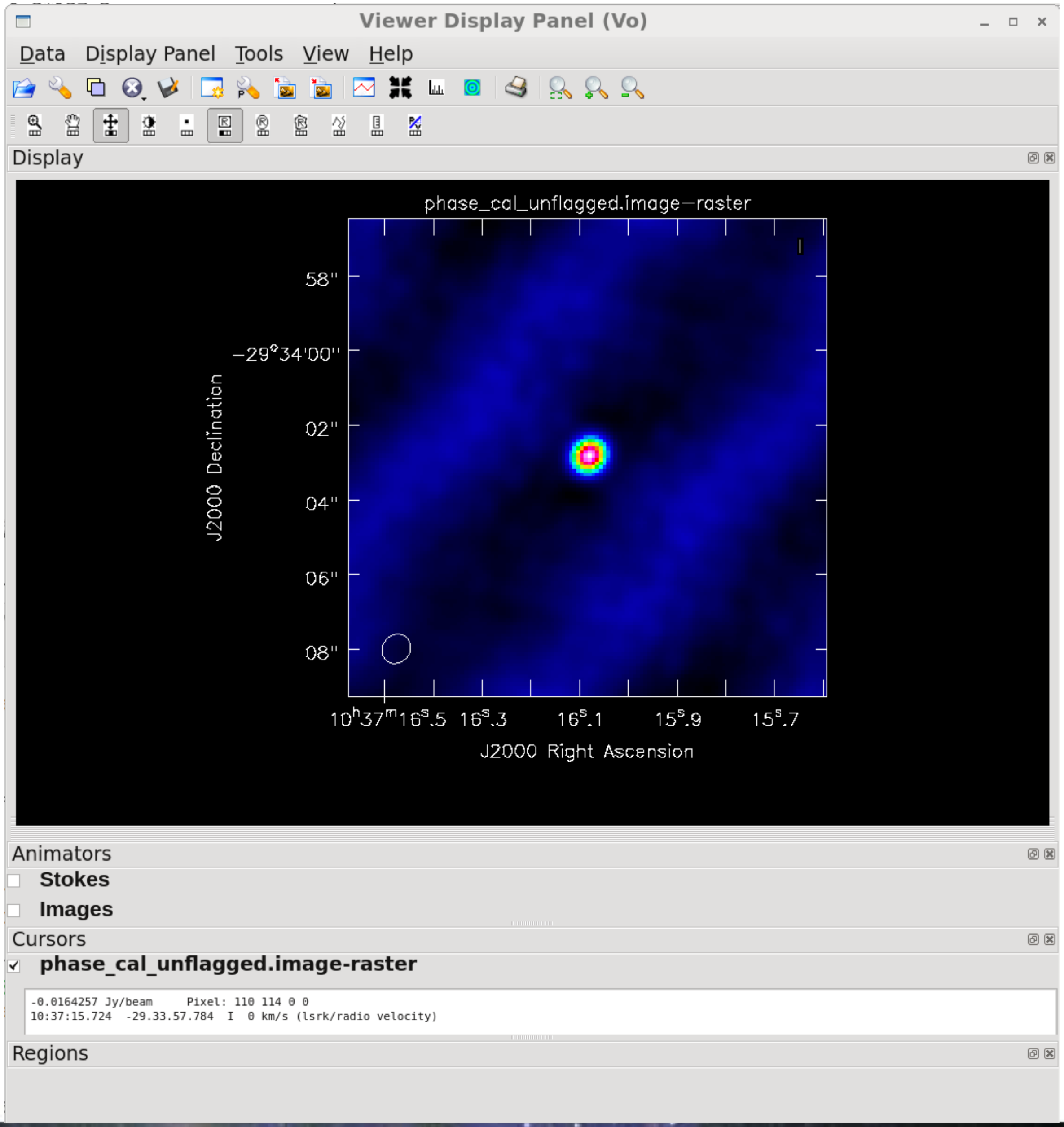
Output images

- twhya_cont.image
- twhya_cont.psf
- twhya_cont.mask
- twhya_cont.model
- twhya_cont.pb
- twhya_cont.pbcor
- twhya_cont.residual

