ALMA data reduction & synthesis imaging

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ESO ALMA Fellow

Outline

- Types of Observations Possible
- General steps for data reduction and calibration
- General steps for imaging, and image analysis

This is not a CASA tutorial

CASA

http://casa.nrao.edu/

Types of Observations

- Molecular line emission
  - Chemistry
  - Dynamics
  - Gas temp/mass

- Continuum emission
  - Dust/gas mass
  - SED
  - Dust temperature

- Masers
  - Distances/Dynamics
  - Density/Temp.

- Ionized line emission
  - Dynamics
  - Electron density

Types of Observations

- Molecular line emission
  - Chemistry
  - Dynamics
  - Gas temp/mass

Polarimetry

- Continuum emission
  - Dust/gas mass
  - SED
  - Dust temperature

- Masers
  - Distances/Dynamics
  - Density/Temp.

- Ionized line emission
  - Dynamics
  - Electron density

Types of Observations

- Molecular line emission
  - Chemistry
  - Dynamics
  - Gas temp/mass

Dynamics: infall, outflow, rotation, sheer, turbulence...

mm/sub-mm interferometers have great spectral resolution

CO ^{13}CO $C^{18}O$

SiO

HCO^+

H_2O

CS

H_2CO

NH_3

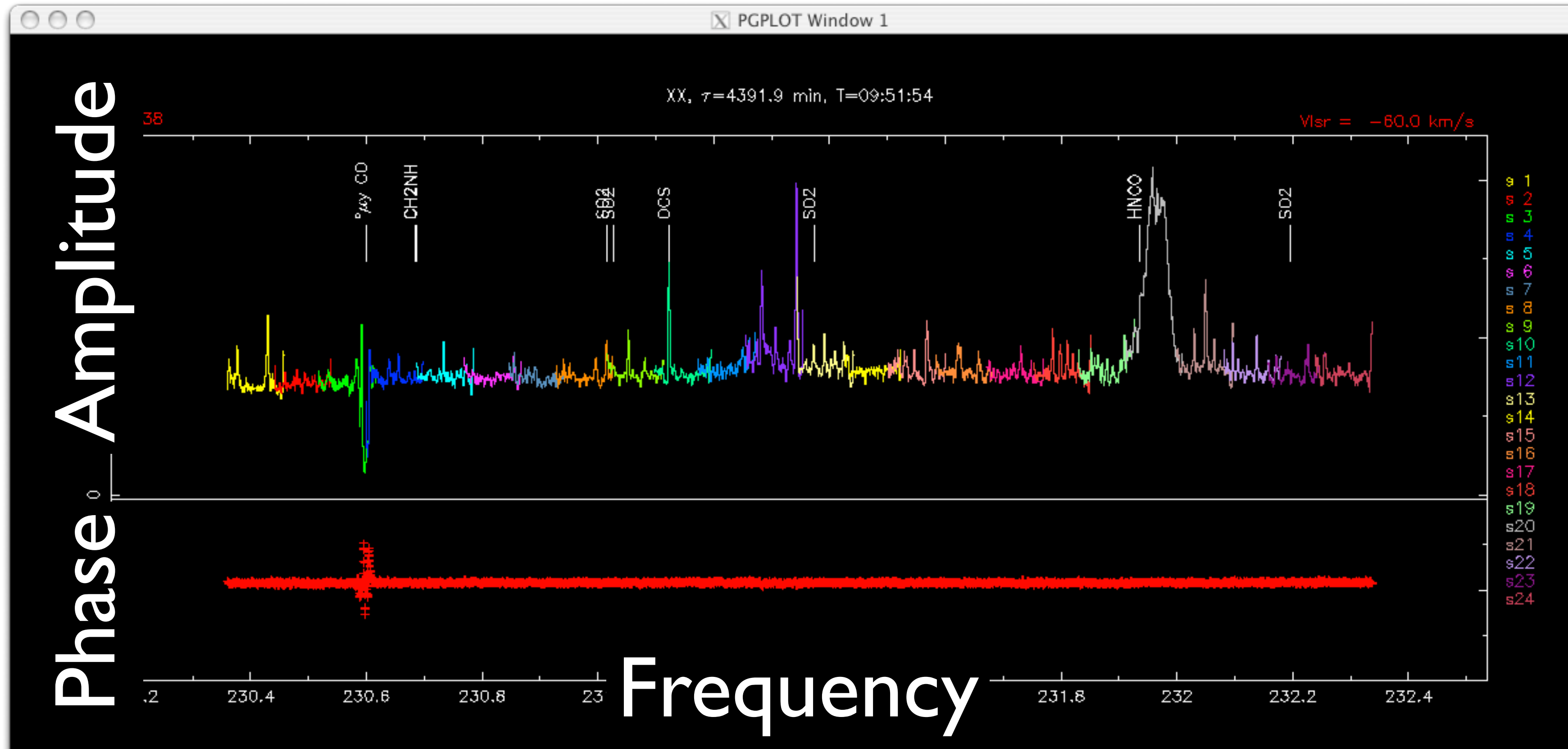
CH_3OH

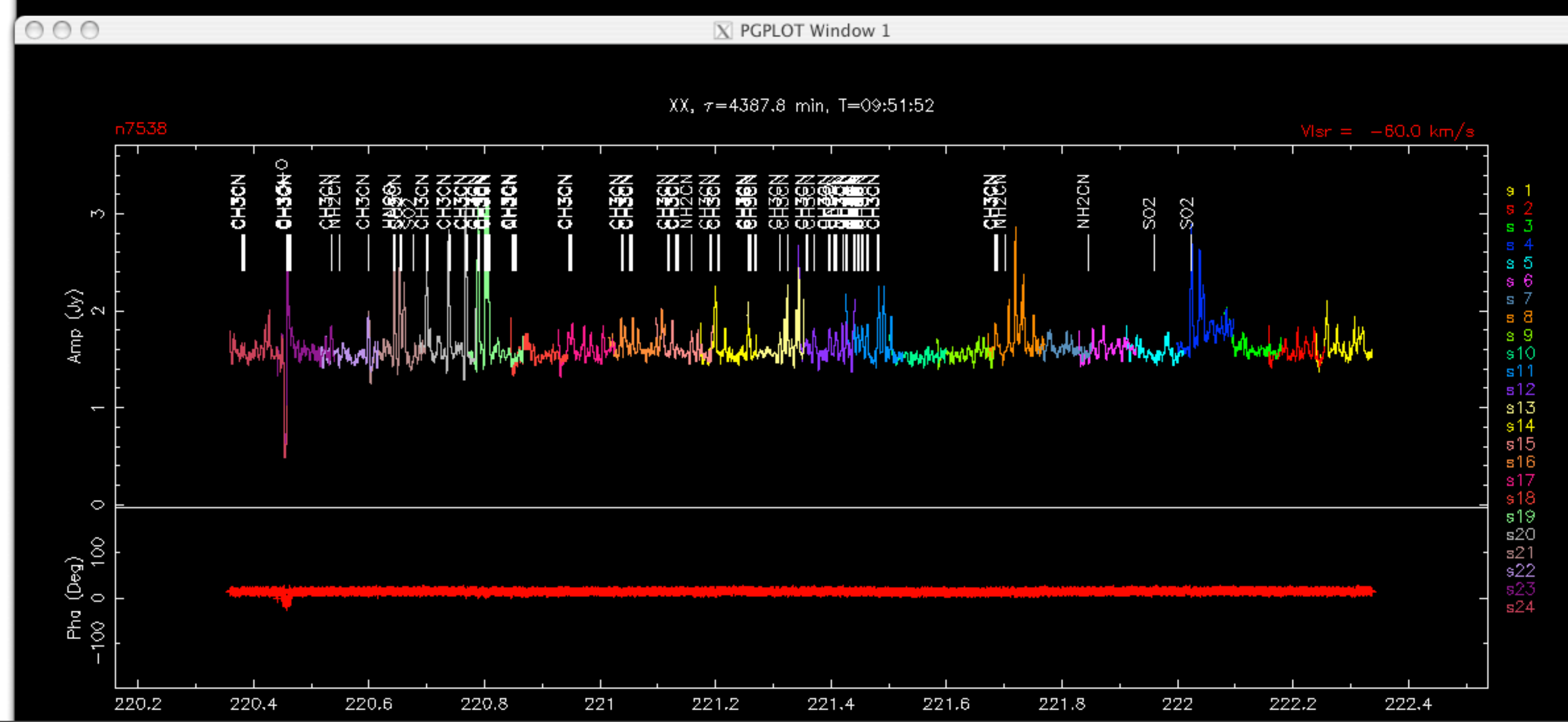
CH_3CN

N_2H^+

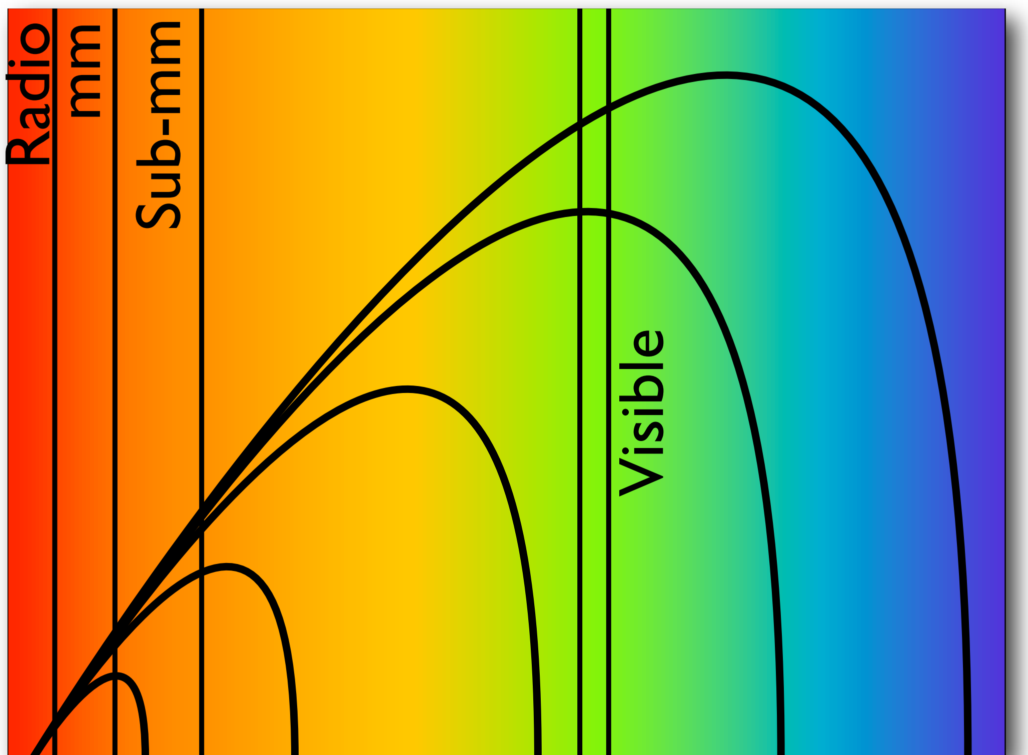
Types of Observations

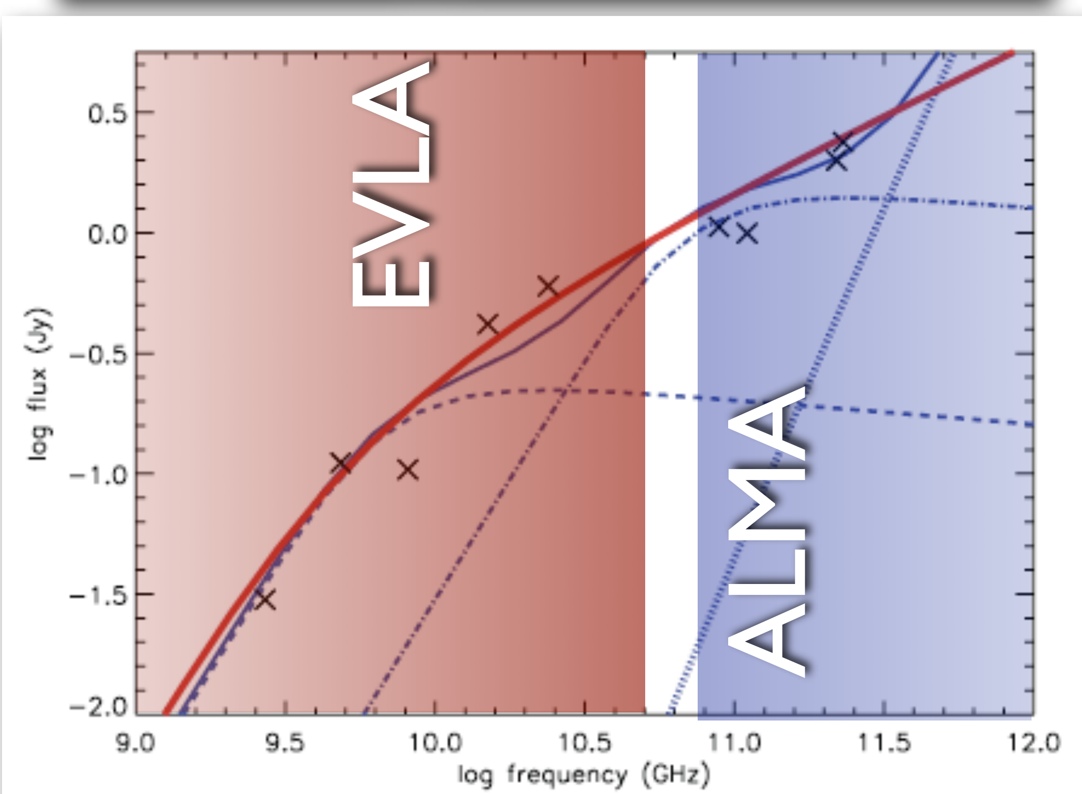
- ALMA can simultaneously measure a large number of lines AND the continuum
- No bolometer array like for SD telescopes





Types of Observations





Keto et al. 2008

- Continuum emission
  - Dust/gas mass
  - SED
  - Dust temperature

free-free vs. thermal radiation

$$M_{\rm clump} = \frac{S_\lambda^{\rm int} d^2}{\kappa_\lambda B_\lambda(T_{\rm dust})}$$

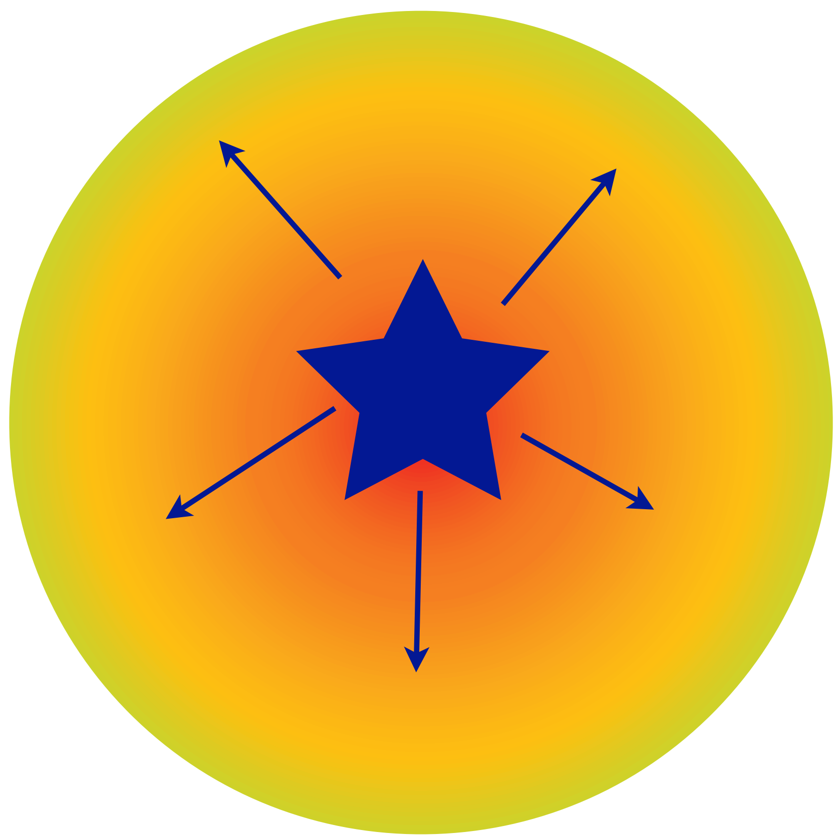
Reid & Wilson 2005

Types of Observations

Pressure Broadening

Electron Densities

Stellar
Mass



Thermal Broadening

Dynamics

Ionization fraction

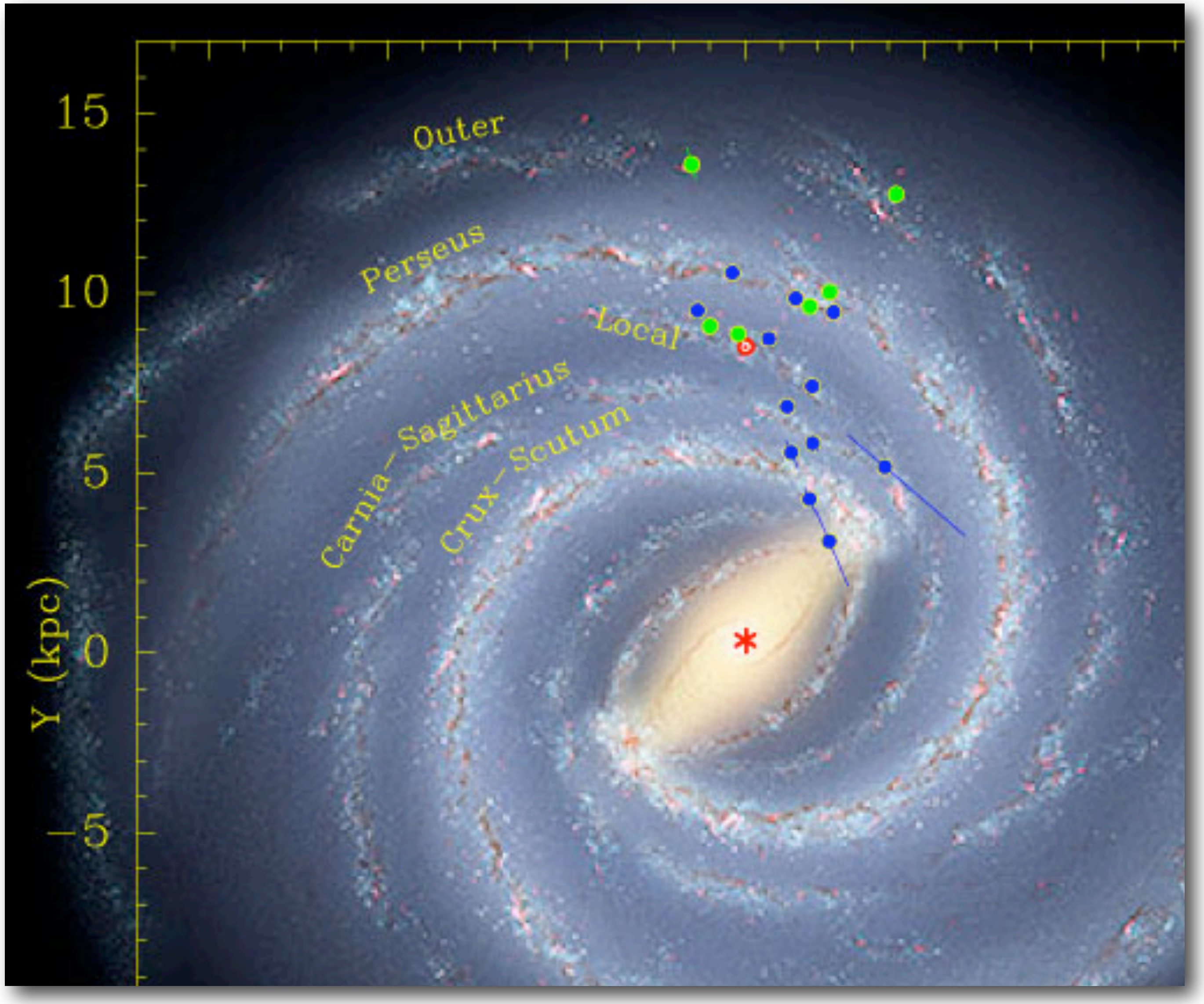
- Ionized line emission
  - Dynamics
  - Electron density

Types of Observations

Modeling gives:
density & temperature

Proper motions:
gas kinematics
& distances

- Masers
  - Distances/Dynamics
  - Density/Temp.



Zeeman effects:
magnetic field

M.J Reid et al.

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  - Dynamics
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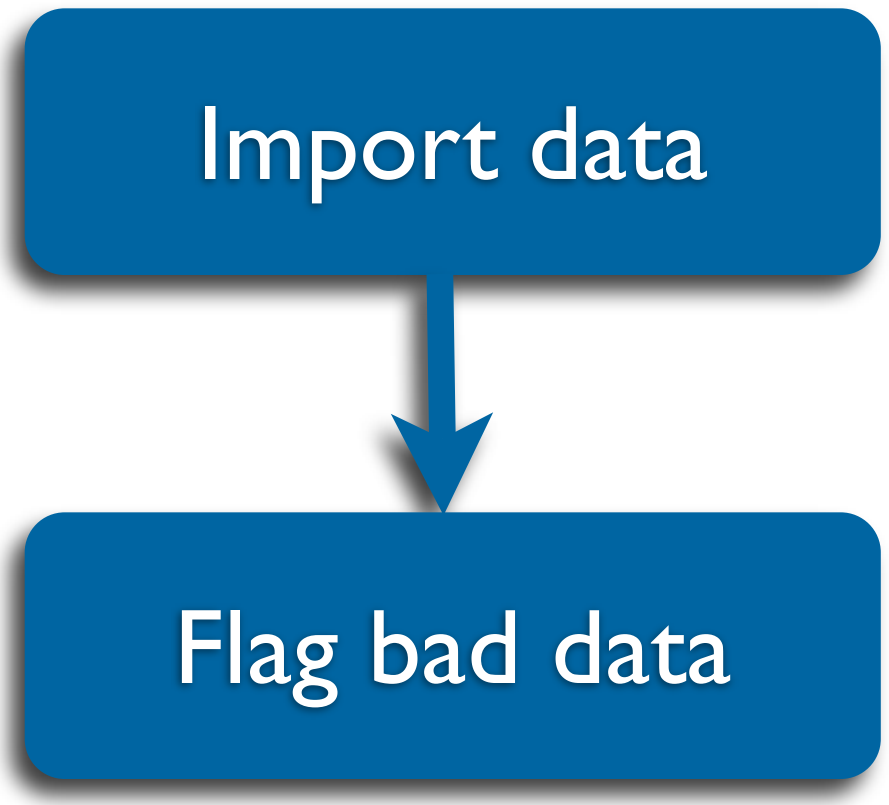
Data Flow