Bad image


Viewer Display Panel (Vo)
Data Display Panel Tools View Help
Display
phase_cal_unflagged.image−raster
58''
−29°34'00''
02''
04''
06''
08''
J2000 Declination
10h37m16s.5 16s.3 16s.1 15s.9 15s.7
J2000 Right Ascension
Animators
Stokes
Images
Cursors
phase_cal_unflagged.image-raster
-0.0164257 Jy/beam Pixel: 110 114 0 0
10:37:15.724 -29.33.57.784 I 0 km/s (lsrk/radio velocity)
Regions

Doing selfcalibration on continuum image

Iterative process with decreasing solint

- clean and save the clean model
- use the model to solve gain solution
- apply the solution to the data

With more than 25 antennas, if image S/N is 20, try phase only selfcal

Do clean conservatively

Be cautious on amp-selfcal (with extended emission)

Doing selfcalibration on continuum image

```
tclean(vis=contvis,
      imagename='twhya_cont_p0',
      field='0',
      spw='',
      specmode='cont',
      gridder='standard',
      deconvolver='hogbom',
      imsize=[250,250],
      cell=['0.08arcsec'],
      weighting='briggs',
      robust=0.5,
      threshold='0mJy',
      niter=5000,
      savemodel='modelcolumn',
      interactive=True)
```

```
gaincal(vis=contvis,
      caltable='pcal1',
      field='0',
      gaintype='T',
      refant='DV22',
      calmode='p',
      combine='spw',
      solint='inf',
      minsnr=3.0,
      minblperant=6)
```

```
applycal(vis=contvis,
      field='0',
      spwmap=[0],
      gaintable=['pcal1'],
      gainfield='',
      calwt=False,
      flagbackup=False,
      interp='linearperobs')
```

Doing selfcalibration on continuum image

```
tclean(vis=contvis,
       imagename='twhya_cont_p1',
       field='0',
       spw='',
       specmode='cont',
       gridder='standard',
       deconvolver='hogbom',
       imsize=[250,250],
       cell=['0.08arcsec'],
       weighting='briggs',
       robust=0.5,
       threshold='0mJy',
       niter=5000,
       savemodel='modelcolumn',
       interactive=True)
```

```
gaincal(vis=contvis,
        caltable='pcal2',
        field='0',
        gaintype='T',
        refant='DV22',
        calmode='p',
        combine='spw',
        solint='30.25s',
        minsnr=3.0,
        minblperant=6)
```

```
applycal(vis=contvis,
         field='0',
         spwmap=[0],
         gaintable=['pcal2'],
         gainfield='',
         calwt=False,
         flagbackup=False,
         interp='linearperobs')
```

Doing selfcalibration on continuum image

```
tclean(vis=contvis,
      imagename='twhya_cont_p2',
      field='0',
      spw='',
      specmode='cont',
      gridder='standard',
      deconvolver='hogbom',
      imsize=[250,250],
      cell=['0.08arcsec'],
      weighting='briggs',
      robust=0.5,
      threshold='0mJy',
      niter=5000,
      savemodel='modelcolumn',
      interactive=True)
```

- Phase selfcal improves the phase decoherence
- After successful selfcal: RMS decreases and peak flux increases

Linecube imaging

```
applycal(vis=linevis, spwmap=[0],  field='0',
        gaintable=['pcal2'], gainfield='', calwt=False,
        flagbackup=False, interp=['linearperobs'])


uvcontsub(vis ='sis14_twhya_calibrated_flagged.ms',
    field = '5', fitspw = '0:225~270',
    excludechans = True, fitorder = 0, solint='int')
```