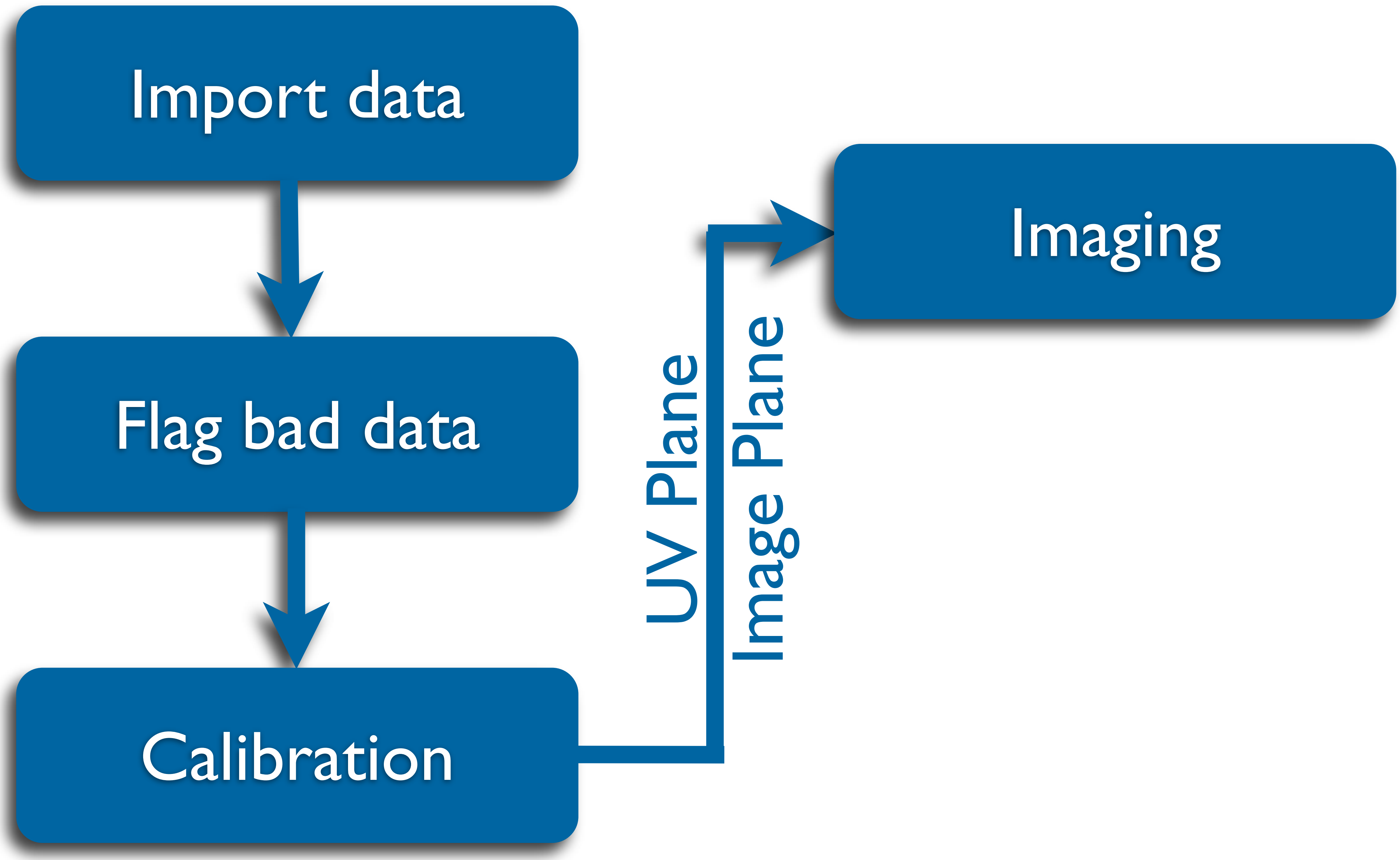
Import data

Data Flow

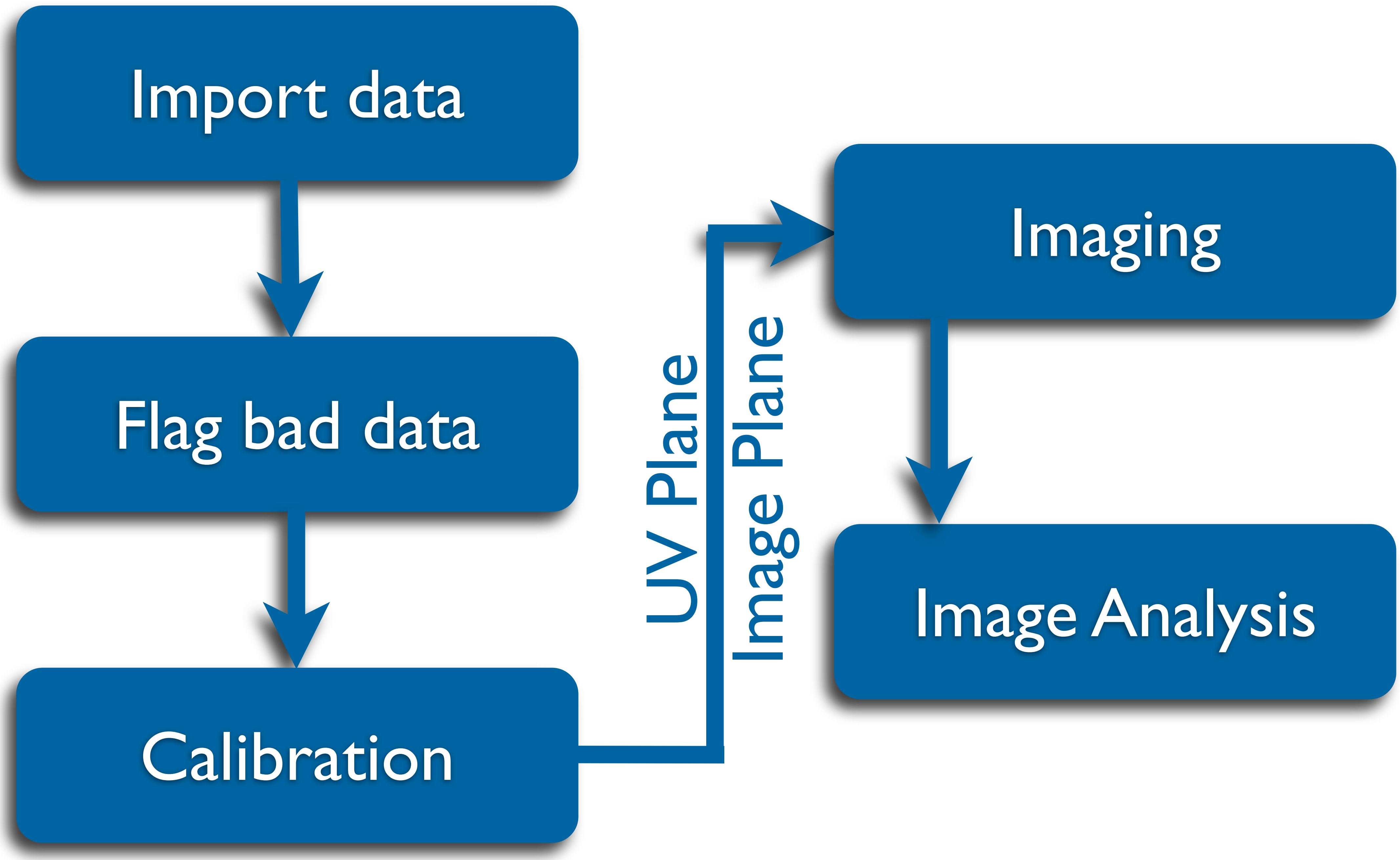


Data Flow

Data Flow

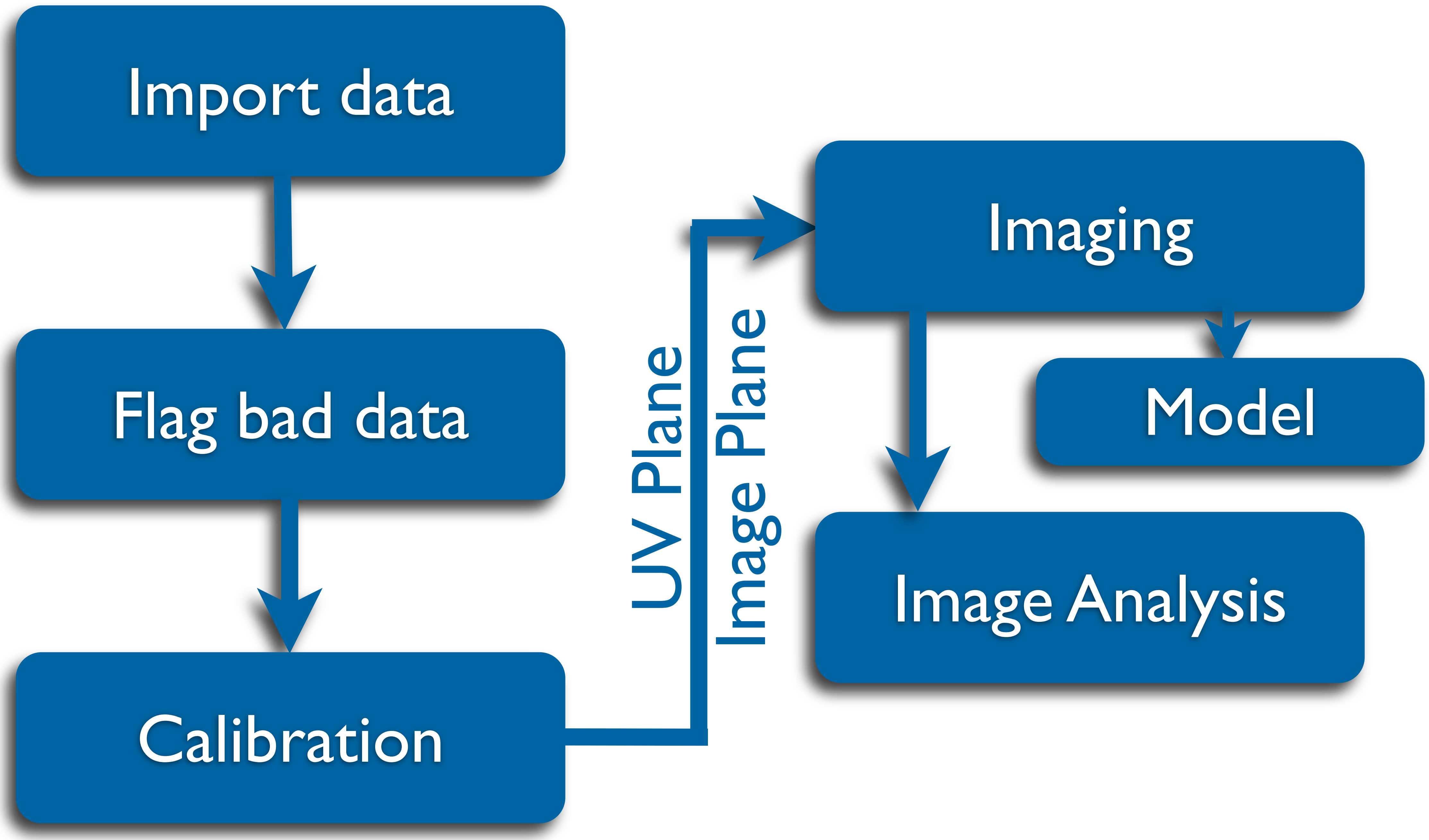

Import data
Flag bad data
Calibration
UV Plane
Image Plane
Imaging

Data Flow

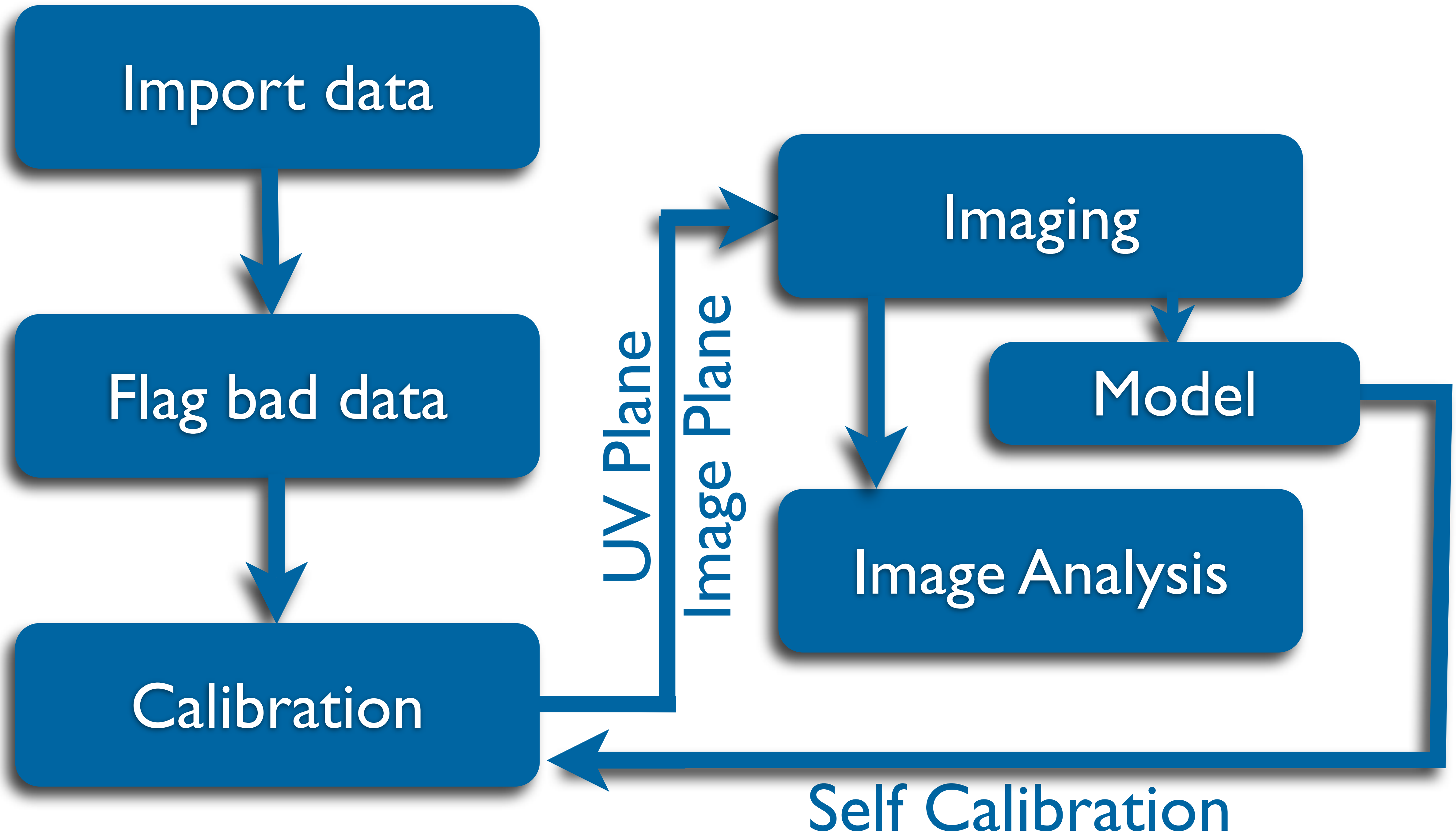


Import data
Flag bad data
Calibration
UV Plane
Image Plane
Imaging
Image Analysis

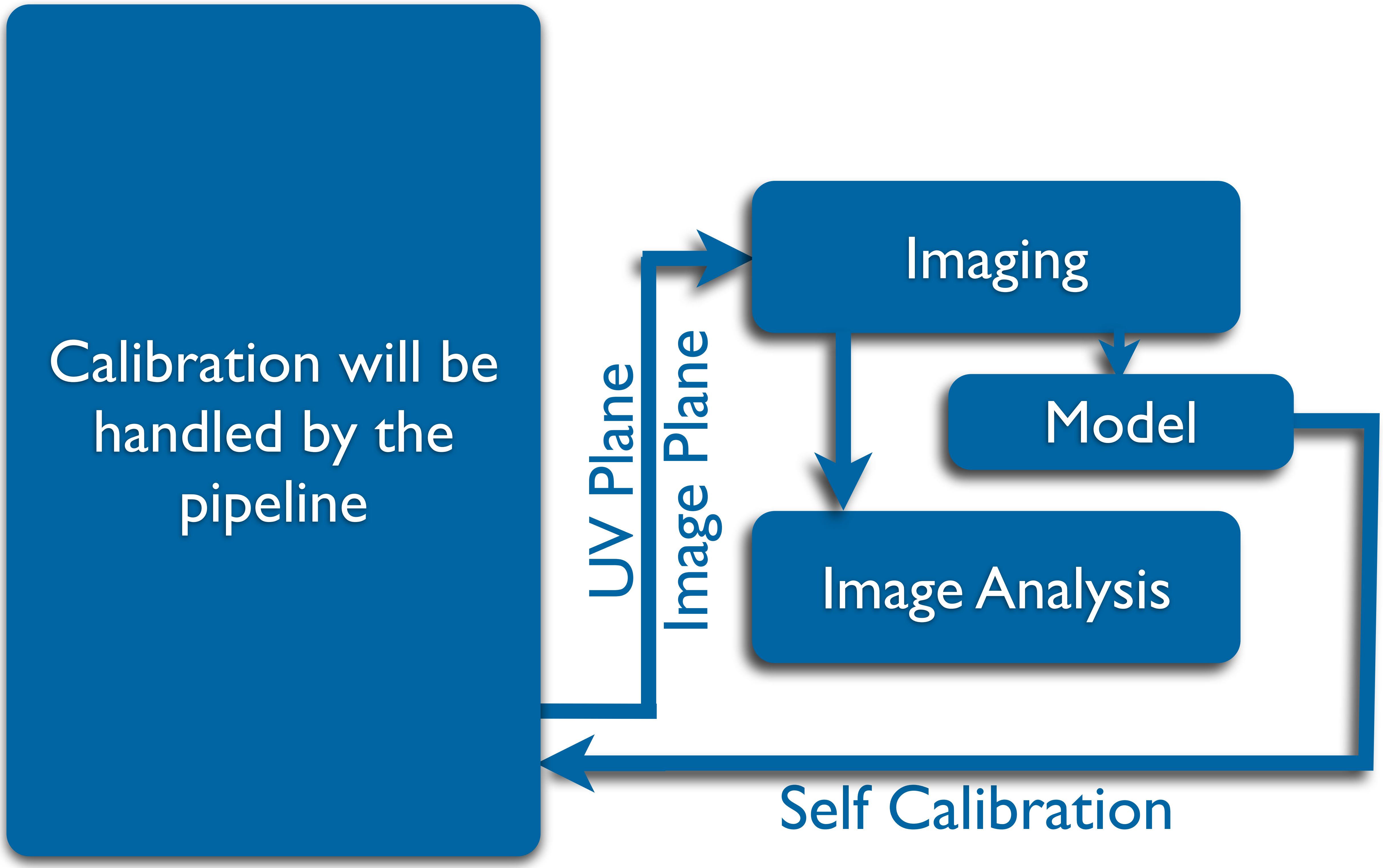
Data Flow


Import data
Flag bad data
Calibration
UV Plane
Image Plane
Imaging
Model
Image Analysis

Data Flow


Import data
Flag bad data
Calibration
UV Plane
Image Plane
Imaging
Model
Image Analysis
Self Calibration

Data Flow


Calibration will be handled by the pipeline
UV Plane
Image Plane
Imaging
Model
Image Analysis
Self Calibration

Importing data

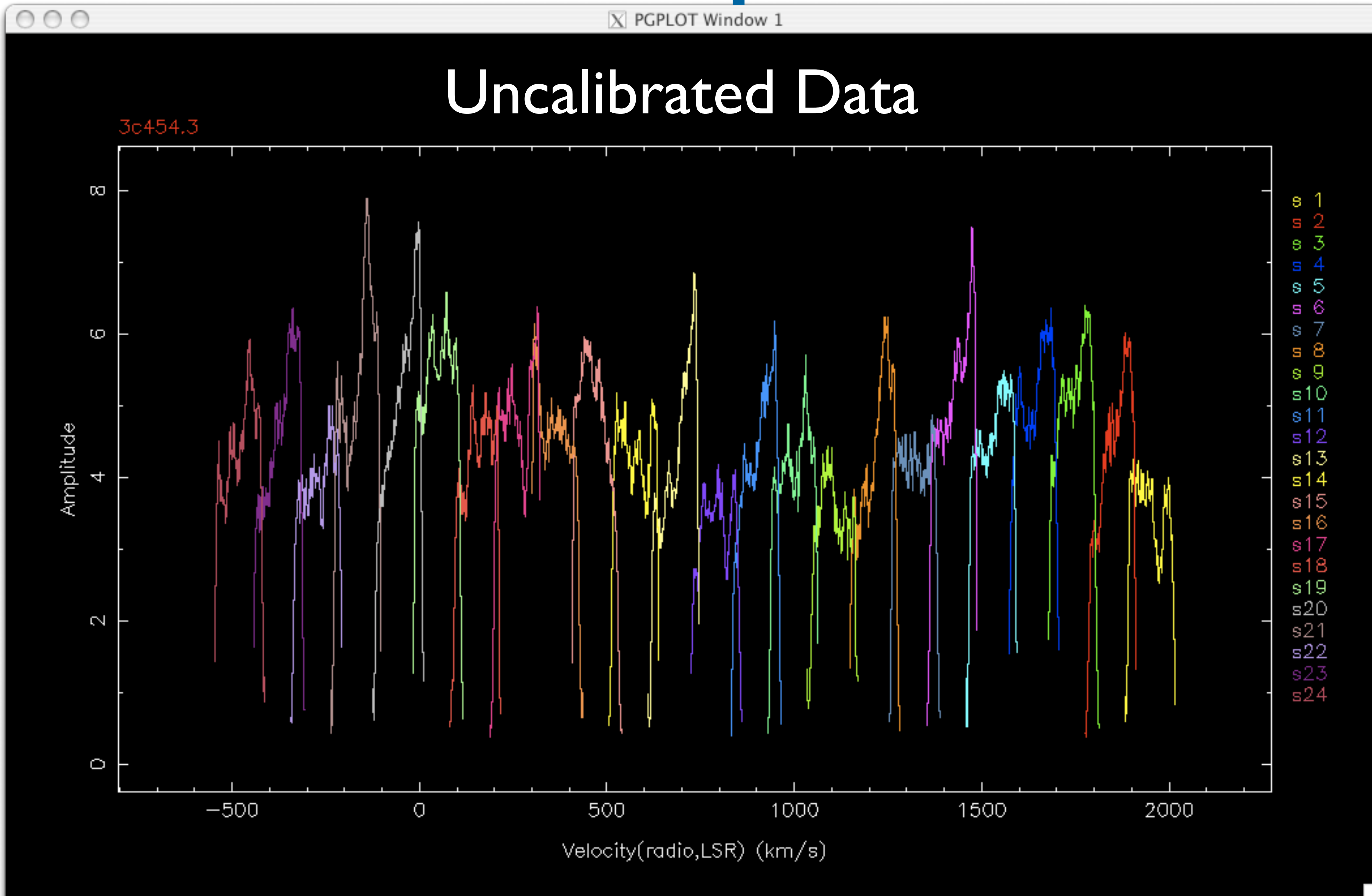
- Data set being used here:
- SMA extended config.
  - 230 GHz line+cont
- NGC 7538 IRS 1

Keto et al. 2008, Klaassen et al. 2009, Klaassen et al. 2010

The Example Data

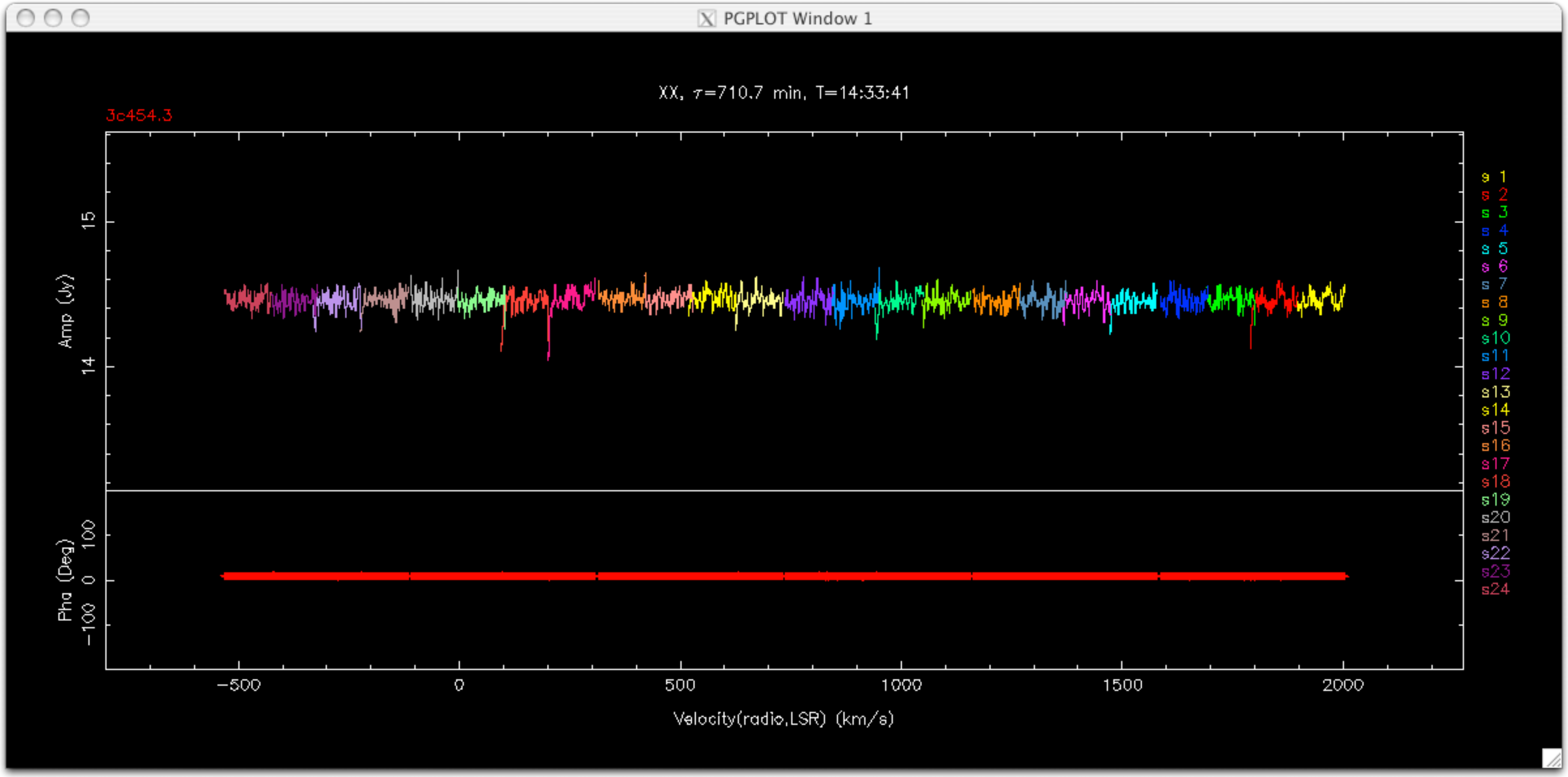
- SMA extended configuration
  - 1” resolution
  - ~1’ field of view
  - ~10” largest observable structures
- 4 GHz simultaneous bandwidth
  - Each half split into 24 chunks