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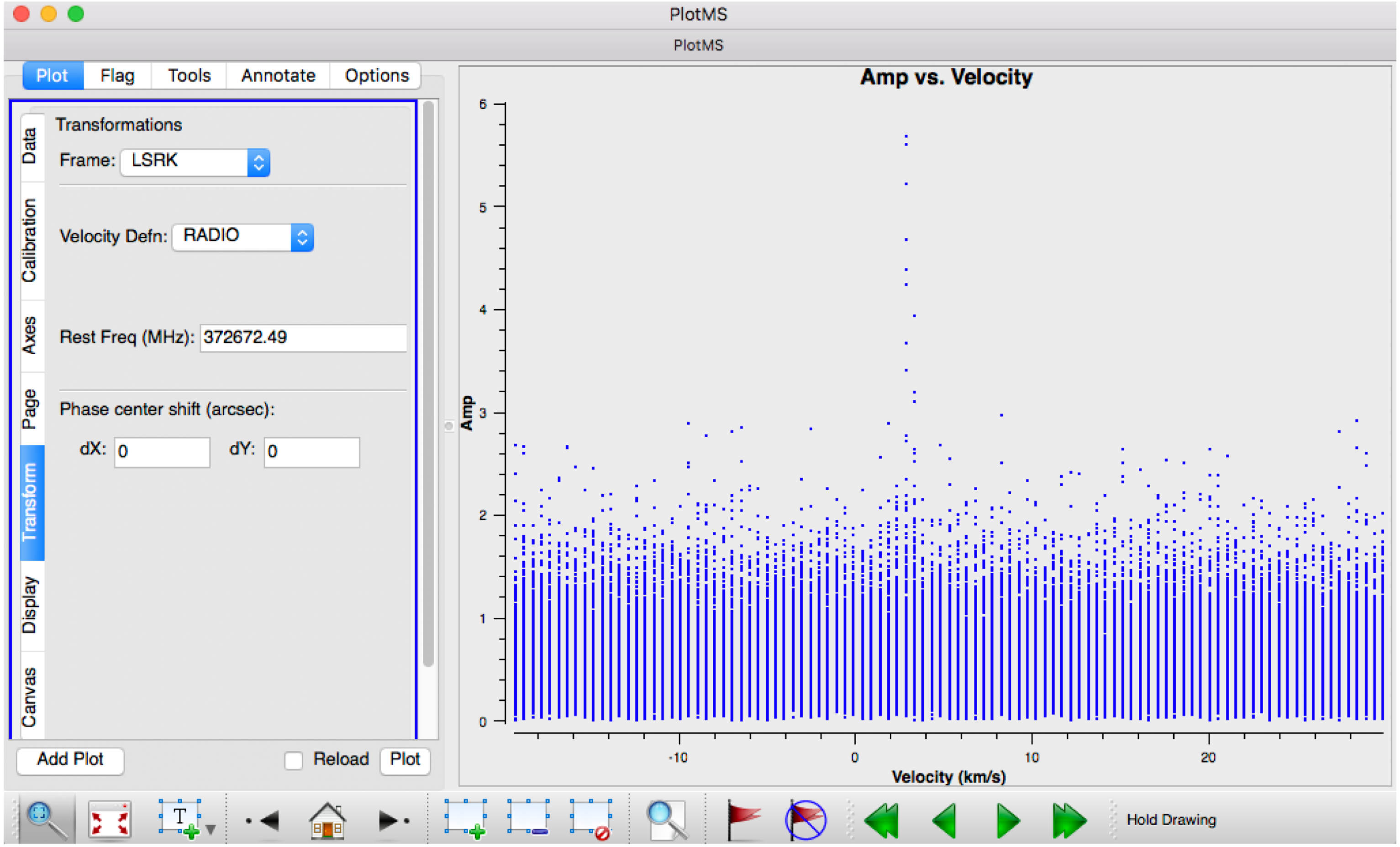
Linecube imaging



nchan=15, nstart='0km/s',width='0.5km/s'
restfreq='372.67249GHz',outframe='LSRK'