The Example Data

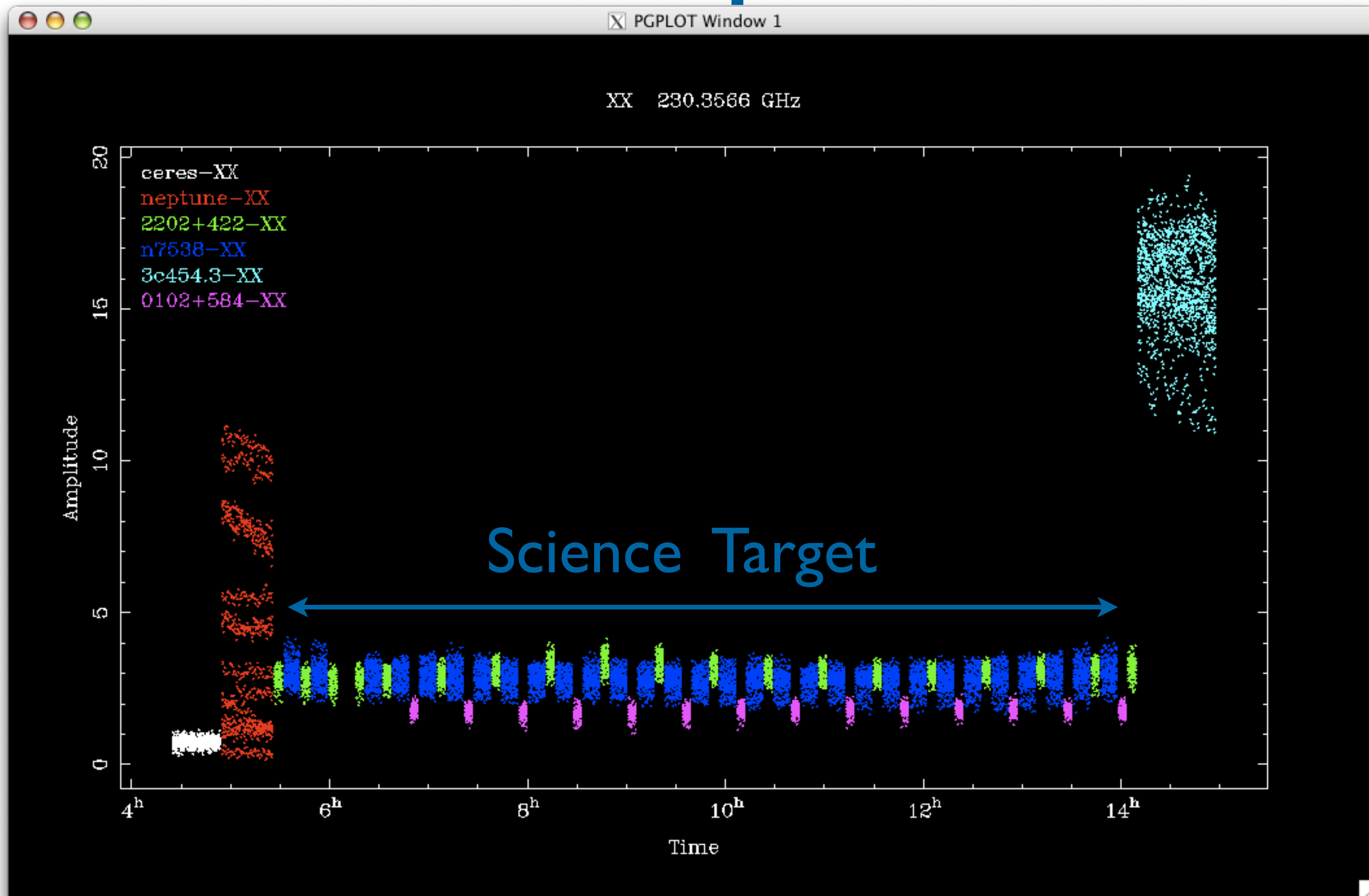


The Example Data

What a calibrator should look like after calibration



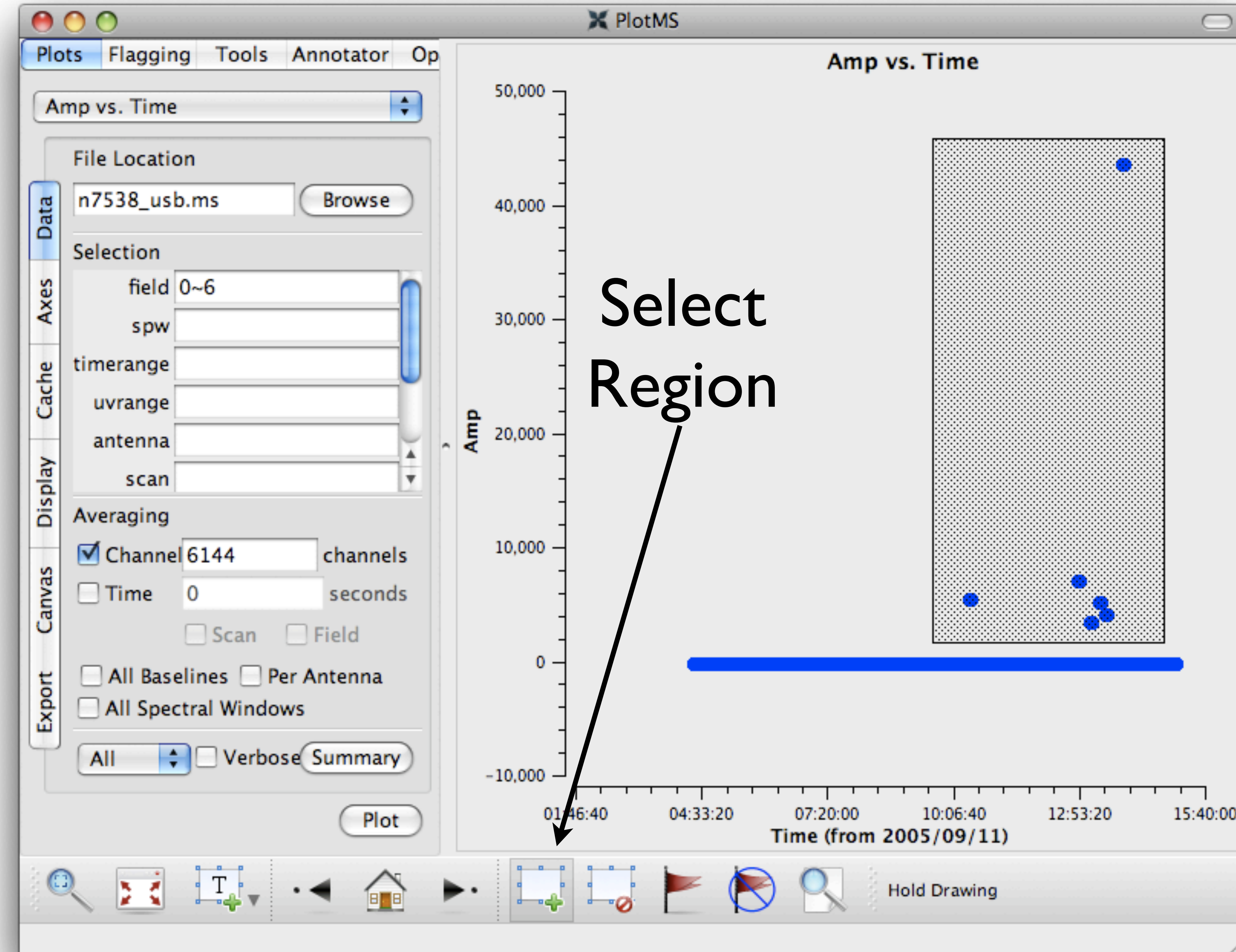
The Example Data



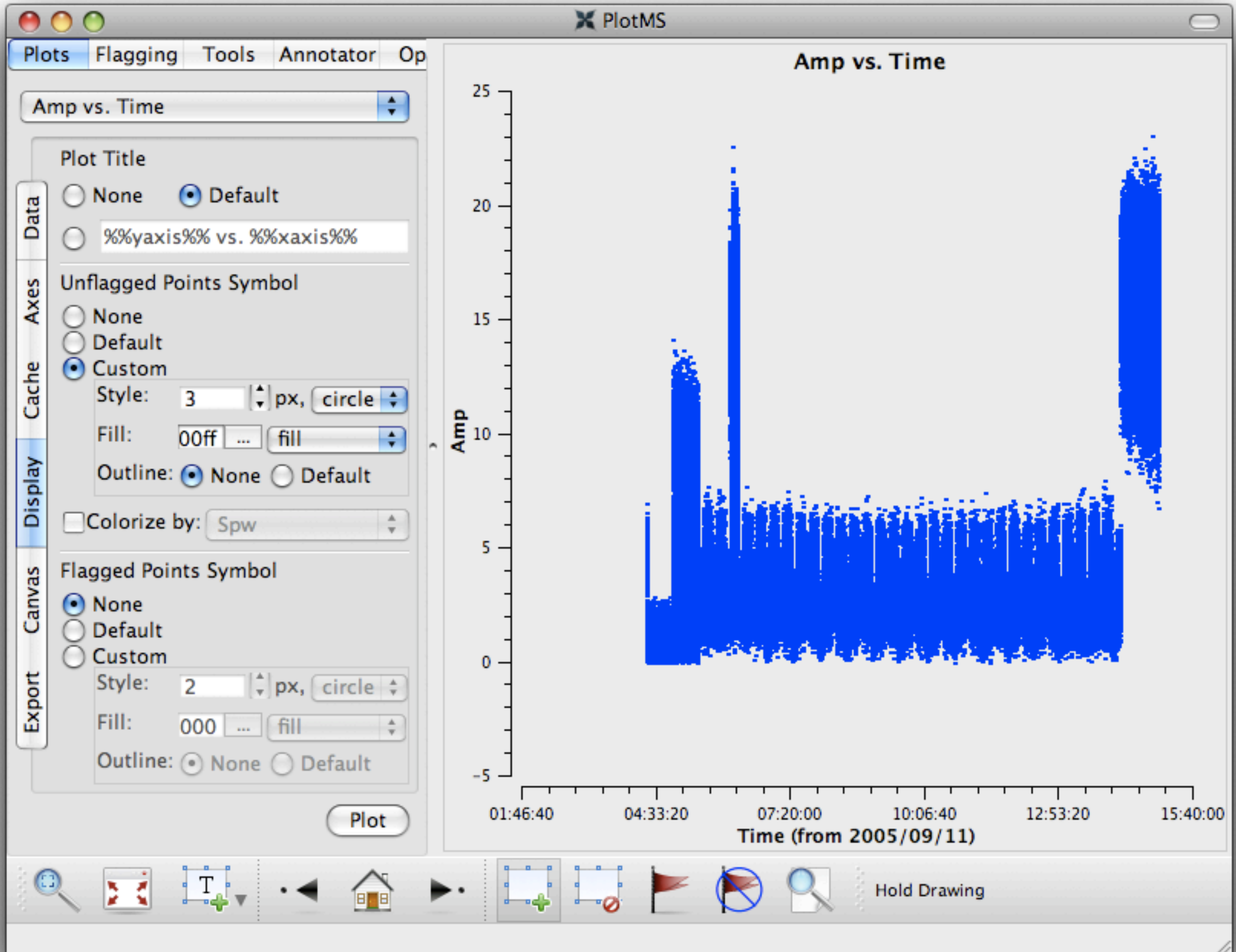
Flagging

- Obviously bad data points need to be removed
  - 'quack'
  - chunk edge channels
  - Anomalously high points

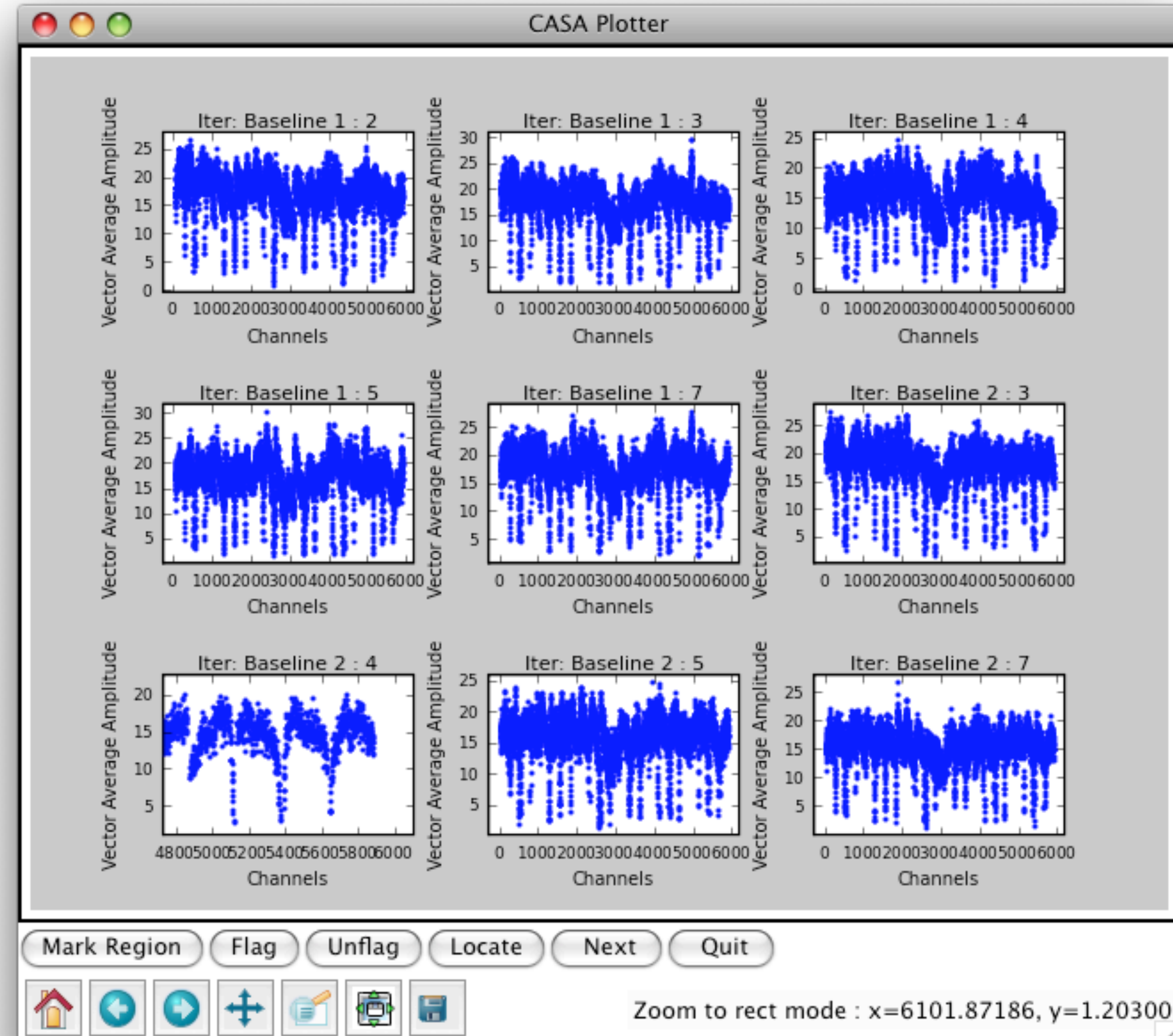
Flagging: Bad data



Flagging: Bad data



Calibration



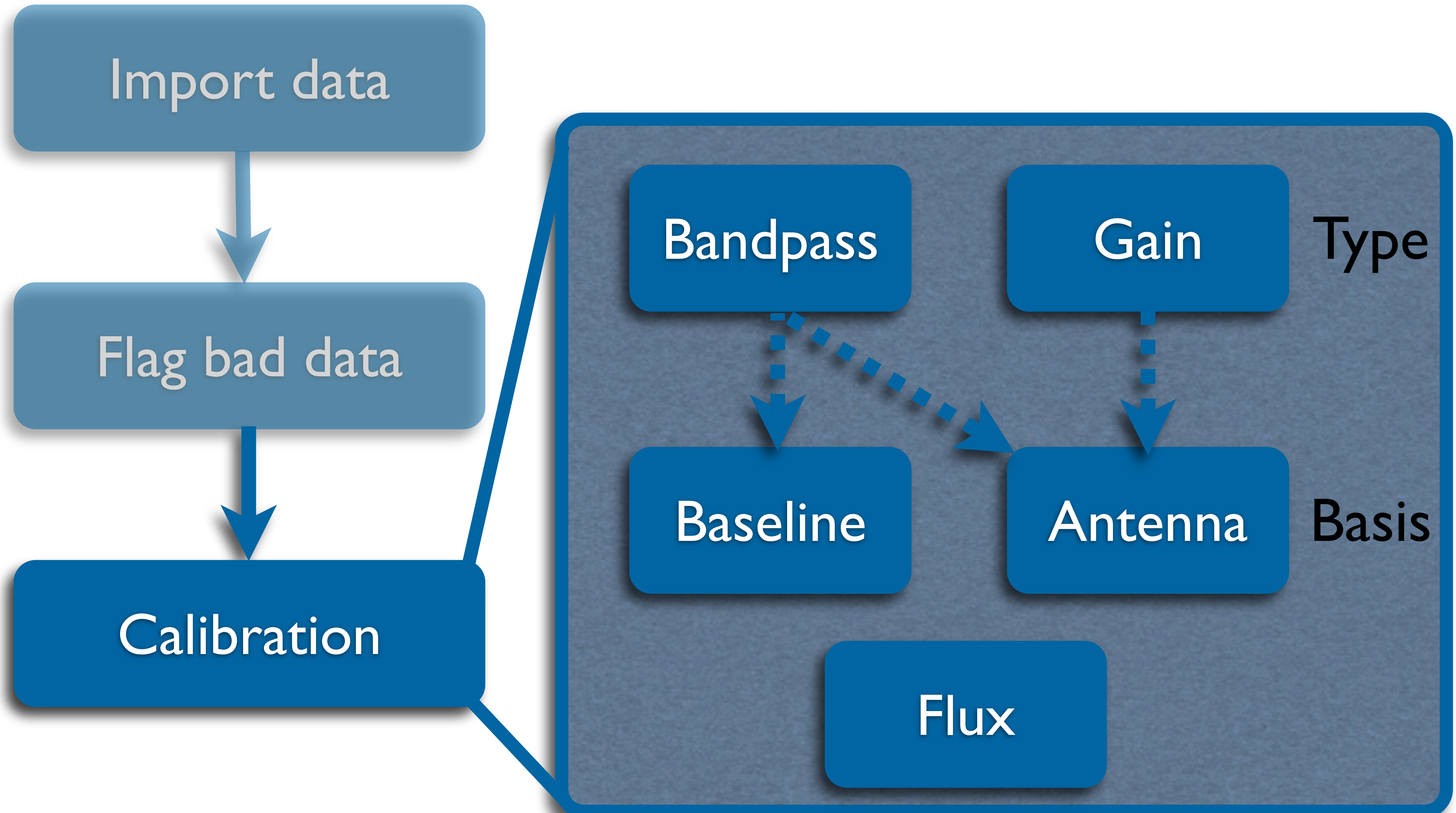
After Flagging

Before Calibration

ALMA data would require >130 pages just like this!

Calibrator: 3c454.3

Calibration



Types of Calibration

4.1 Calibration Tasks

The standard set of `calibration` solving tasks (to produce calibration tables) are:

- **`bandpass`** — complex bandpass (B) calibration solving, including options for channel-binned or polynomial solutions (§ 4.4.2),
- **`gaincal`** — complex gain (G,T) calibration solving, including options for time-binned or spline solutions (§ 4.4.3),
- **`polcal`** — polarization calibration including leakage and angle (§ 4.4.5),
- **`blcal`** — *baseline-based* complex gain or bandpass calibration (§ 4.4.6).

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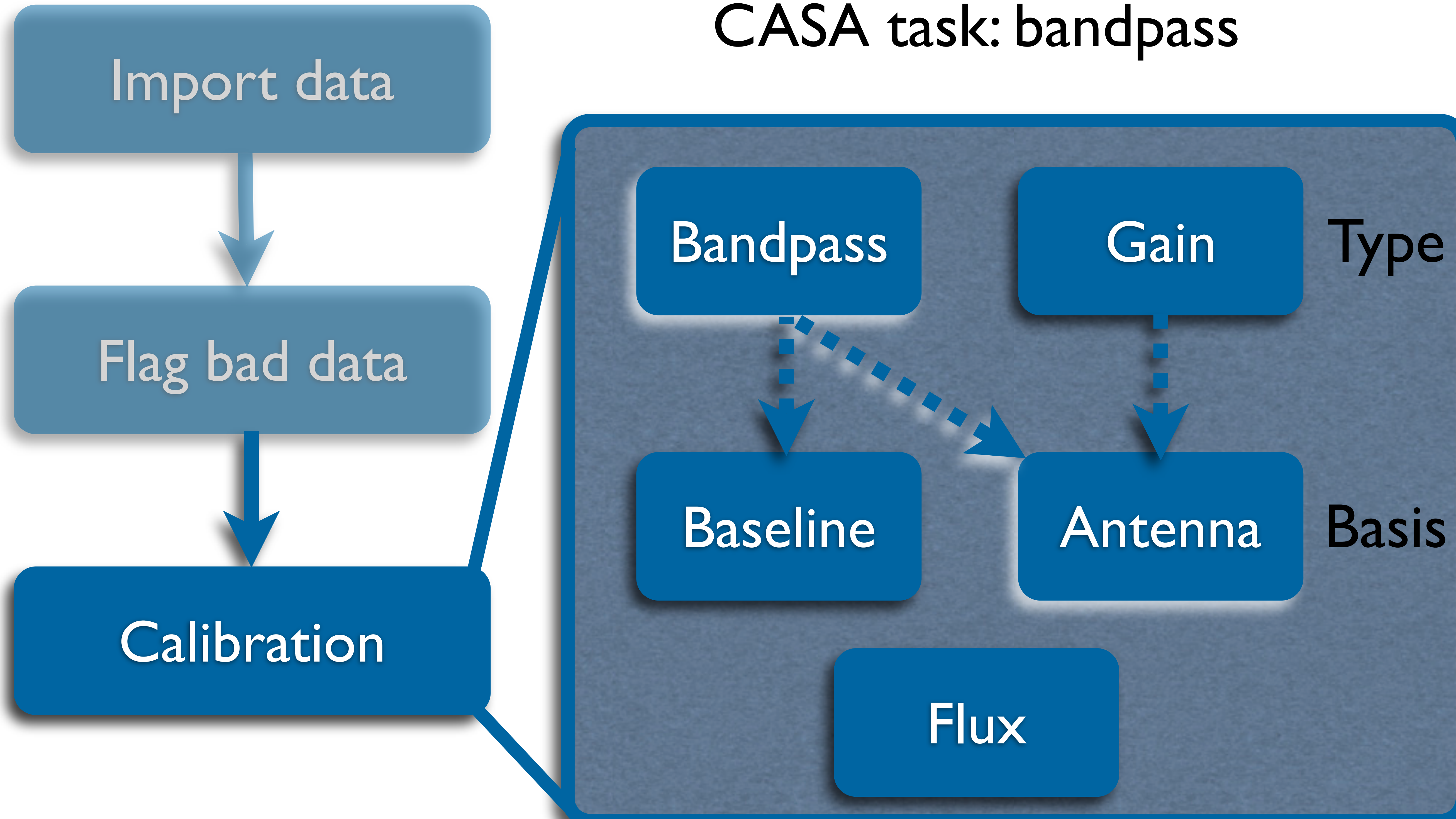
- **`blcal`** — *baseline-based* complex gain or bandpass calibration (§ 4.4.6).

Choosing Calibrators

- Bandpass: bright & unresolved
  - often Quasars
- Gain: close to the source, ‘bright’
  - quasars or (unresolved) planets
- flux: stable, known fluxes & bright
  - quasars & planets

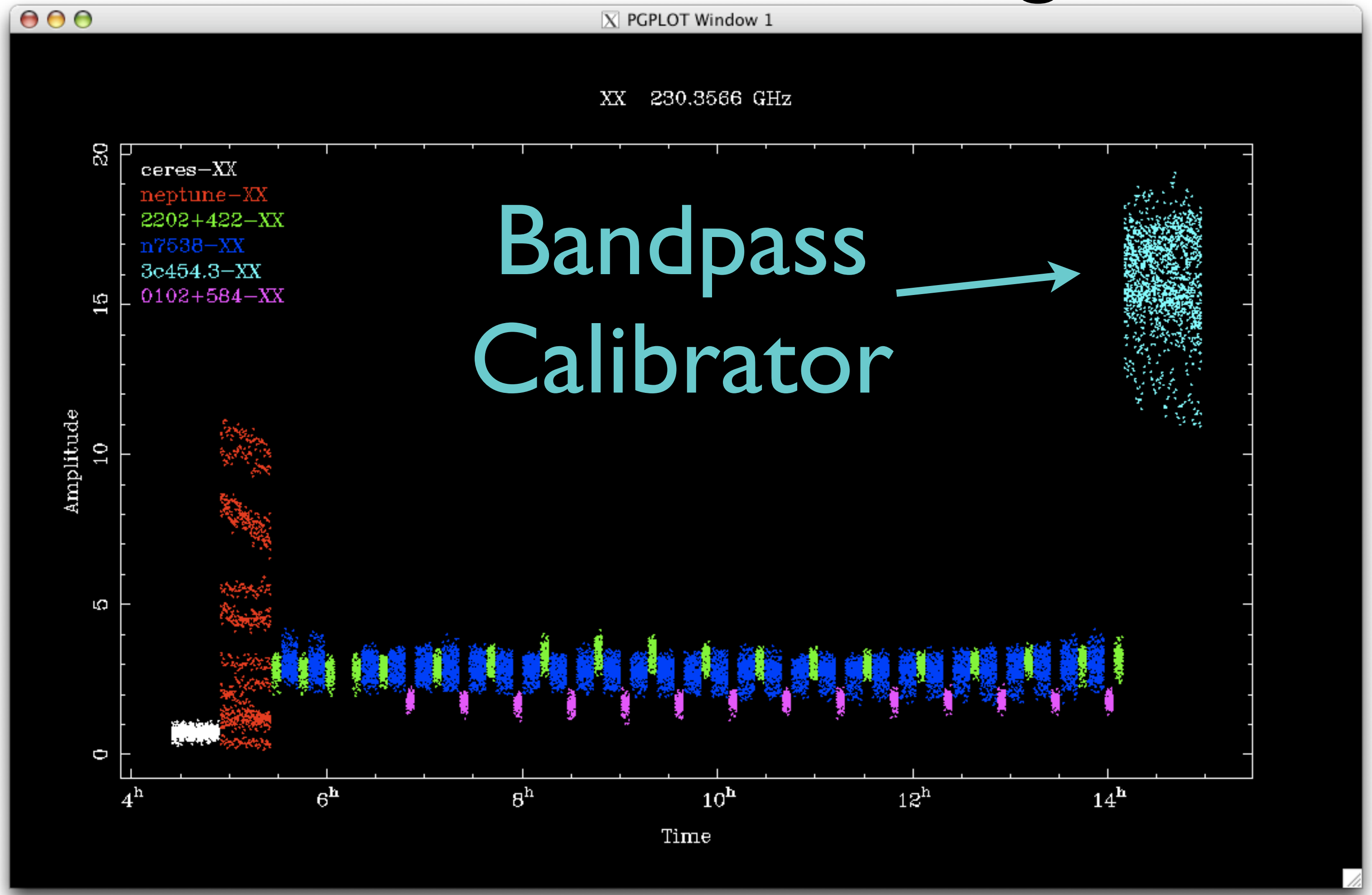
Calibration: Bandpass

CASA task: bandpass

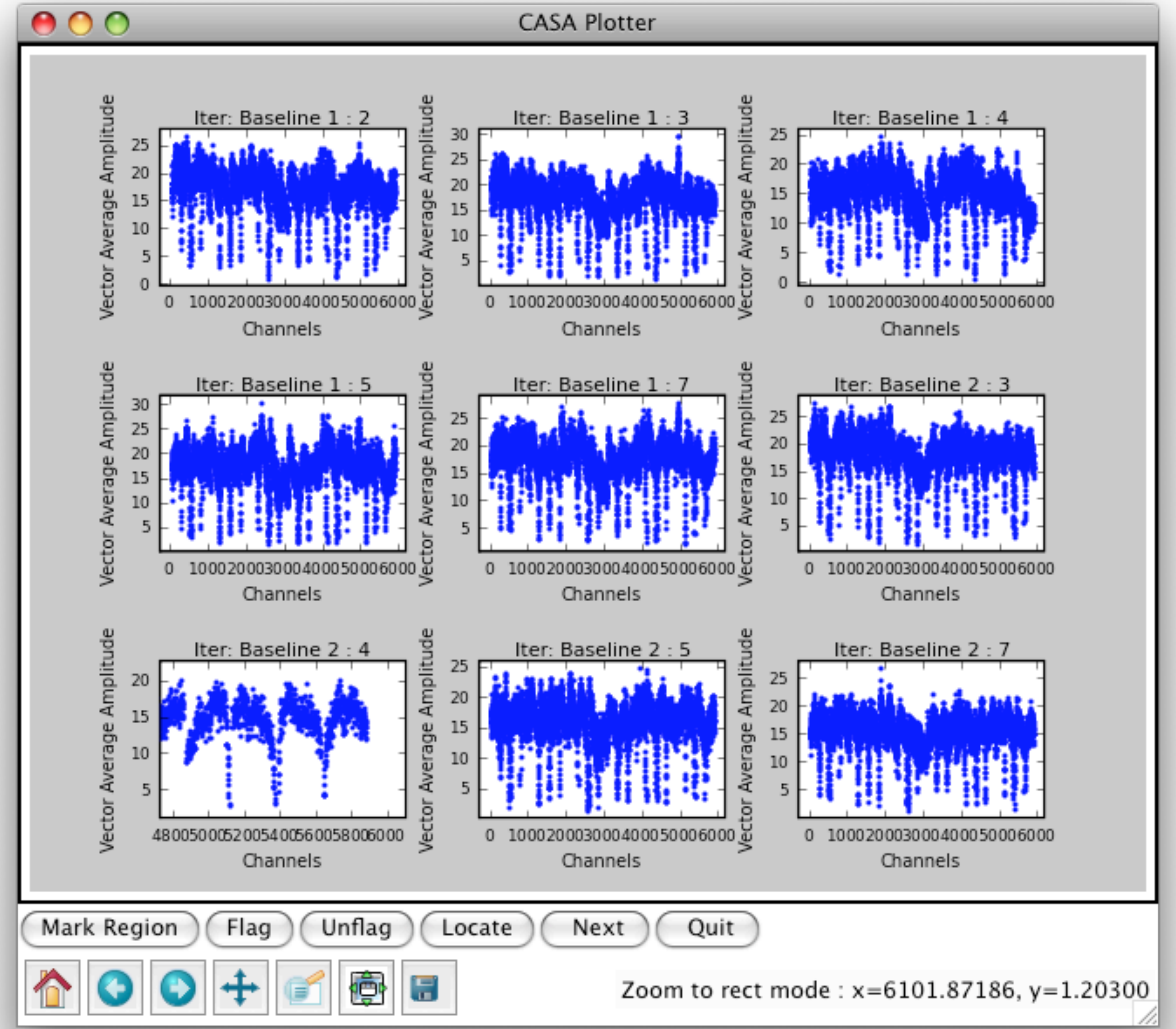


Antenna Based Bandpass Calibration

- Correcting for variations in intensity as a function of frequency, not time
- Calibrator is 'stared' at once or twice during the observations
- May have to do a 'quick' gain calibration first (which doesn't get applied to the final dataset)

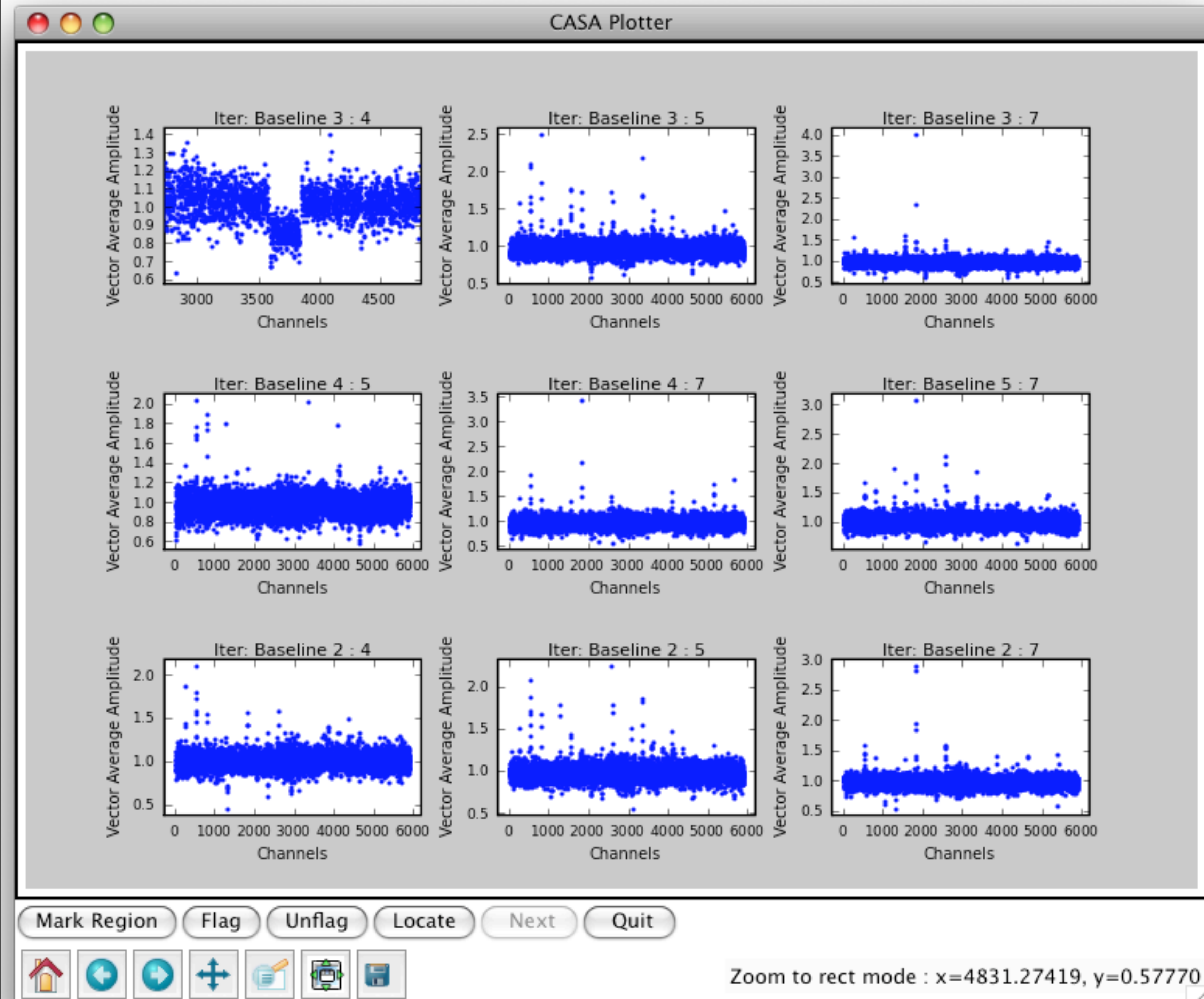


Antenna Based Bandpass Calibration



- Each chunk in the SMA dataset needs to be 'flattened'
- here, we correct for the spectral response

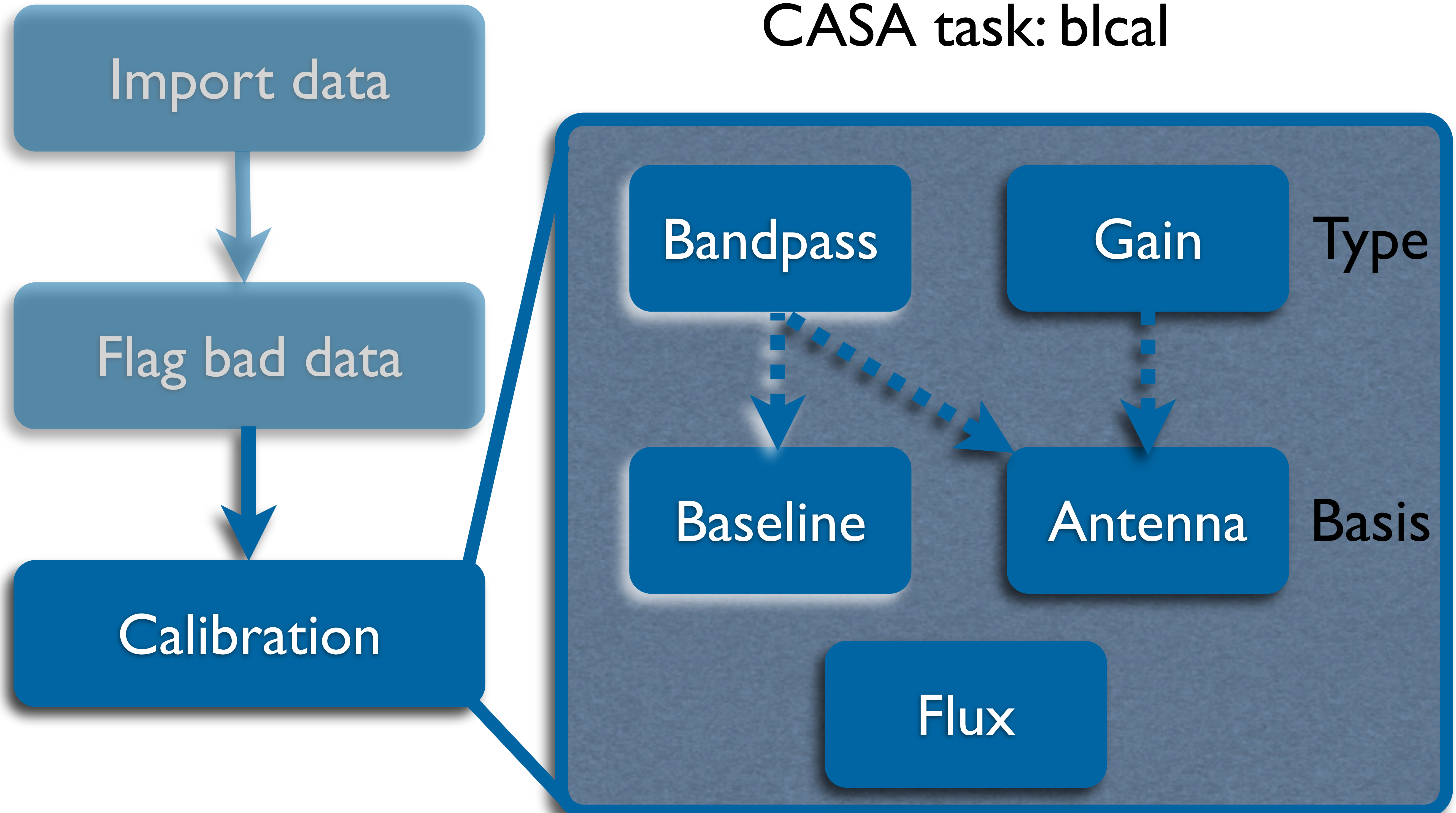
Antenna Based Bandpass Calibration



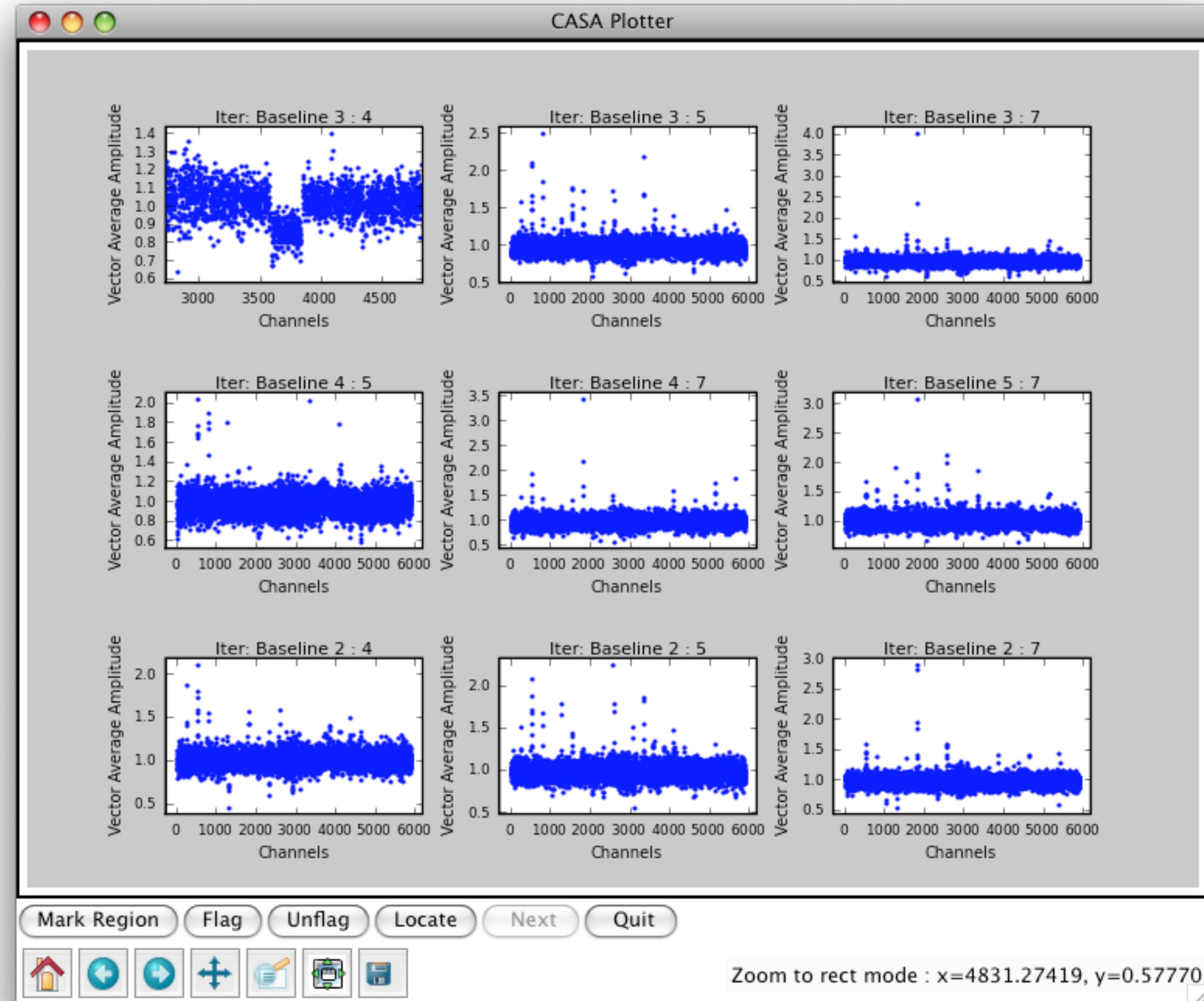
- The response of each chunk has been accounted for
- but, there are still baseline based problems with the bandpass