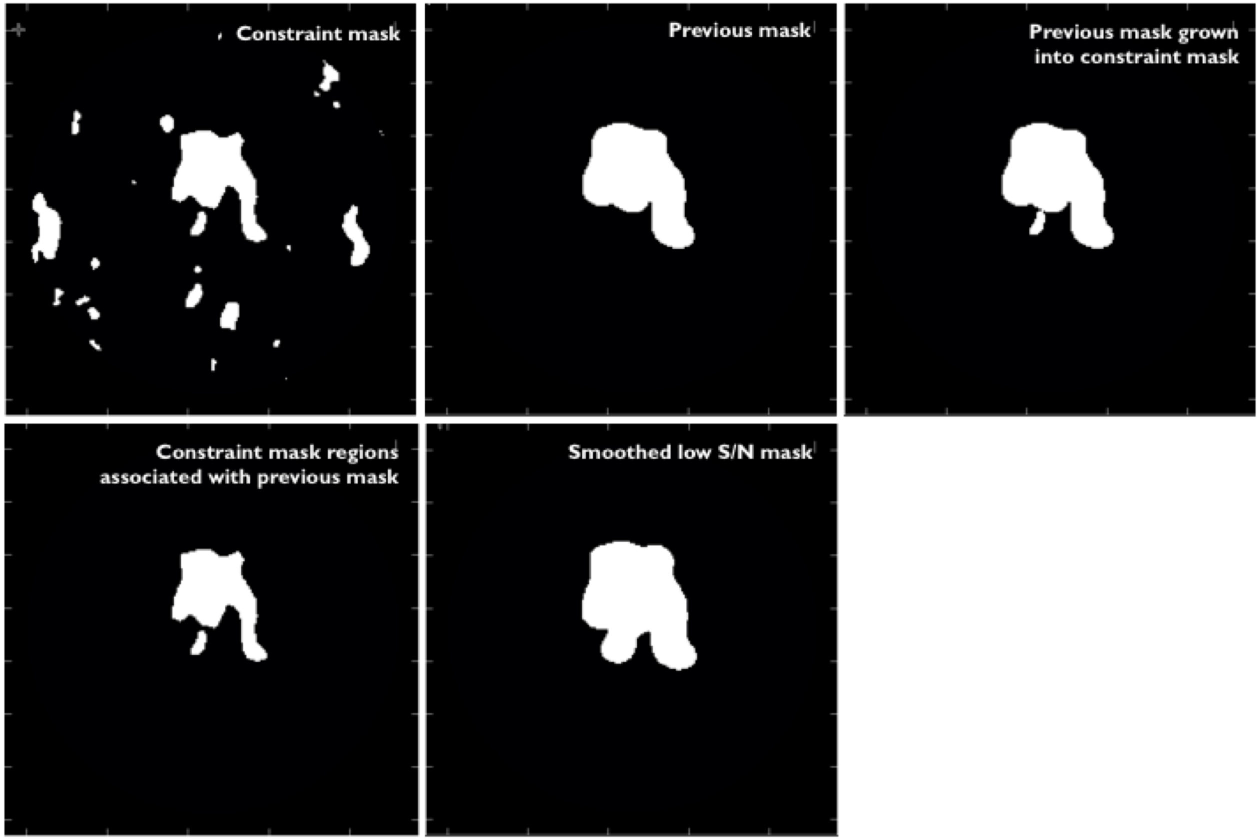
Linecube imaging

```
tclean(vis = linevis, imagename = 'twhya_n2hp’,
      field = '0’, spw = '0’, specmode = 'cube’, nchan = 15,
      start = '0.0km/s’, width = '0.5km/s',
      outframe = 'LSRK’, restfreq = '372.67249GHz',
      deconvolver= 'hogbom’, gridder = 'standard',
      imsize = [250, 250], cell = '0.08arcsec',
      phasecenter = 0, weighting = 'briggs’, robust = 0.5,
      restoringbeam='common’, interactive = True,
      pbcor=True, niter=5000)
```