Calibration: Bandpass

CASA task: blcal

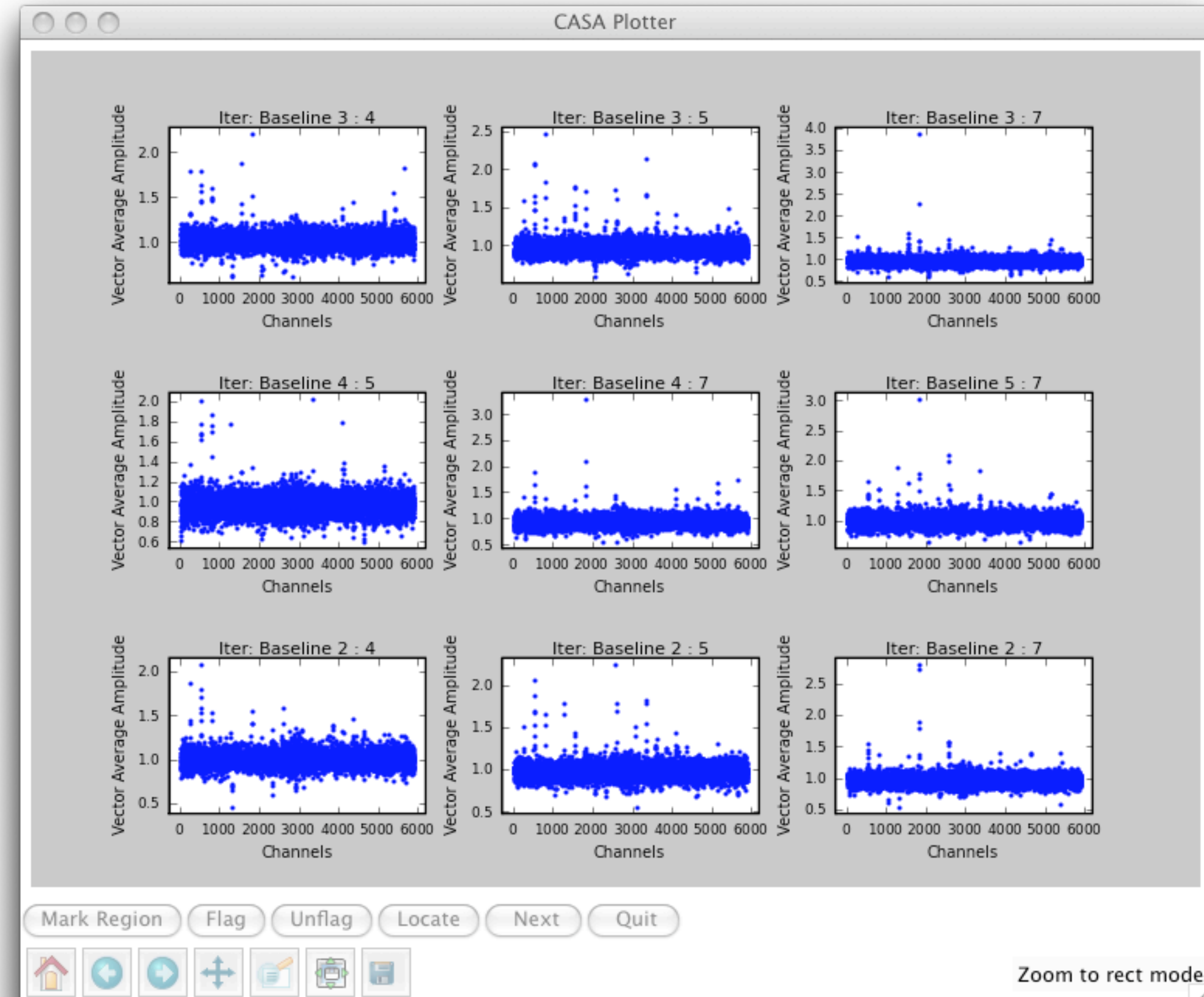


Baseline Based Bandpass Calibration



- Now the amplitudes are consistent between spectral windows
- Still on 3c454

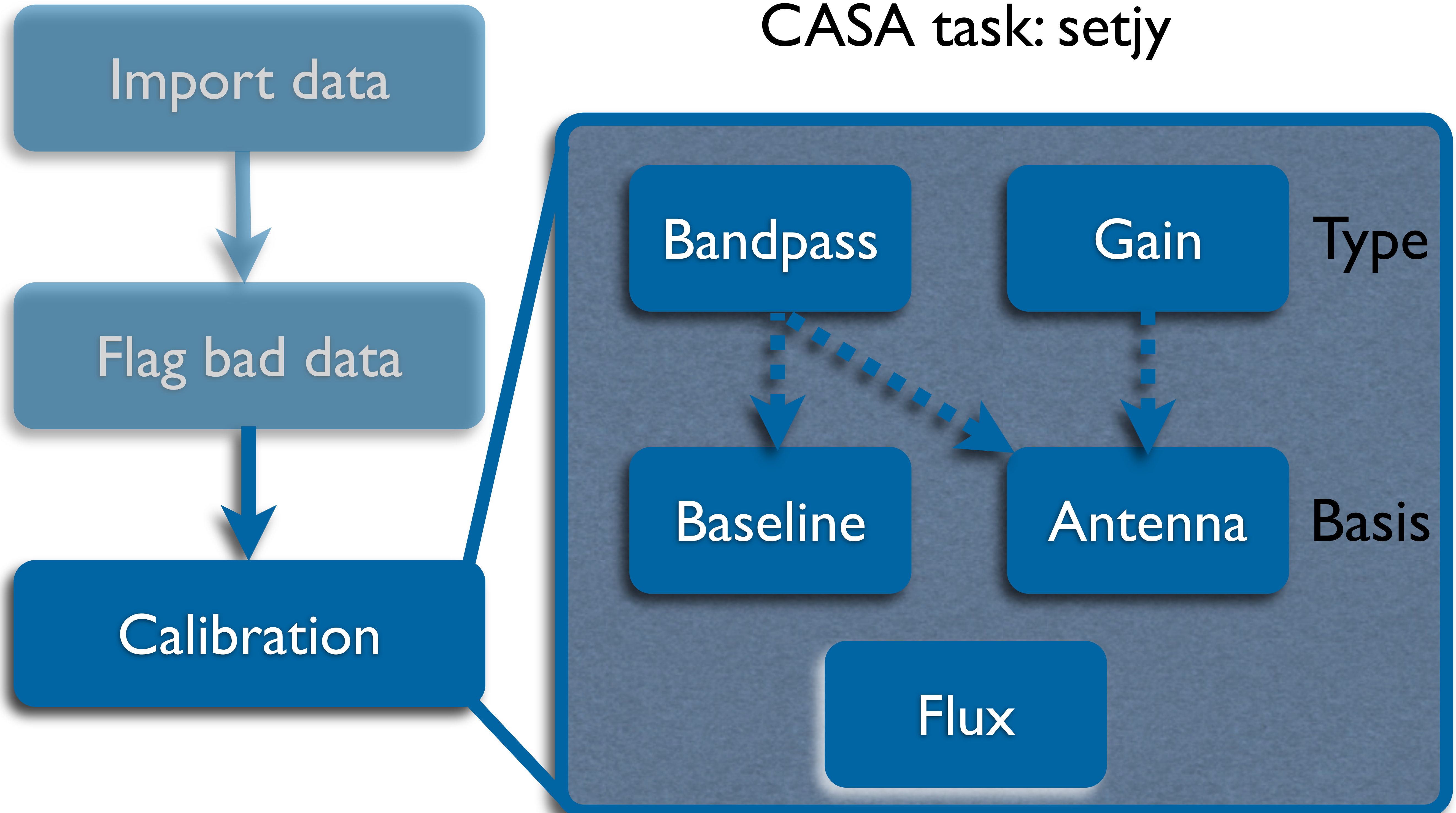
Baseline Based Bandpass Calibration



- Now the amplitudes are consistent between spectral windows
- Still on 3c454

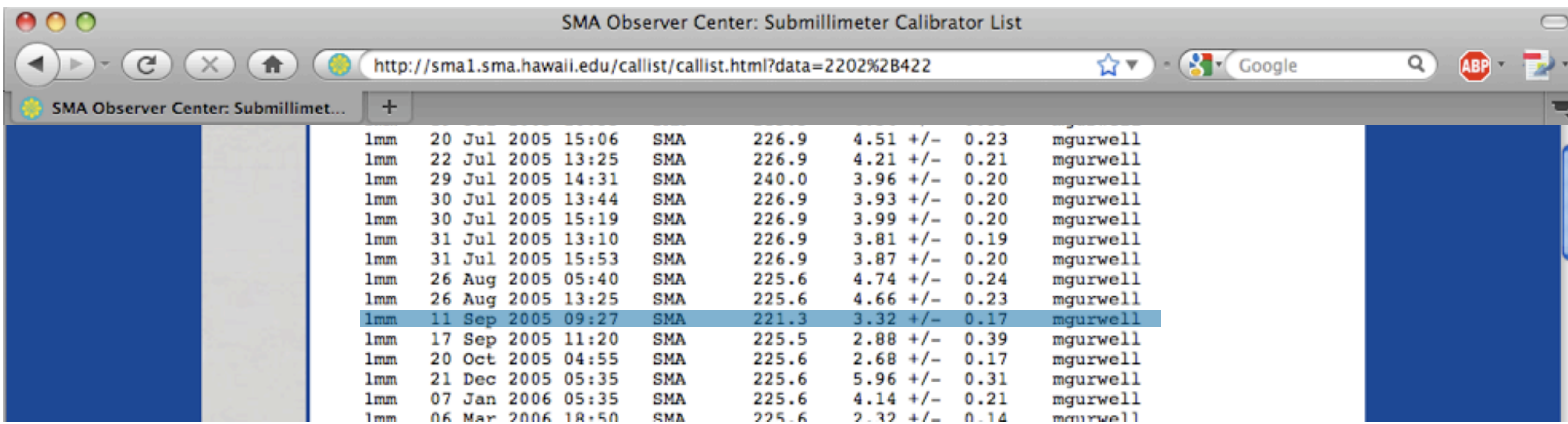
Calibration: Flux

CASA task: setjy



Set flux scaling

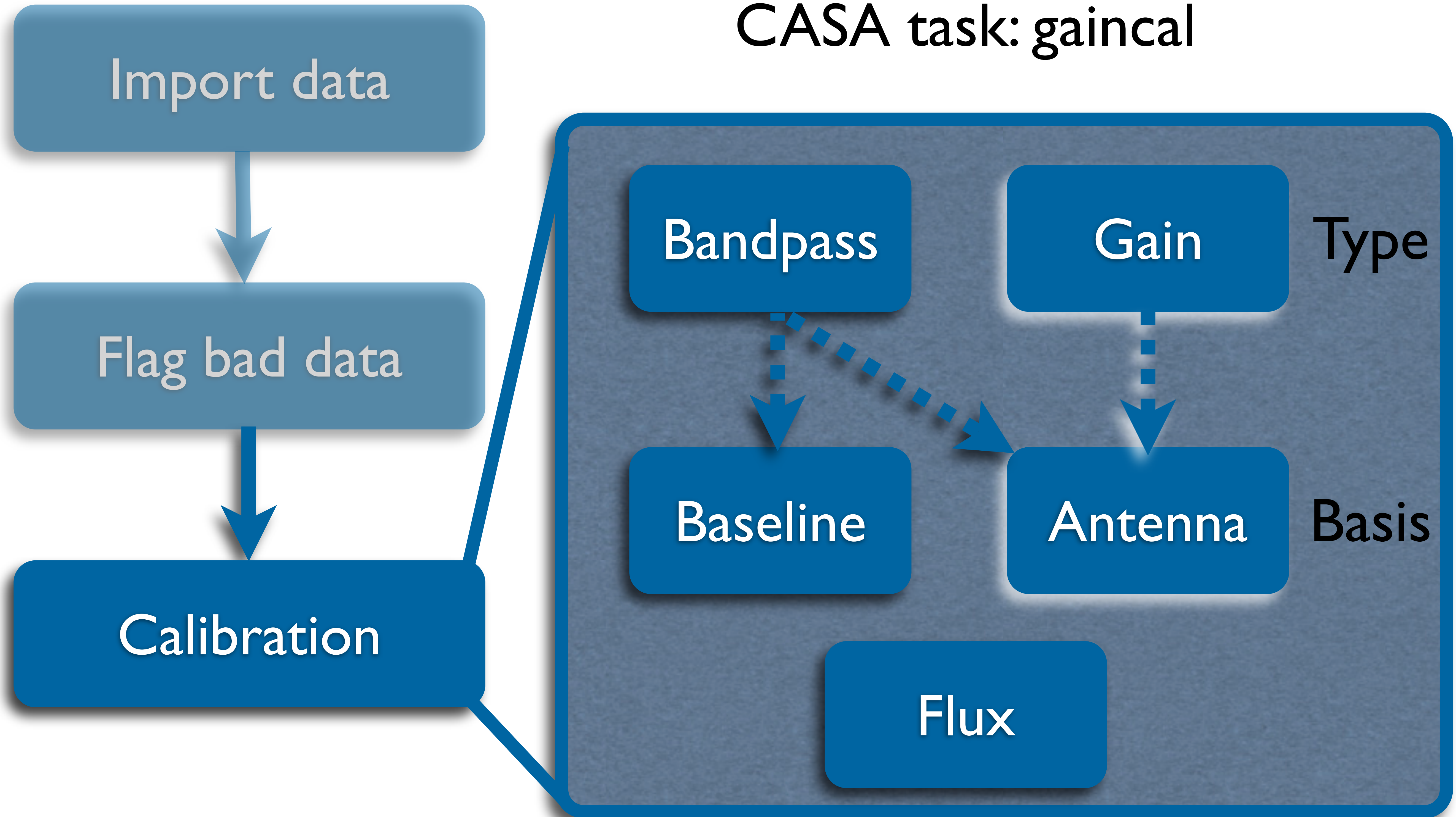
- Before doing gain calibration, set the scaling
  - This is why the fluxes of gain calibrators need to be well characterized




```
setjy(vis='n7538_usb.ms',field='3',
spw='0~23',fluxdensity=[3.32,0.0,0.0,0.0])
```

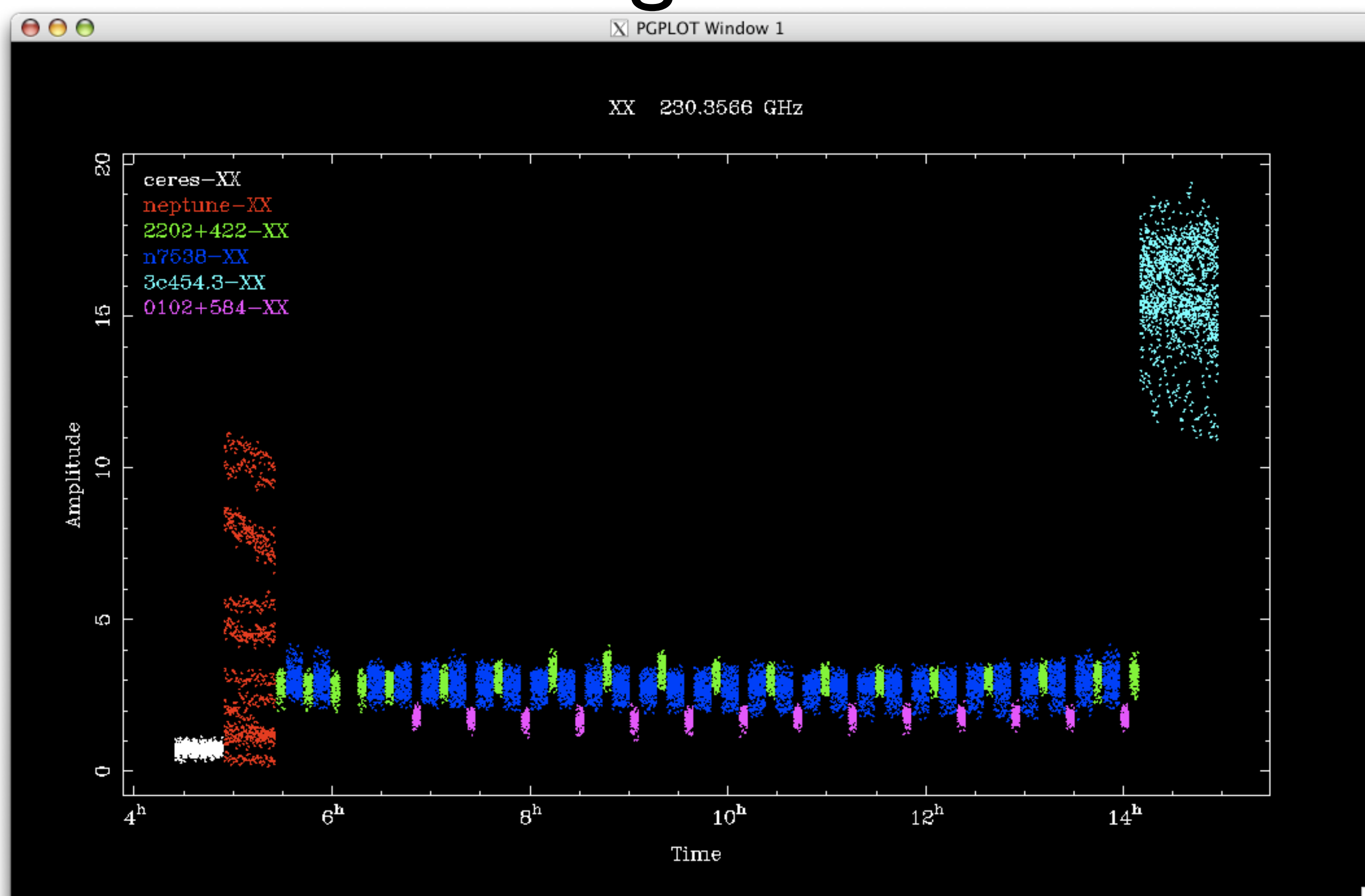
Calibration: Gain

CASA task: gaincal



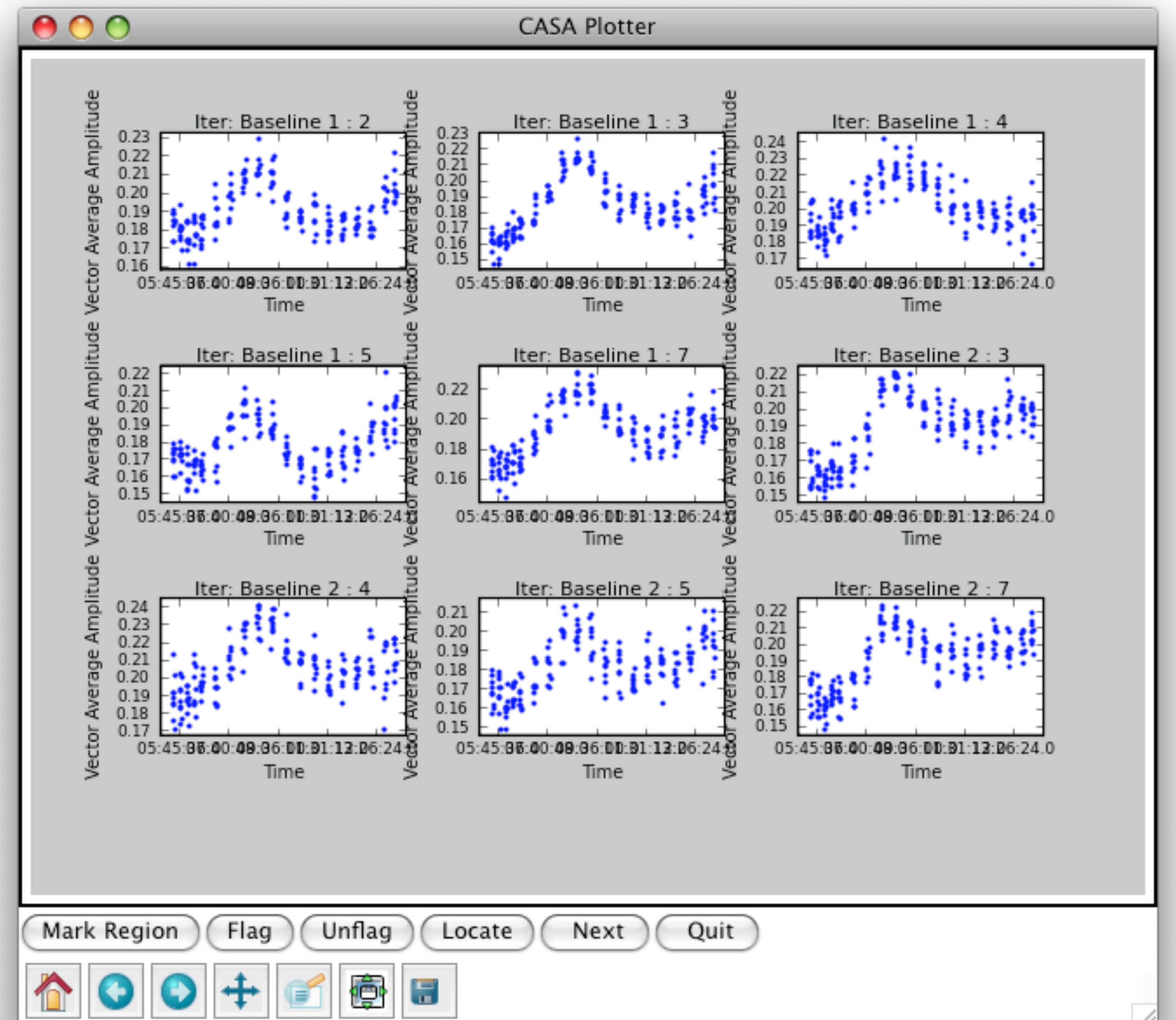
Gain Calibration

- Correct for variations in intensity as a function of time, not frequency
- This type of calibration is done using sources near the science target
- These calibrators are observed interspersed with the science target



ence Gain2 Science Gain1 Science Gain2 Science Gain1 Scien

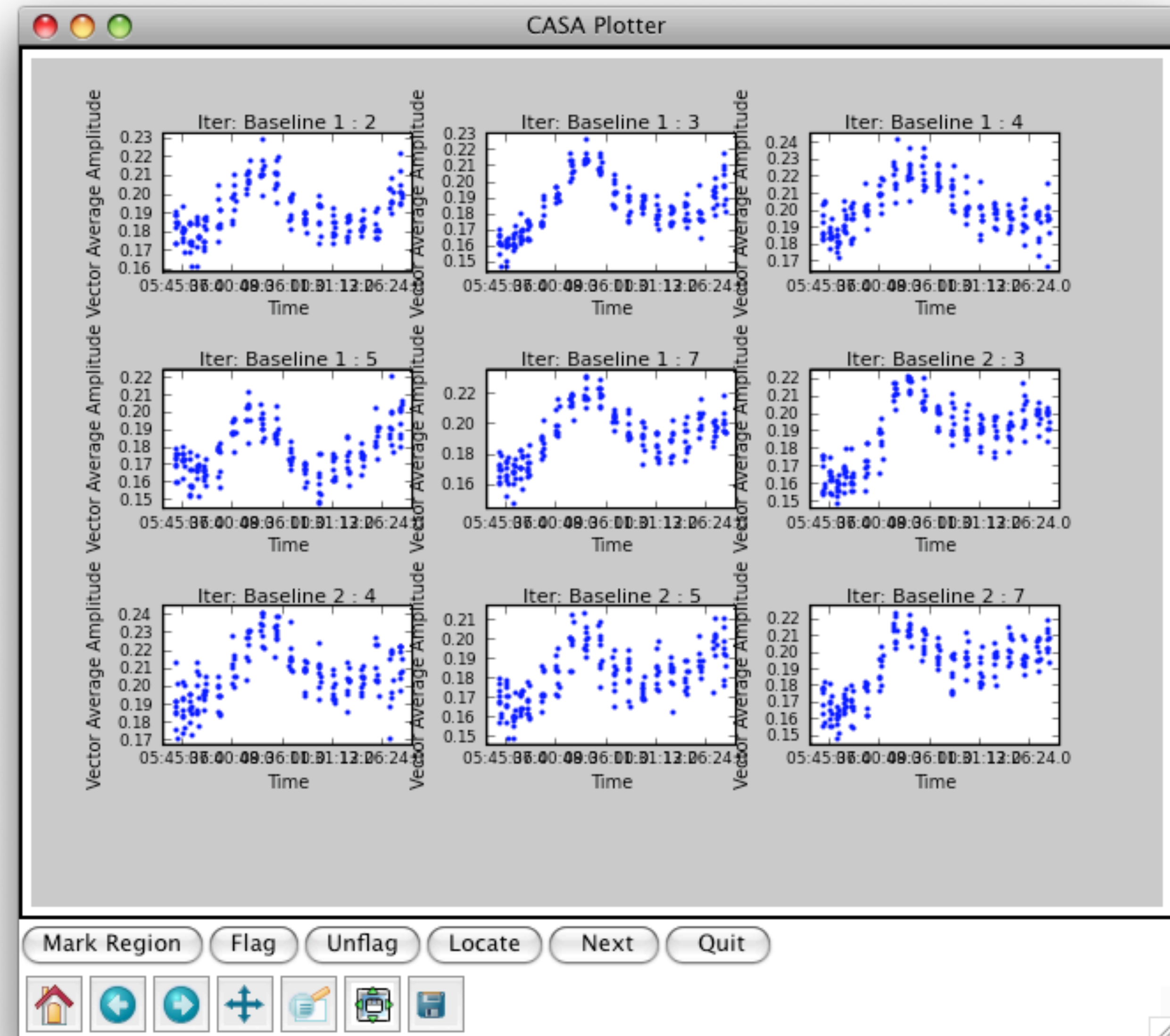
Gain Calibration



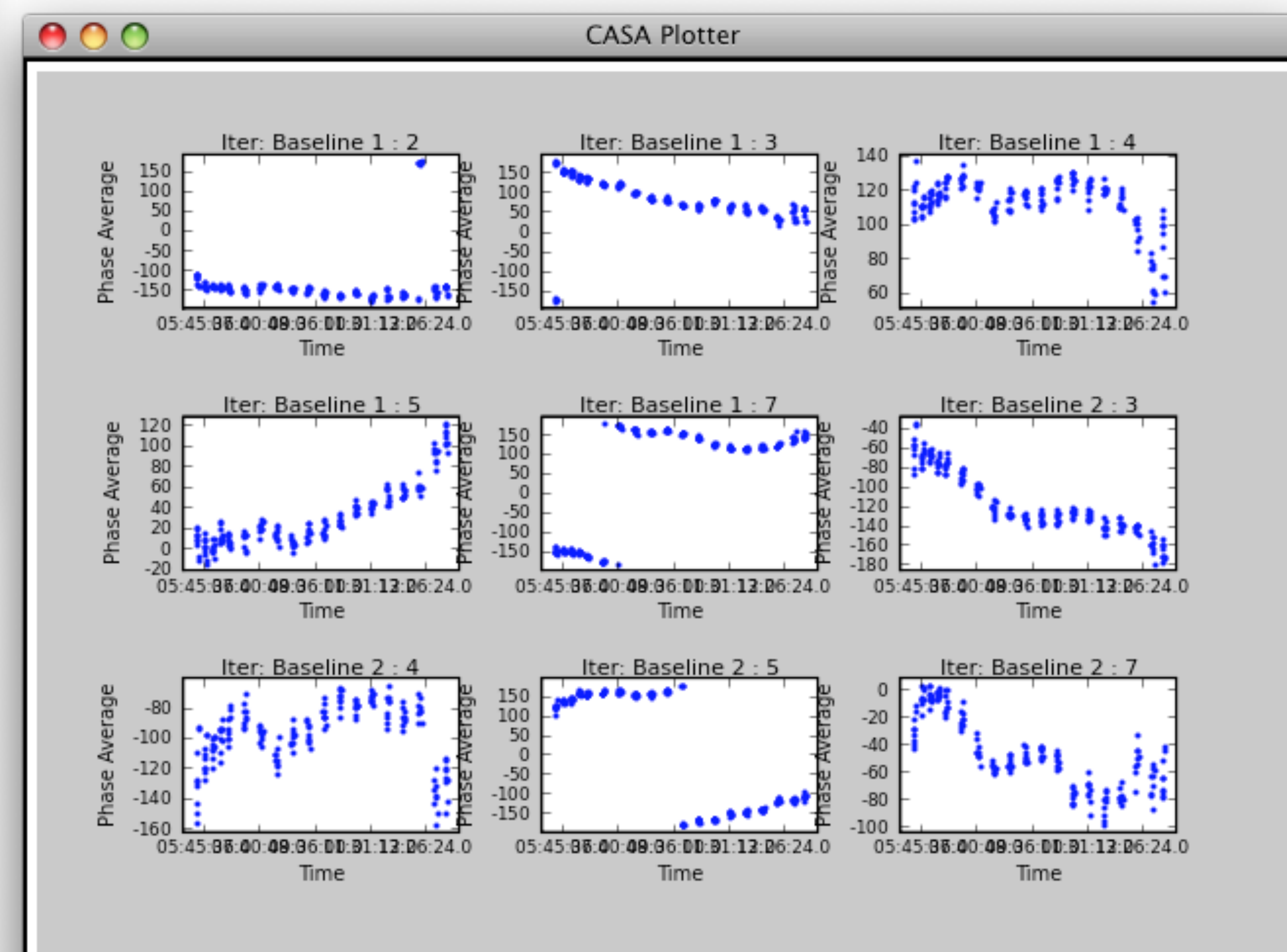
Amplitude and Phase of one of the gain calibrators as a function of time

2202+422
(bllac)

Gain Calibration



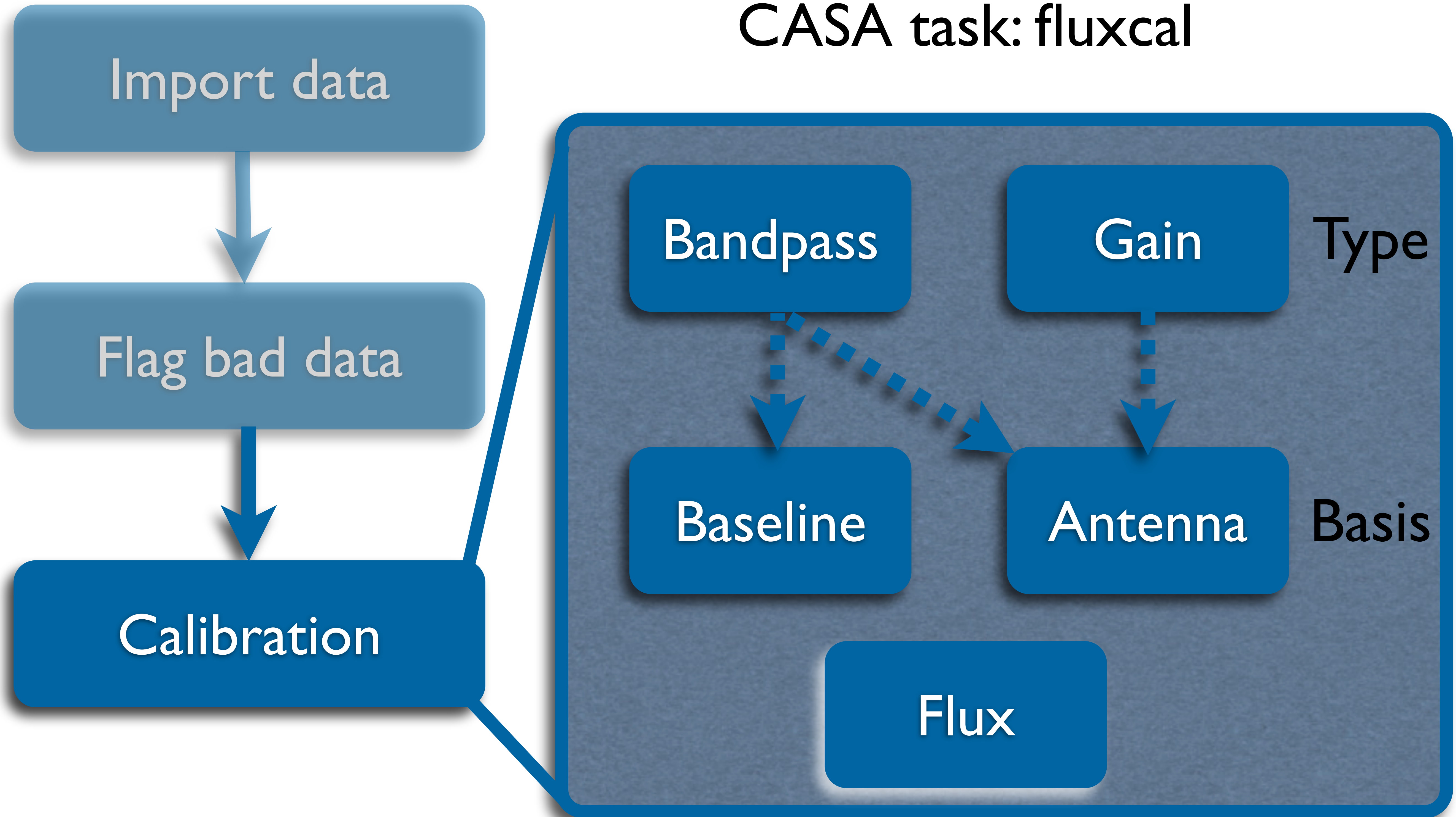
Amplitude and Phase of one of the gain calibrators as a function of time



2202+422
(bllac)

Calibration: Gain

CASA task: fluxcal

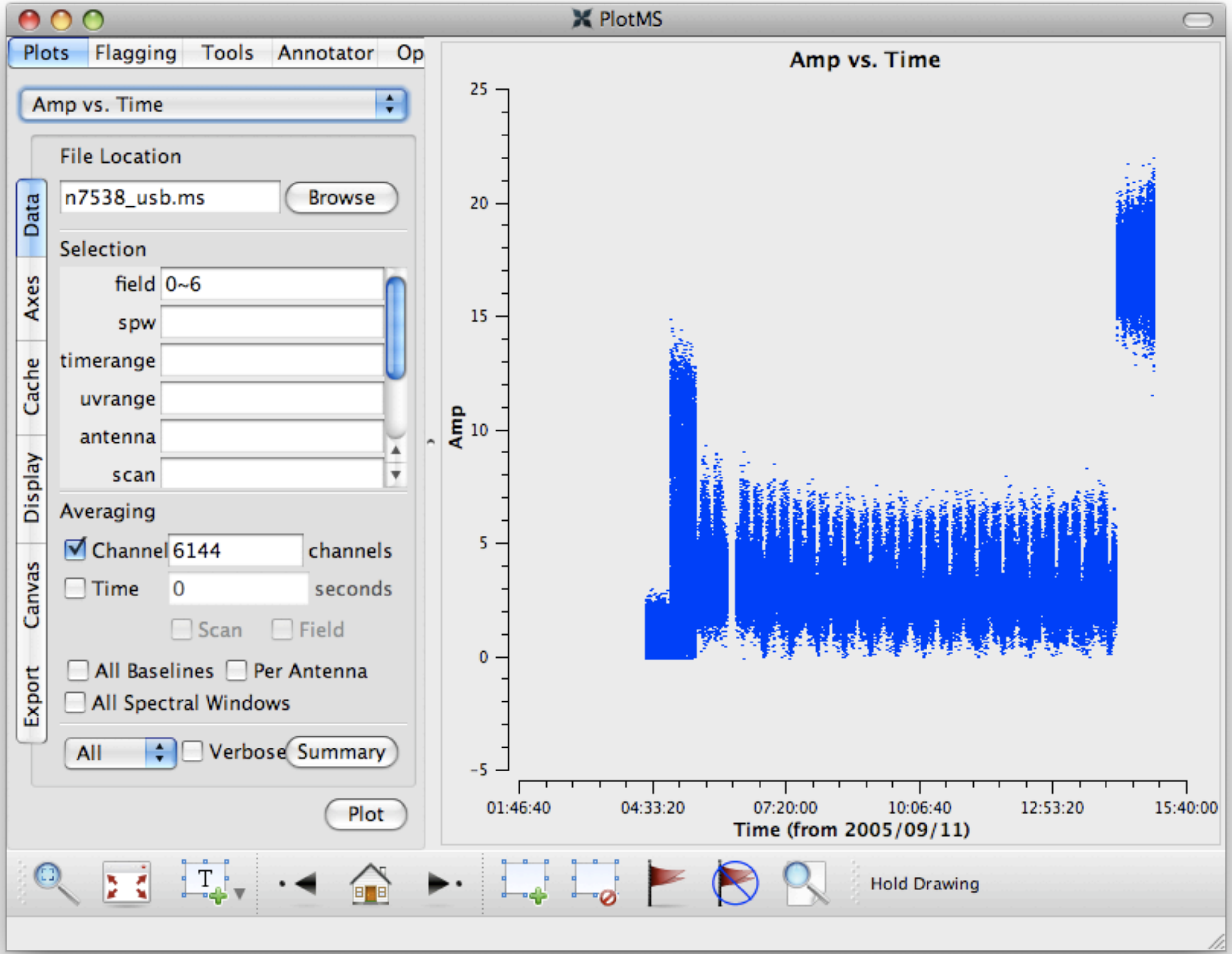


Applying Calibrations

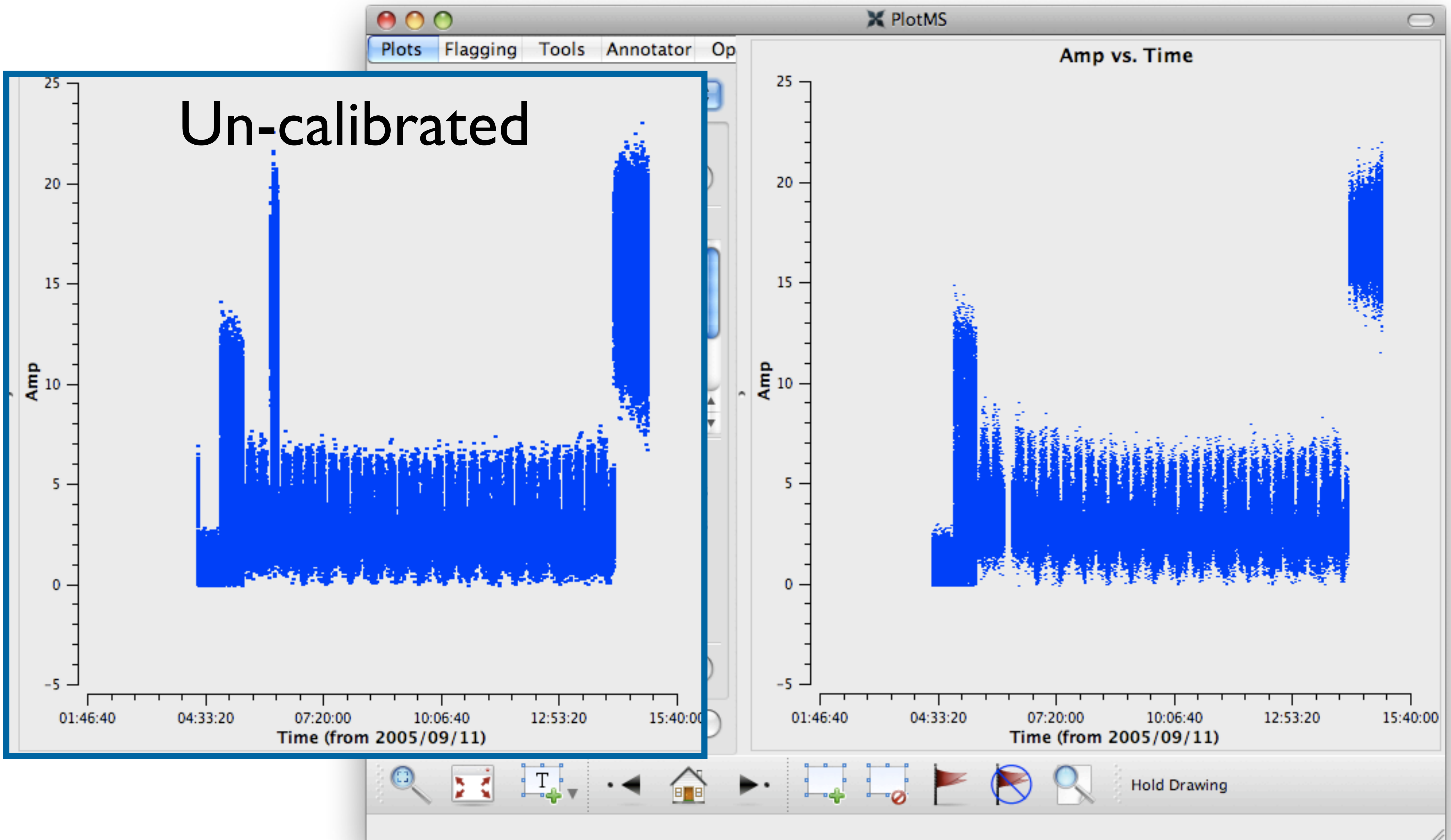
- After calculating all of the calibration factors, they must be applied to both the calibrators AND the science source(s)

```
applycal(vis='n7538_usb.ms',spw='0~23', field='5',
         gaintable=['n7538_usb.ms.allpcal',
        'n7538_usb.ms.fluxcal','n7538_usb.ms.bpoly',
        'n7538_usb.ms.blcal2'],spwmap=[[0],[0],[],[]],
         gainfield=['5','5','5','5'])
```

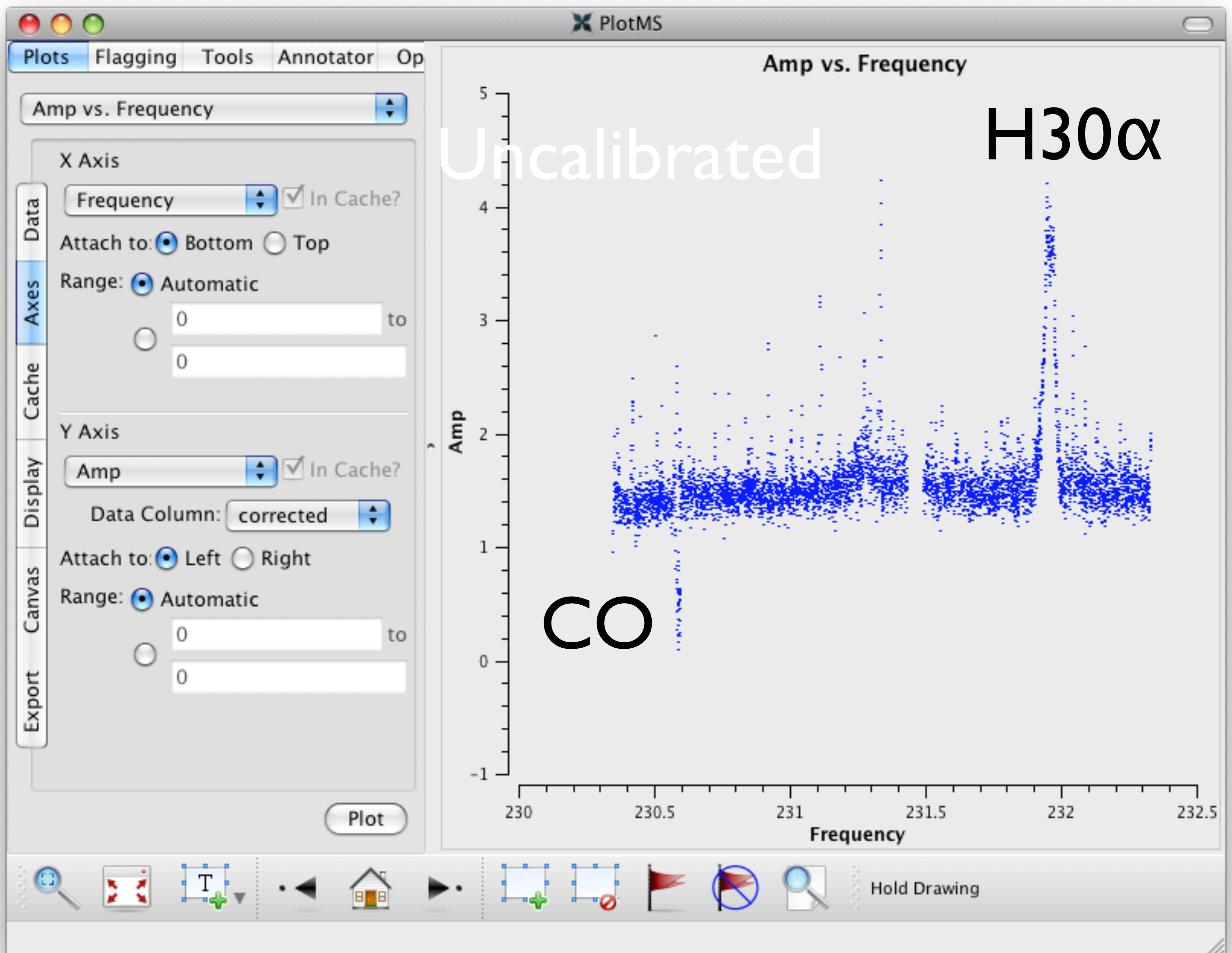
Applying Calibrations



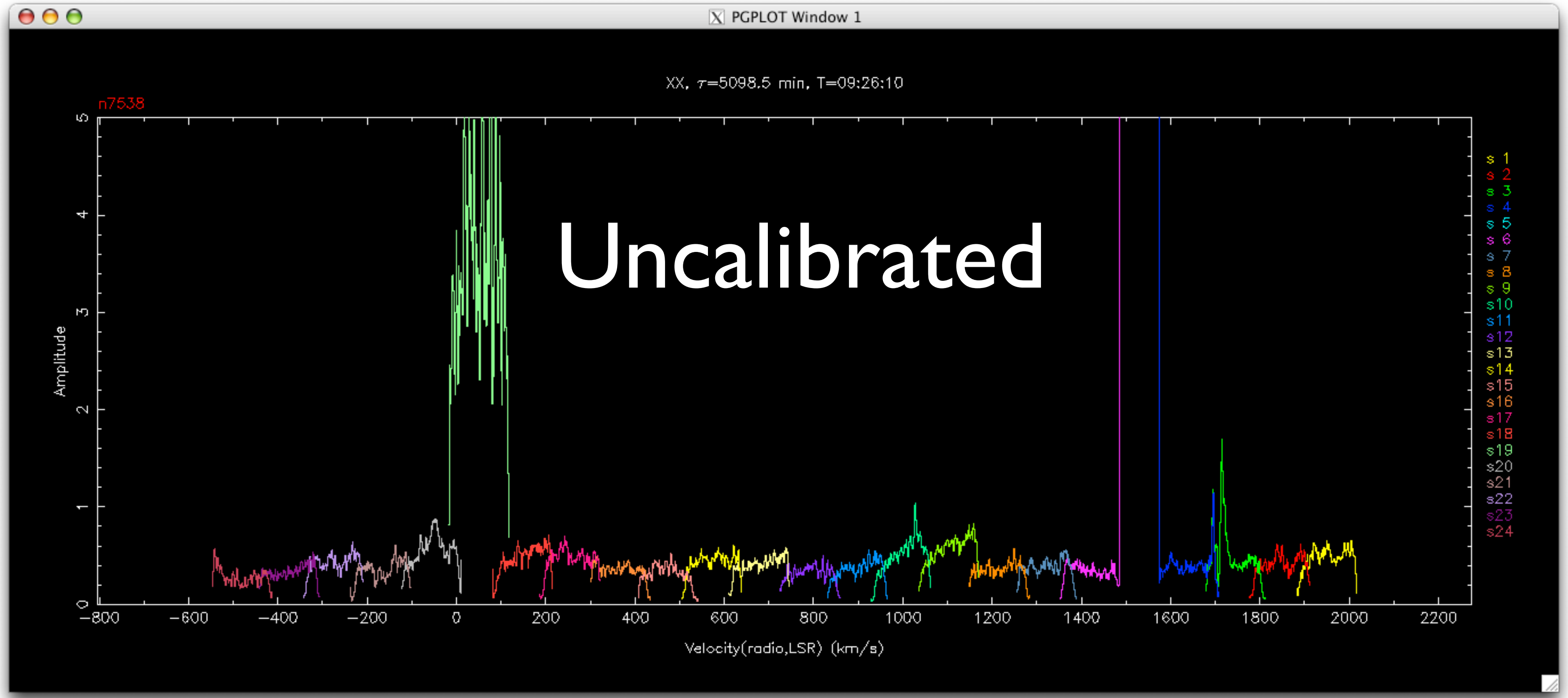
Applying Calibrations

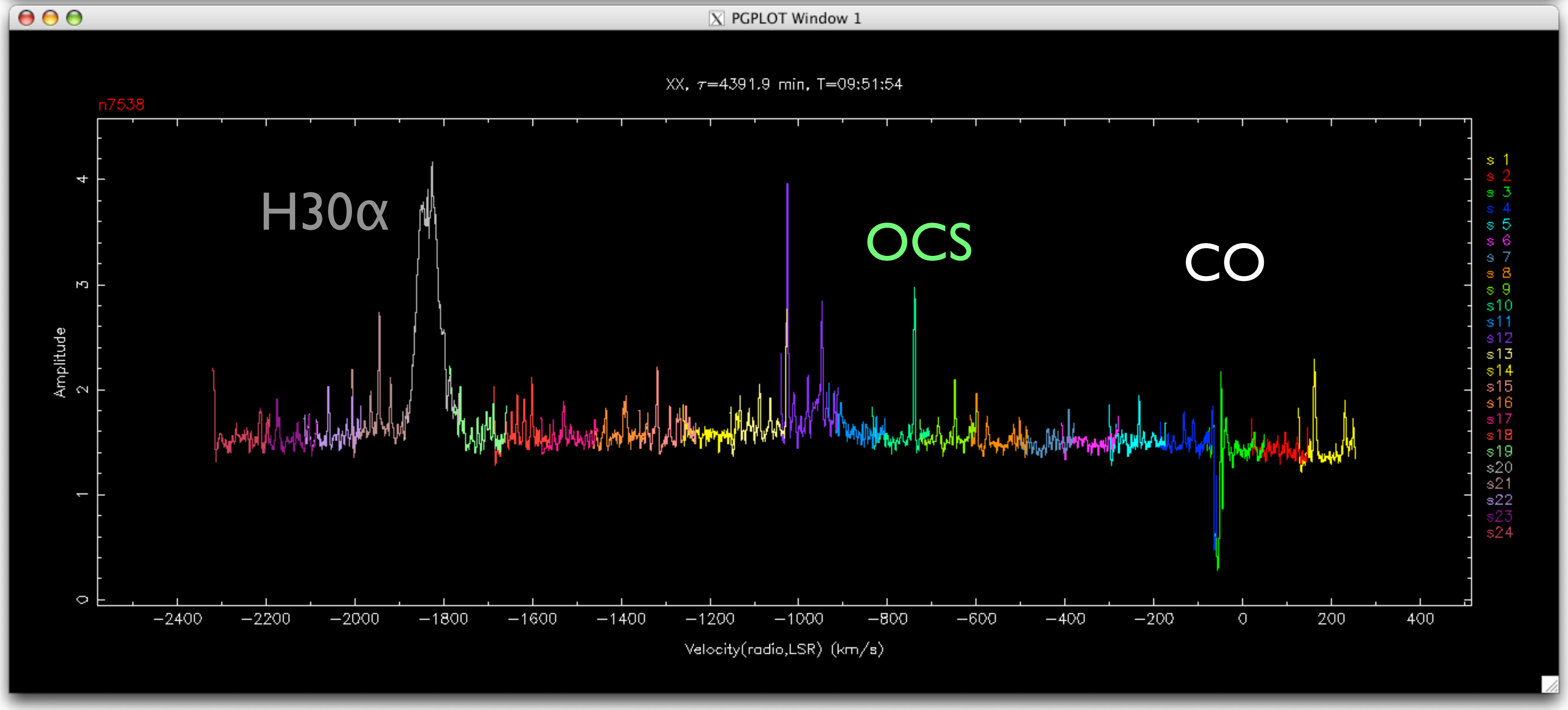


Calibrated Source



Calibrated Source





Data Pipeline

- ALMA will have a data reduction pipeline
- Fully calibrated data will be delivered to the users (you)

Data Pipeline

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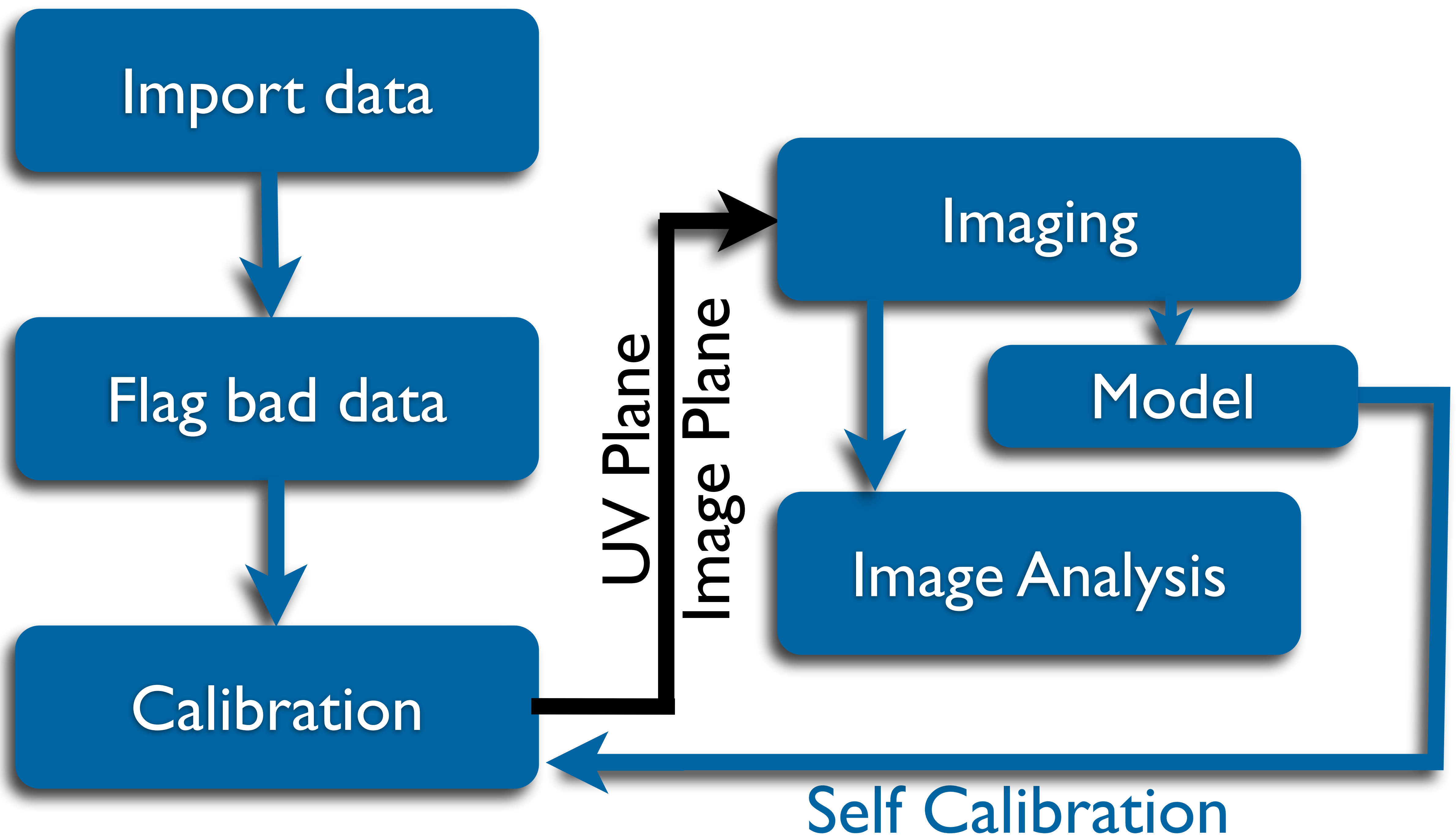
So, you don't really have to worry about this too much (unless you want to)

Data Flow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Imaging

Either in the UV plane or the Image plane, the continuum emission needs to be separated from the spectral line emission

- Continuum Imaging
  - single channel
  - taken from line free regions of the band
- Line Imaging
  - multiple channels
  - only invert near the desired line, not the whole dataset!

Inverting to the Image Plane

Invert — Create dirty image

Clean — Find clean components

Restore — Apply cleaning to dirty image

Inverting to the Image Plane

Invert

Create dirty image

All of this is done in the CASA command

Clean

Find clean components

`'clean'`

Apply cleaning to dirty image

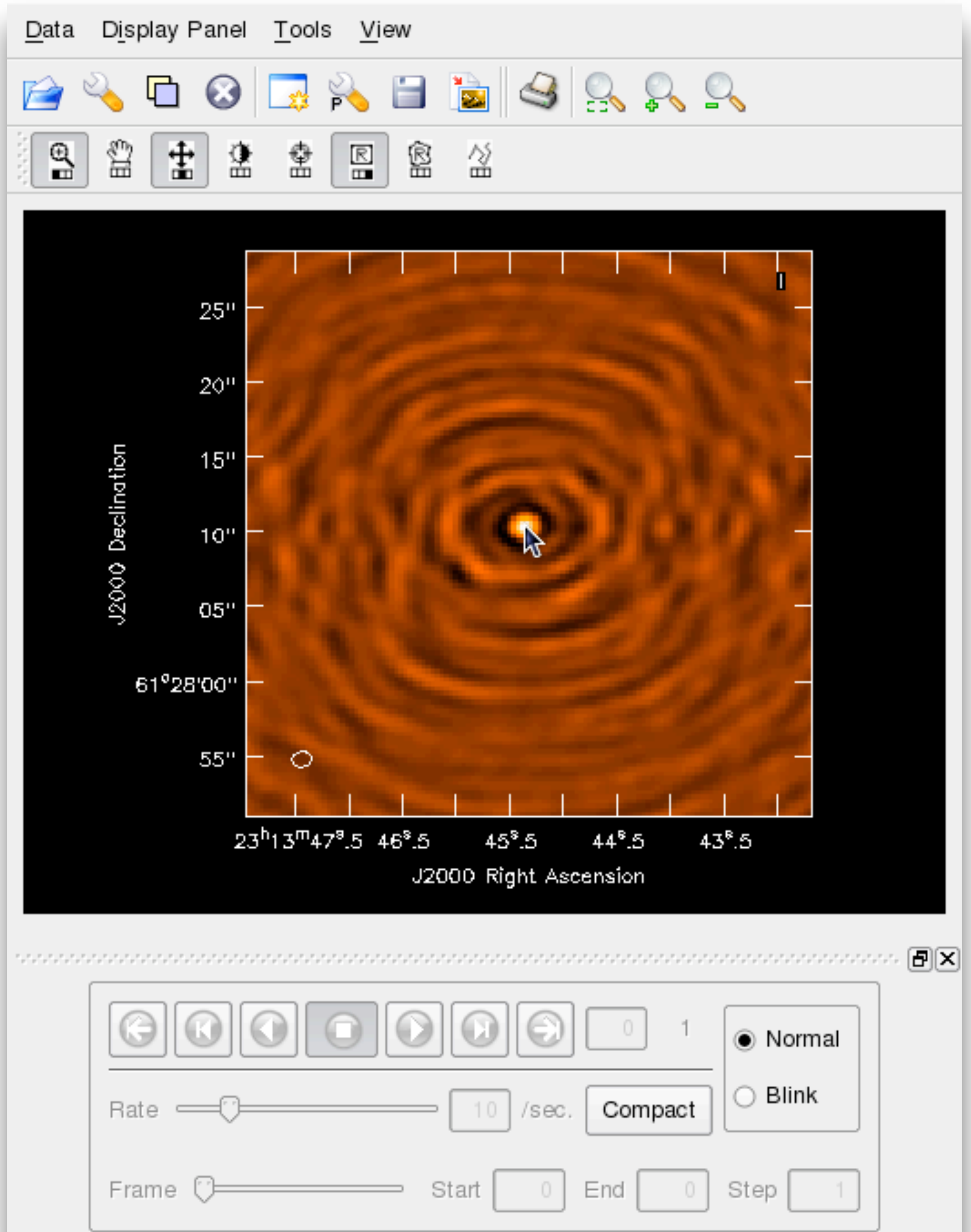
Restore

Dirty Image

- Invert to the image plane using `niter=0`

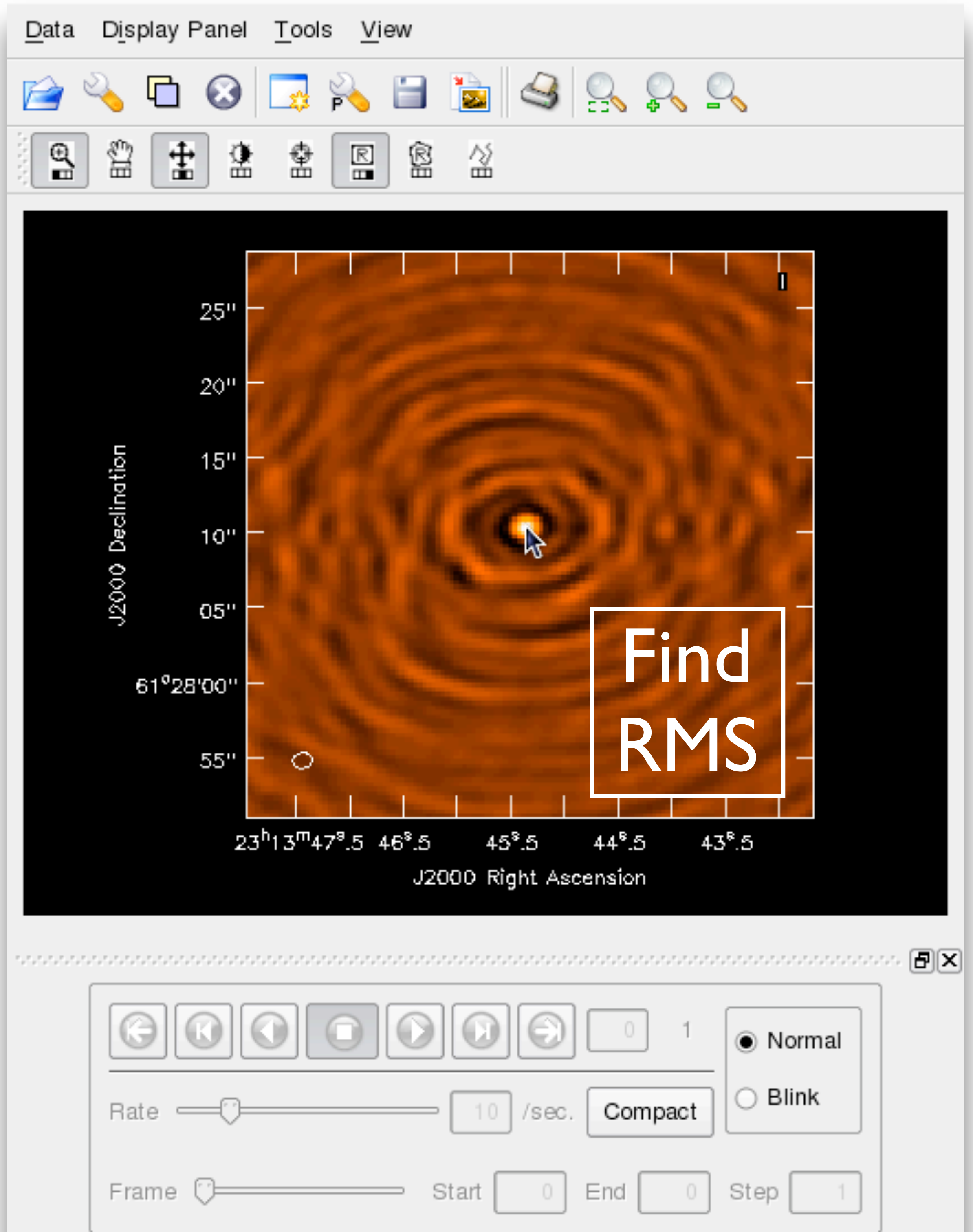
```
clean(vis='n7538_edge_clip.ms.cont',
 imagename='n7538.cont.dirty',
 field='0',spw='4~9,13~17,21~23',
 niter=0,gain=0.1,
 threshold=0.0,interactive=F,
 imsize=500,cell='0.3',pbcor=F,minpb=0.1)
```