Automasking

- Done at every time when minor cycle starts
- Noise threshold mask (noise vs sidelobe)
- Low noise threshold mask (previous mask grows into low noise region)
- Absorption mask (negative threshold, not growing into low noise region)
- Pruned and smoothed
- Combined to create clean mask
- Multiple threshold parameters control the procedure of creating each mask

Automasking



Automasking

```
tclean(vis=linevis,
    imagename='twhya_automask_n2hp_dirtycube',
    field='0',
    spw='0',
    specmode='cube',
    nchan=15,
    start='0.0km/s',
    width='0.5km/s',
    outframe='LSRK',
    restfreq='372.67249GHz',
    deconvolver='hogbom',
    gridder='standard',
    imsize=[250,250],
    cell='0.08arcsec',
    weighting='briggs',
    robust=0.5,
    restoringbeam='common',
    interactive=False,
    niter=0,
    threshold='0.0Jy')
```

Dirty cube:

figure out the value for threshold and get an idea of what the emission/noise looks like

Automasking

Set clean threshold 0.02 Jy/beam and thresholds for automasking

```
tclean(vis = linevis,
       imagename = 'twhya_automask_n2hp',
       field = '0',
       spw = '0',
       specmode = 'cube',
       nchan = 15,
       start = '0.0km/s',
       width = '0.5km/s',
       outframe = 'LSRK',
       restfreq = '372.67249GHz',
       deconvolver= 'hogbom',
       gridder = 'standard',
       imsize = [250, 250],
       cell = '0.08arcsec',
       phasecenter = 0,
       weighting = 'briggs',
       robust = 0.5,
       restoringbeam='common',
       interactive = False,
       threshold='0.02Jy',
       pbcor=True,
       niter=100000,
       usemask='auto-multithresh',
       sidelobethreshold=2.0,
       noisethreshold=3.8,
       lownoisethreshold=1.5,
       minbeamfrac=0.3,
       growiterations=75,
       negativethreshold=15.0)
```

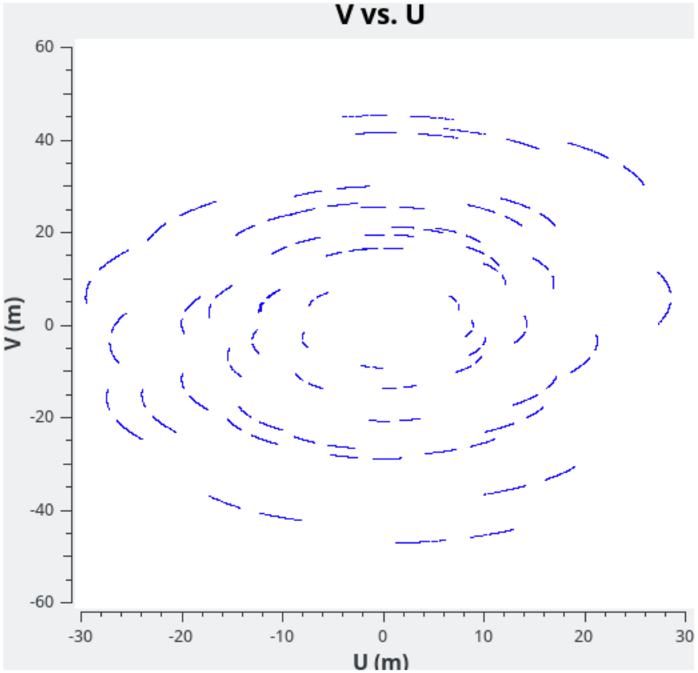
ALMA pipeline imaging

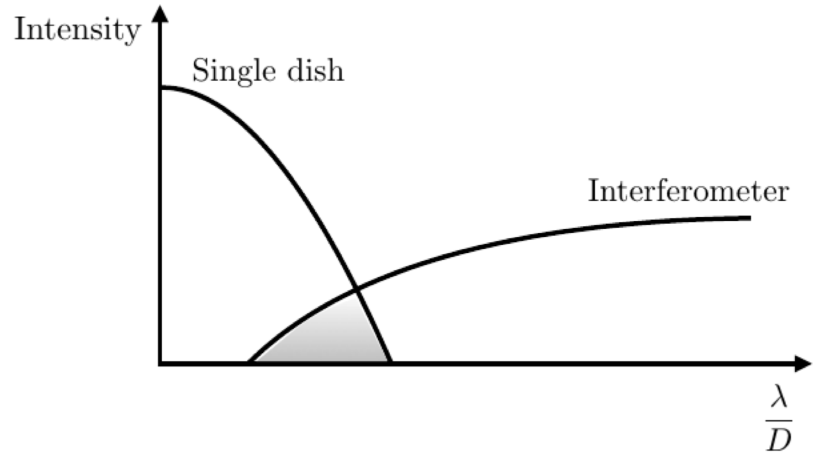
- Use CASA version with pipeline heuristics installed (unfortunately not available for CASA 5.3)
- Launch casa with pipeline: casa --pipeline
- Check pipeline tasks in CASA session: CASA<1> tasklist
- For detail information, try for example, CASA<2> help hifa_importdata
- pipeline mode: “automatic” vs “interactive”
- Will create pipeline weblog with imaging result
- findcont and automasking, are the two most valuable aspects.

ALMA pipeline imaging

```
vislist=['sis14_twhya_calibrated_for_pl.ms']
pipelinemode="automatic”
h_init()
hifa_importdata (vis=vislist, dbservice=False,
pipelinemode=pipelinemode)
hif_checkproductsize()
hif_mstransform (pipelinemode=pipelinemode)
hifa_flagtargets (pipelinemode=pipelinemode)
hif_makeimlist (specmode='mfs', pipelinemode=pipelinemode)
hif_findcont(pipelinemode=pipelinemode)
hif_uvcontfit(pipelinemode=pipelinemode)
hif_uvcontsub(pipelinemode=pipelinemode)
hif_makeimages (pipelinemode=pipelinemode)
hif_makeimlist (specmode='cont', pipelinemode=pipelinemode)
hif_makeimages (pipelinemode=pipelinemode)
hif_makeimlist (specmode='cube', pipelinemode=pipelinemode)
hif_makeimages (pipelinemode=pipelinemode)
h_save()
```

Combining with single dish





Short spacing problem

- negligible for compact object much smaller than primary beam
- for large extended source, IF loses its sensitivity to the extended emission
- Need single dish to fill the gap

by courtesy of Plunkett

Feathering:

- Combine images in Fourier space
- Well sampled and overlaped uv coverage
- Well defined PB for both SD and IF
- Image and PB for SD regridded onto IF image (**imgrid**)
- Align frequency axis and image axis (**imtrans**)
- All images trimmed to the same size (**imsubimage**)
- SD image multiplied by IF PB (**immath**)
- Run CASA task **feather**