Dirty Image



- First look at the image plane!
- Fourier transform of UV plane visibilities
- Next step: `niters>0`

Dirty Image



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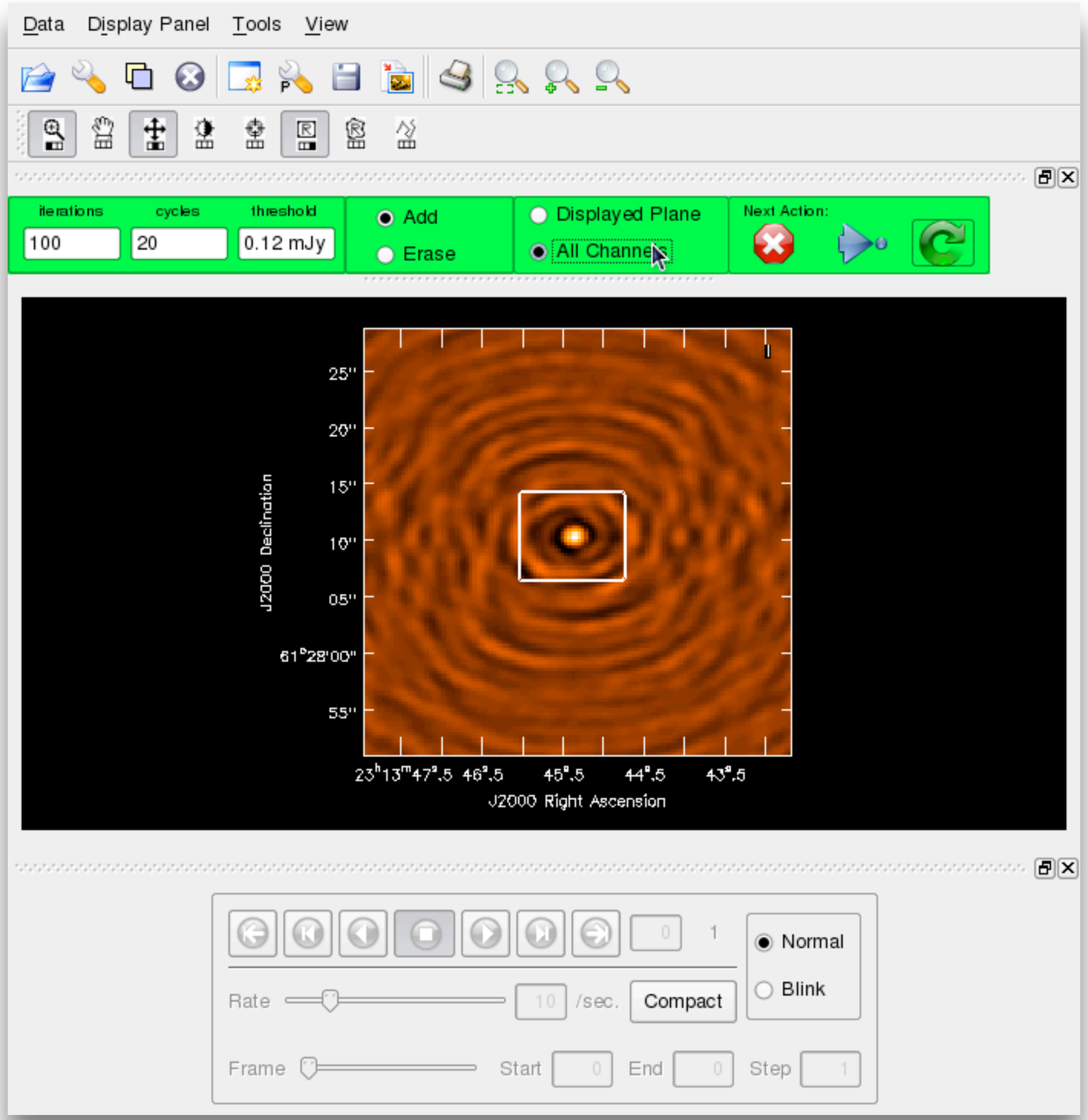
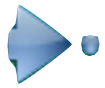
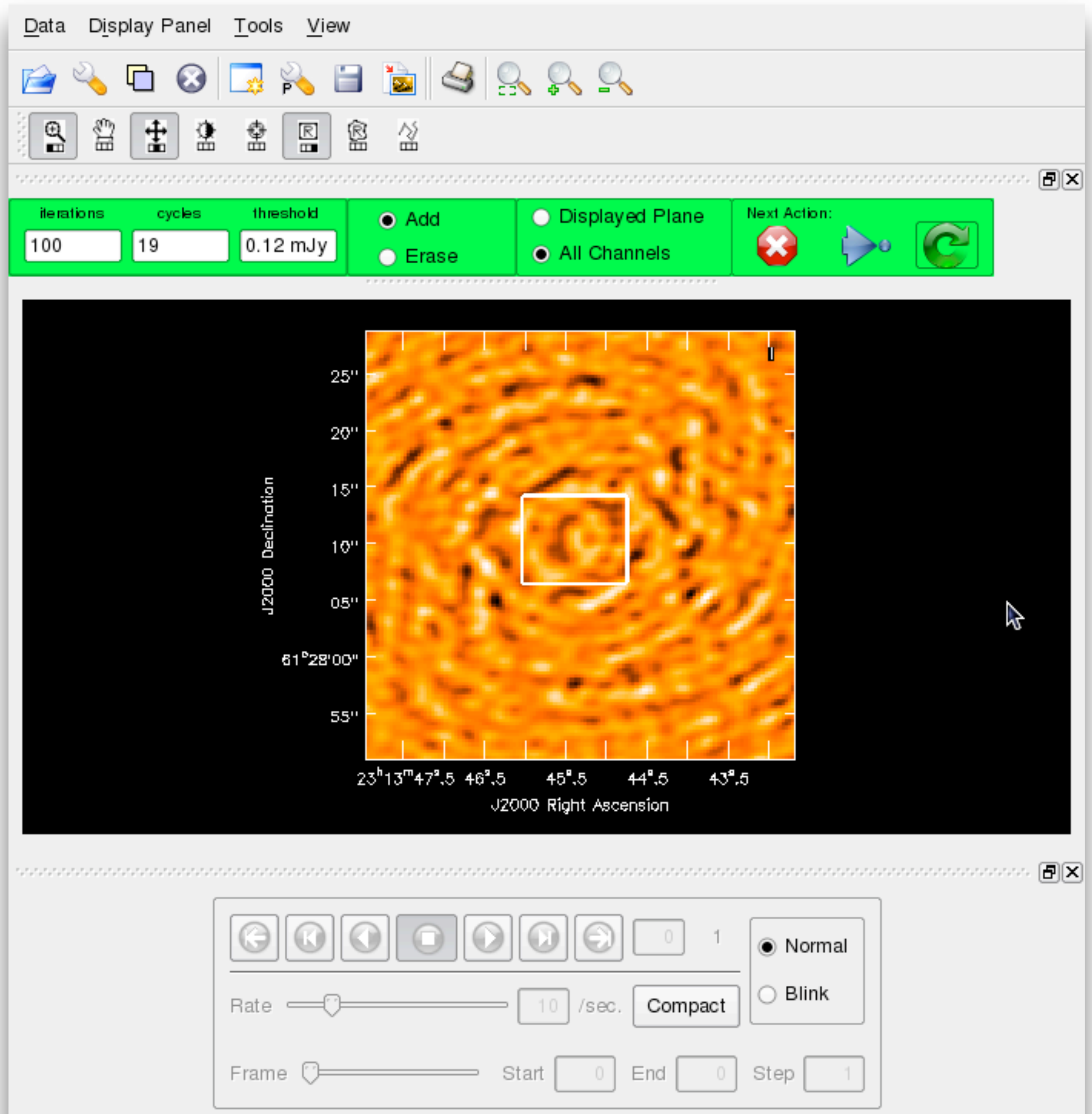
Cleaning



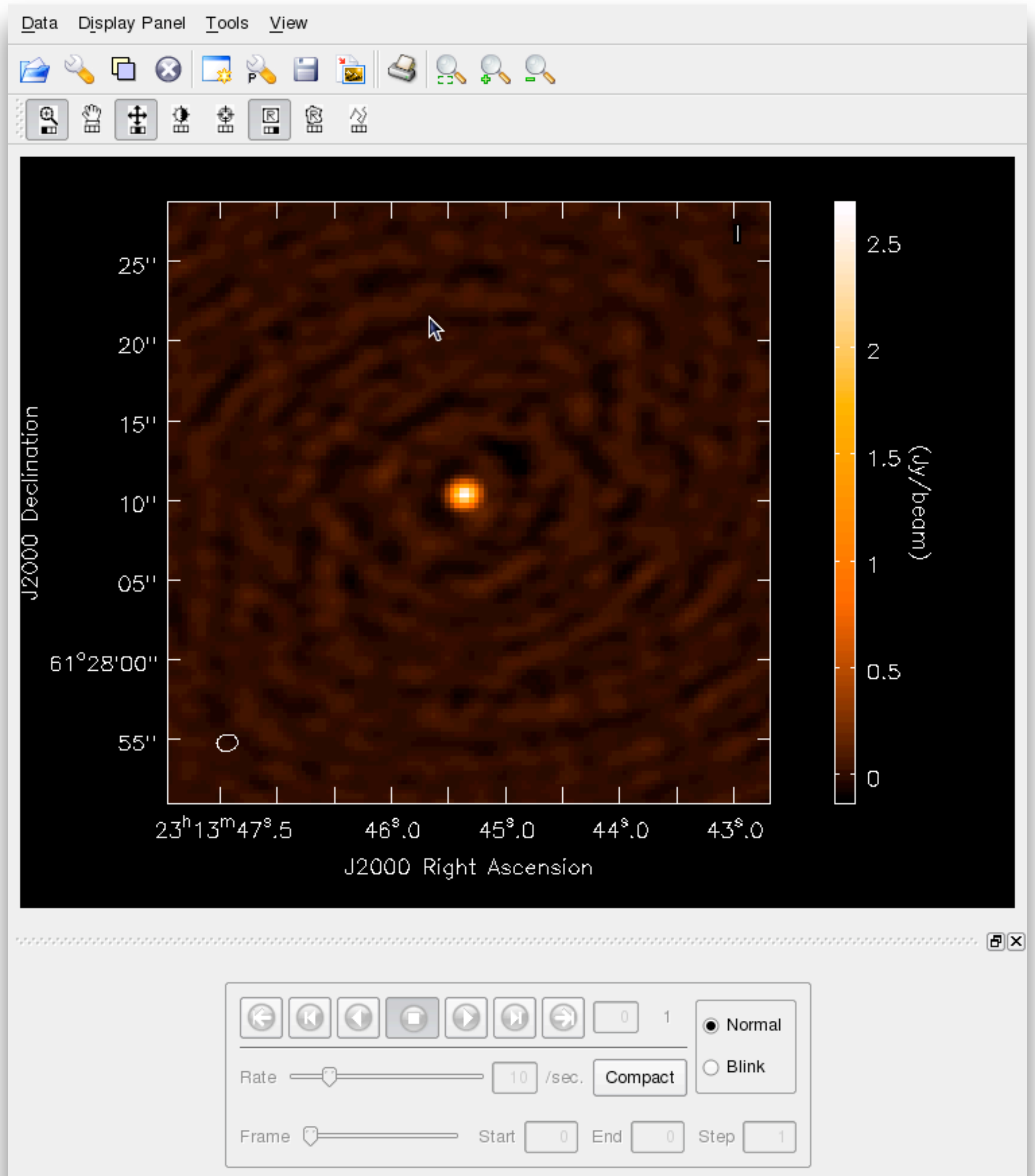
- Create a clean box around the emission
- Continue cleaning:
  interactively 
  automatically 

Cleaning

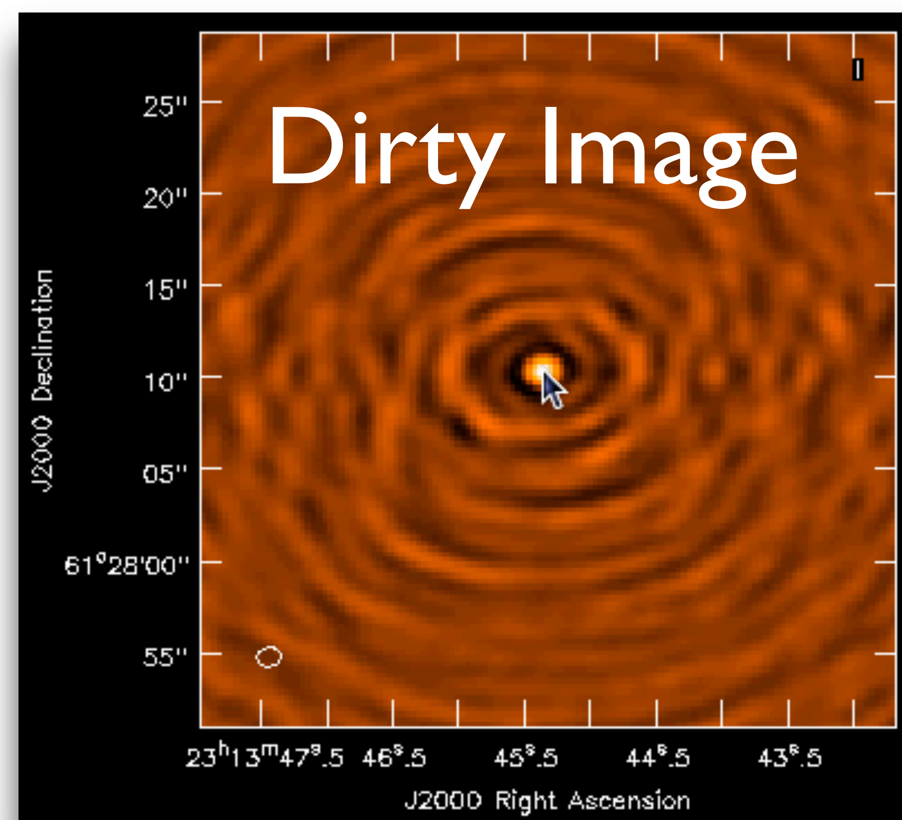


- Create a clean box around the emission
- Continue until residuals are noiselike

Restoring

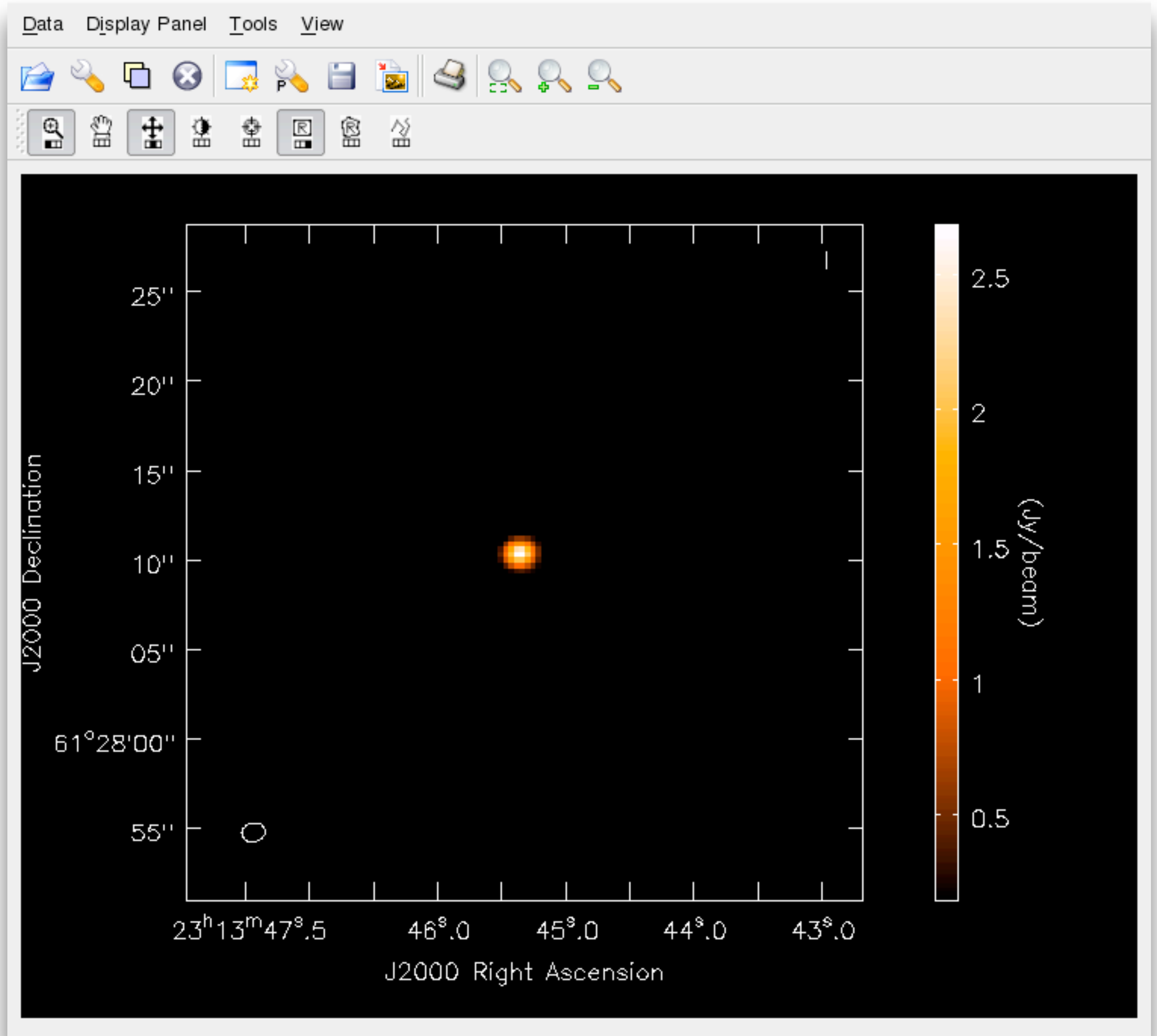


- Apply the cleaning model to the dirty image

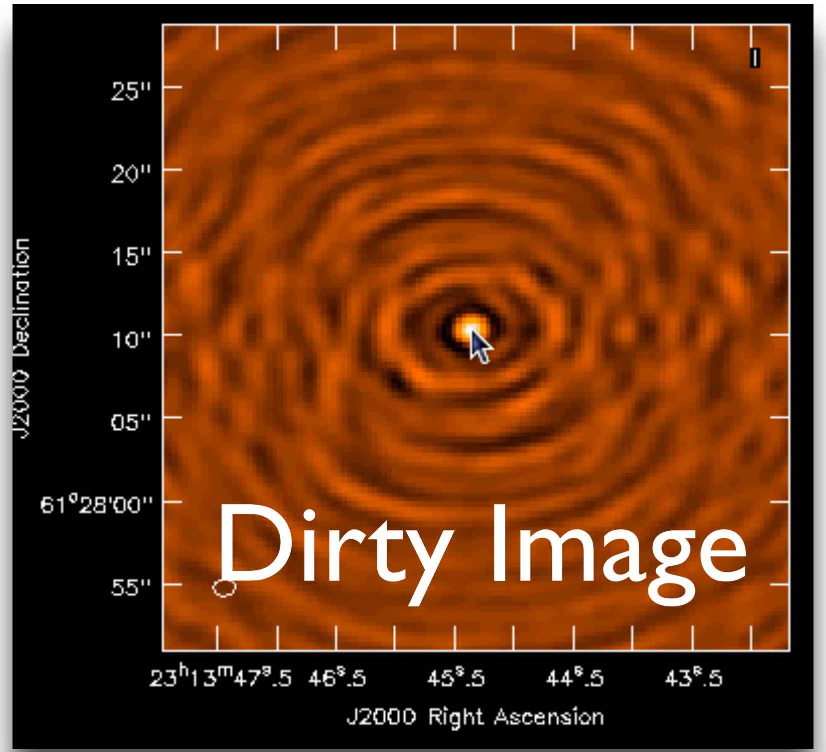


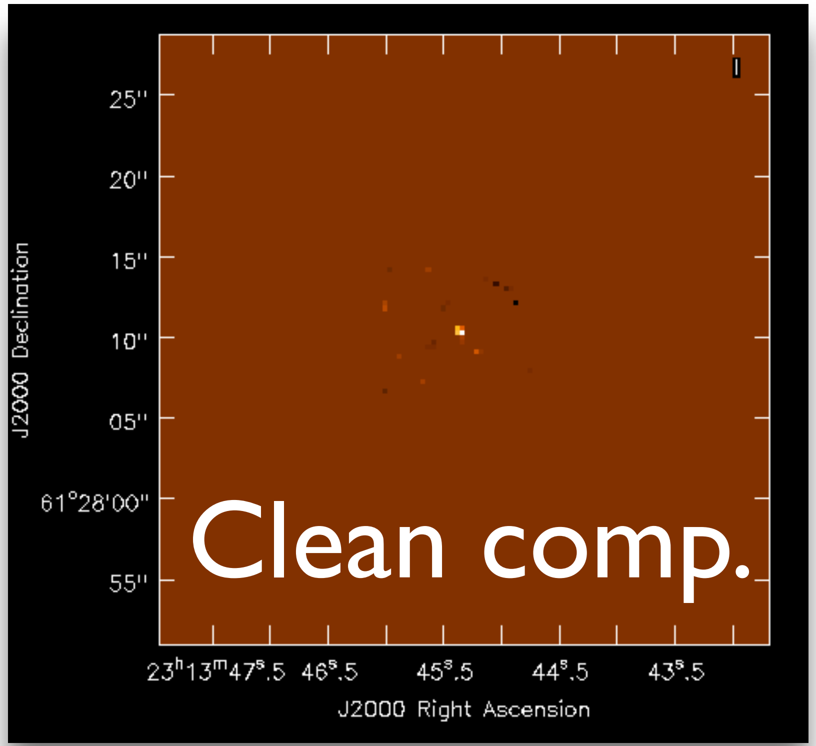
Final Continuum image

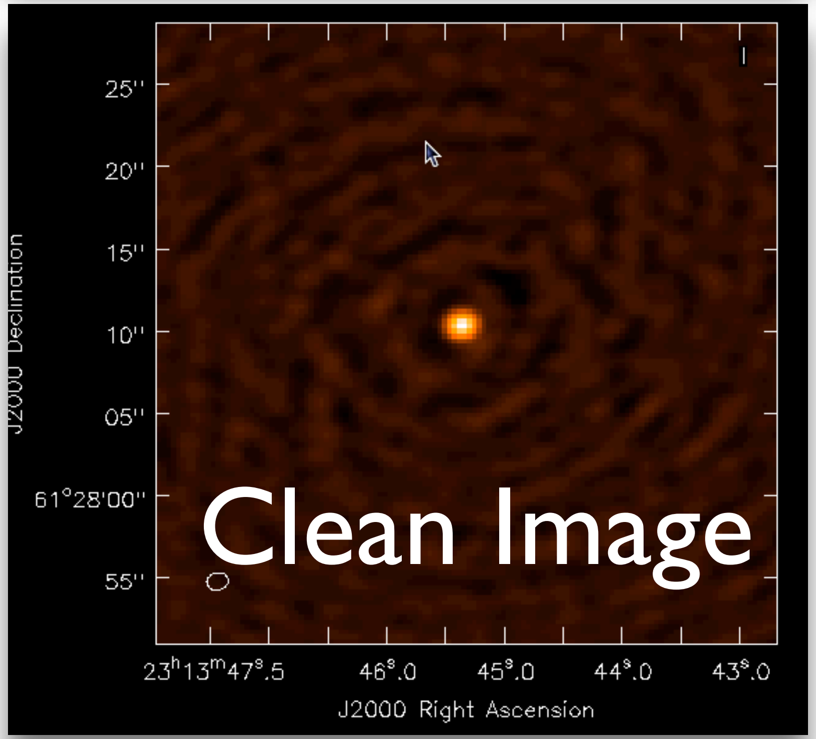
- For this science target, the continuum emission is unresolved (at the 1” resolution of the SMA)