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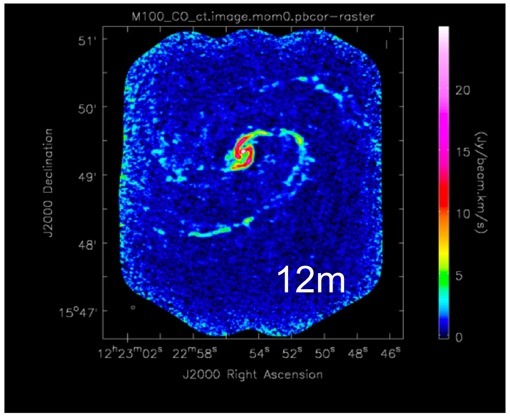
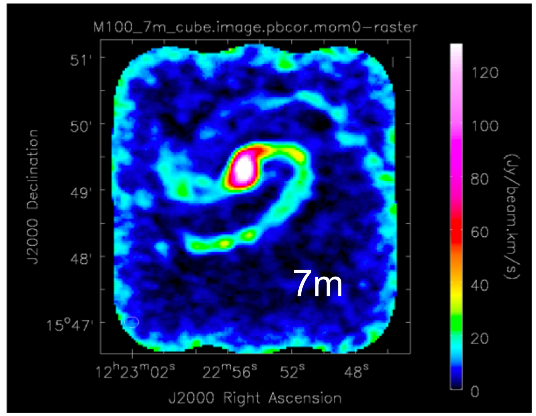
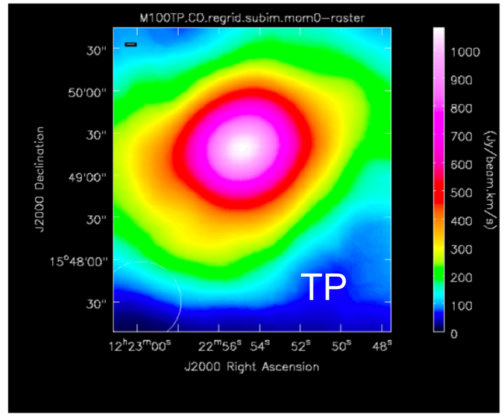
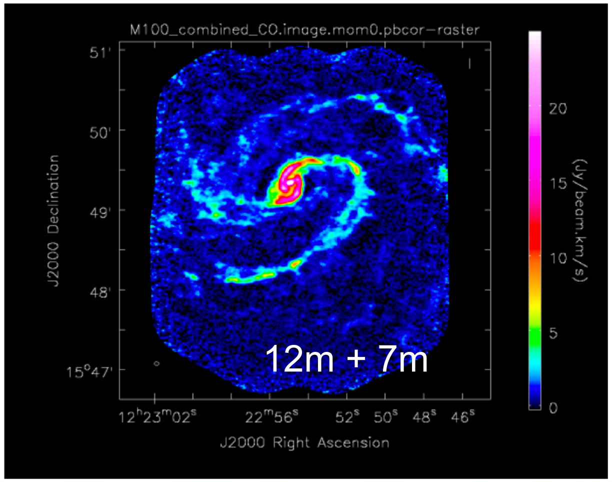
Example:

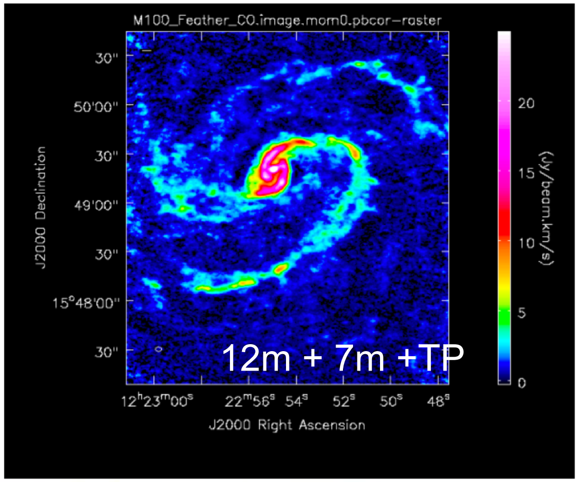
https://casaguides.nrao.edu/index.php/M100_Band3_Combine_5.1











Combining with single dish (resources)

CASA guide for this tutorial
https://casaguides.nrao.edu/index.php/ALMAguides
see “General Imaging Tutorial” section

CASA feather
https://casaguides.nrao.edu/index.php/M100_Band3_Combine_5.1

TP2VIS
https://github.com/tp2vis/distribute

Waiting the data (for old datasdet)
https://casaguides.nrao.edu/index.php/DataWeightsAndCombination

Overview of feathering
https://arxiv.org/pdf/1707.02272.pdf

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