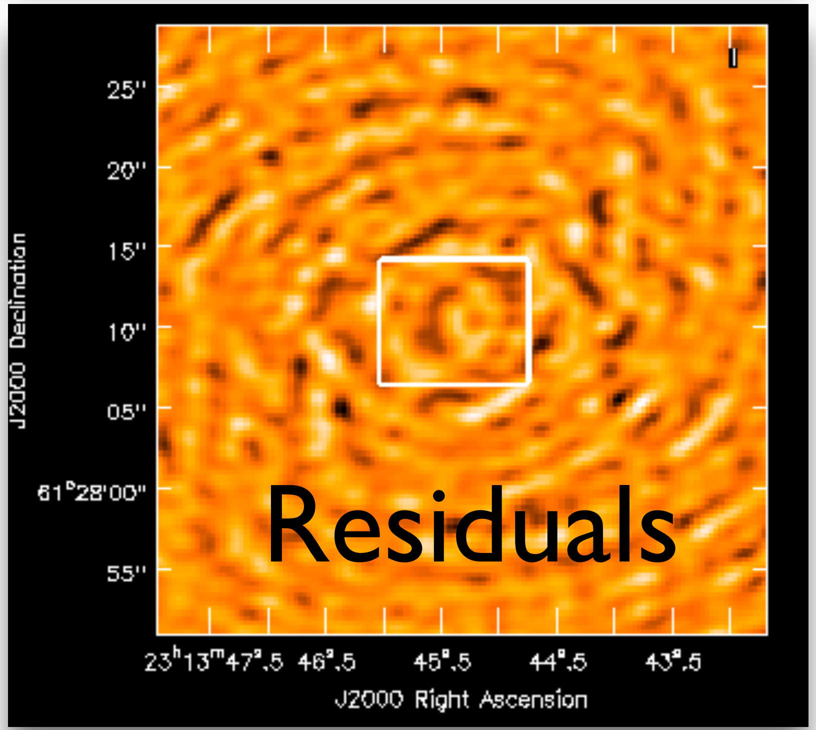


Imaging Process

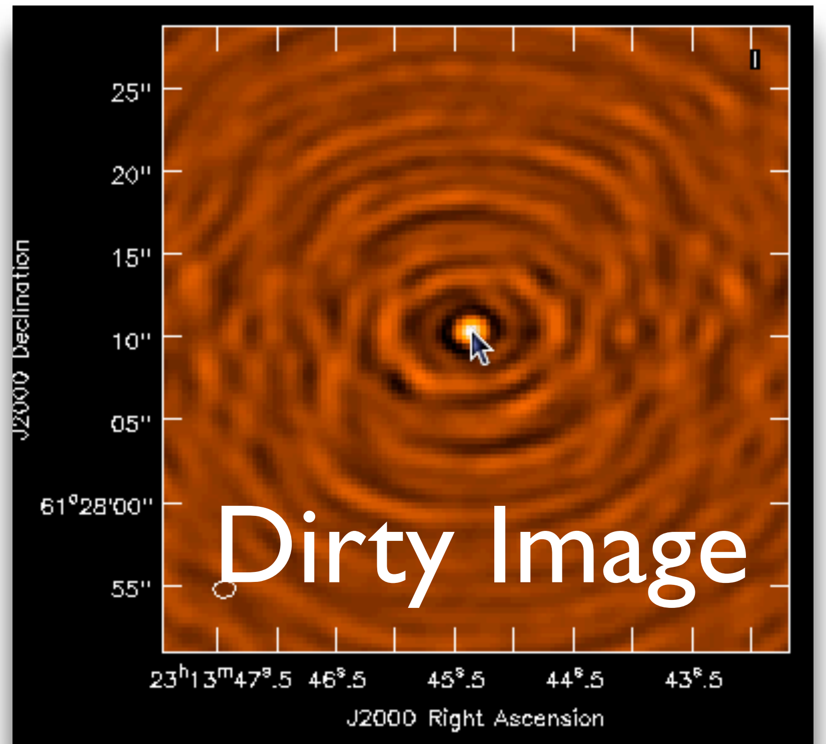


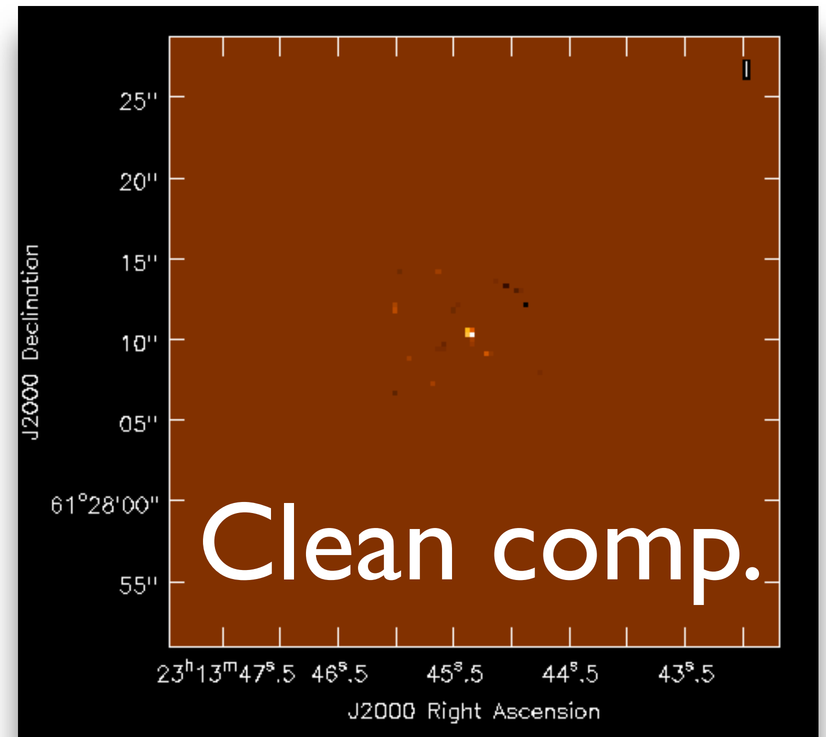


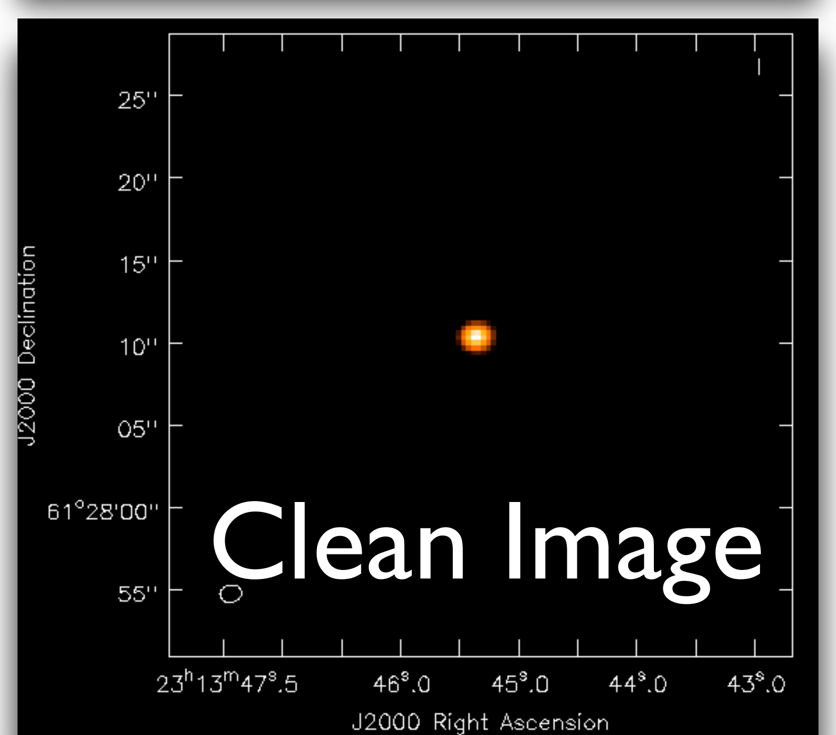


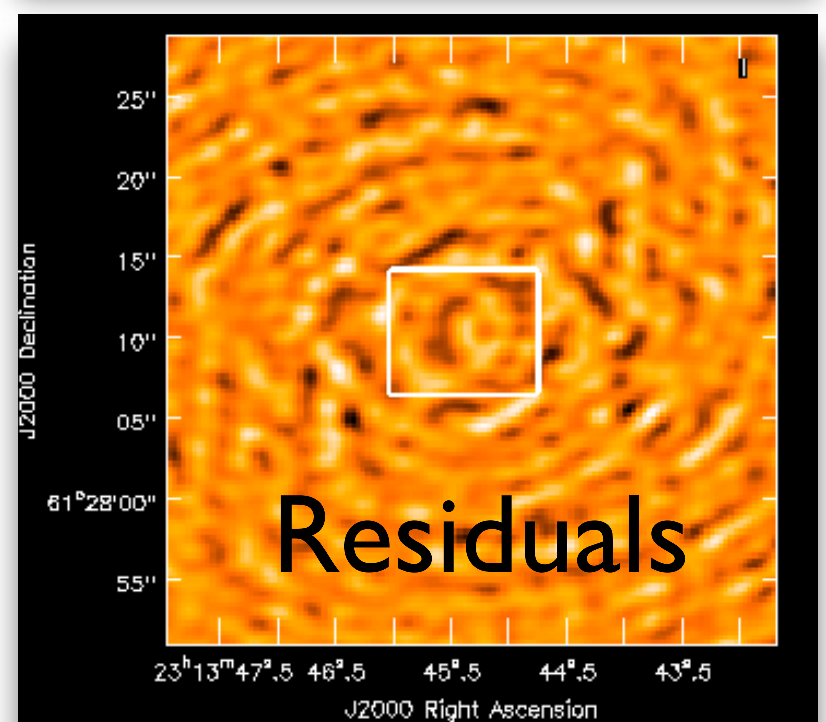


Imaging Process

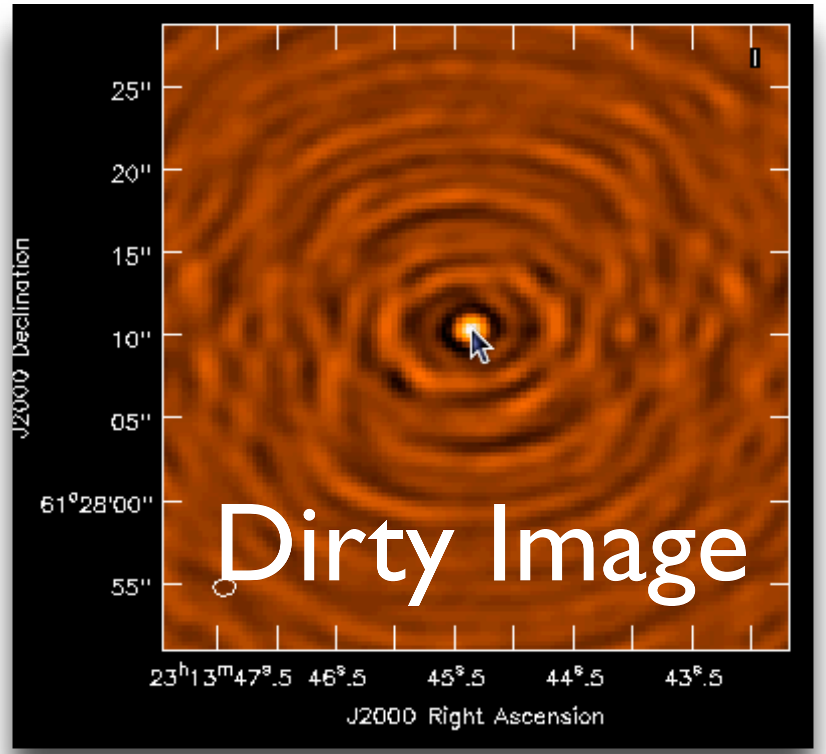


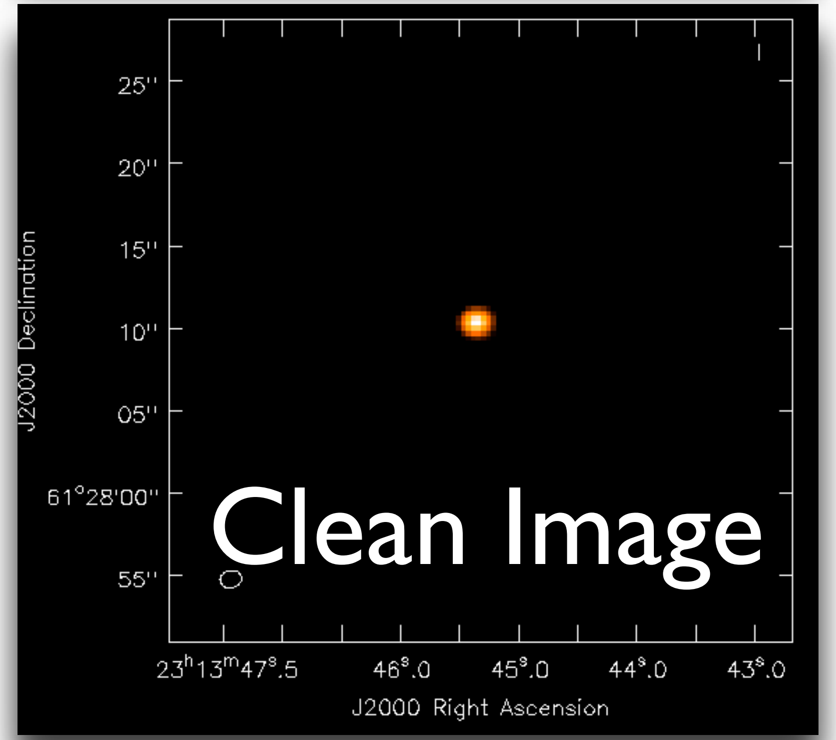


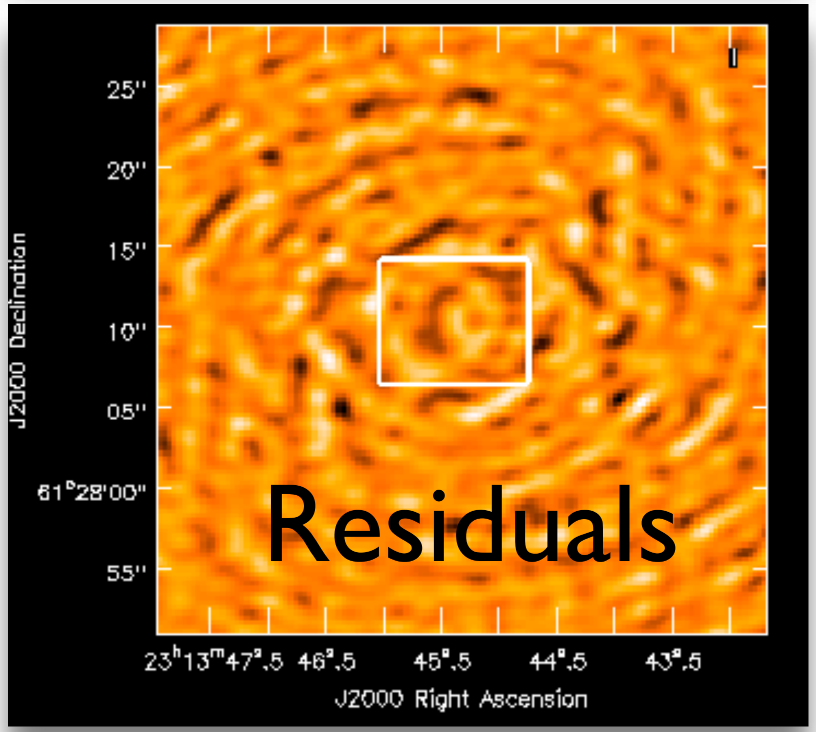




Imaging Process

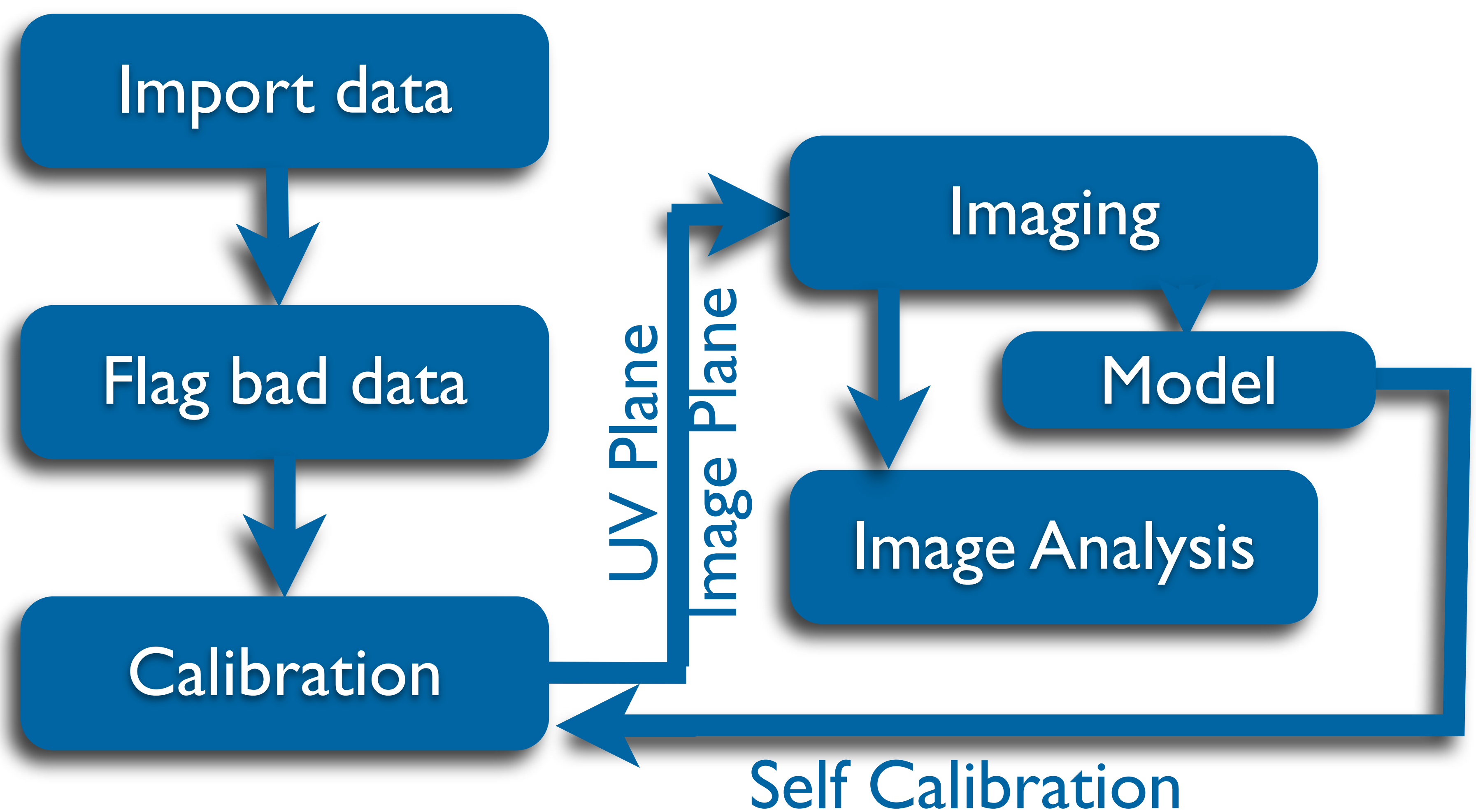


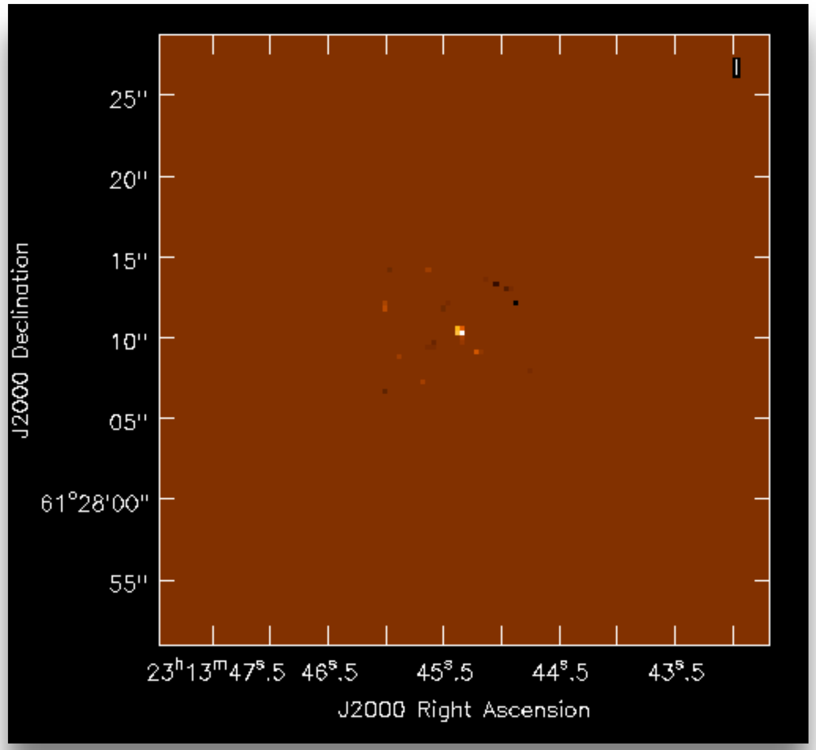




Self-Calibration

- Take modelled clean components of the science target as an extra calibration source in the UV plane

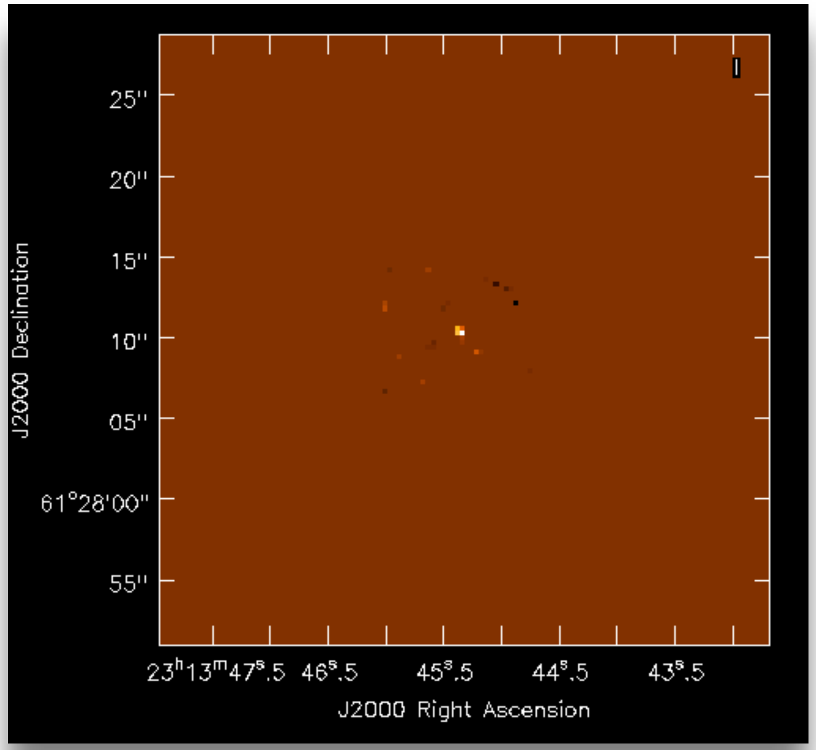




Self-Calibration

- Take modelled clean components of the science target as an extra calibration source in the UV plane

```
gaincal(vis='n7538_usb.ms',
   caltable='n7538.ms.selfcal',
   field='5',spw='0~23',
   selectdata=False,gaincurve=False
   gaintype='G',minsnr=2.0,
   refant='3',calmode='ap',
   solint='int',combine='spw')
```



Self Calibration

Spectral Line Data

- Similar process for spectral line data

```
clean(vis='n7538_edge_clip.ms.contsub',
   imagename='n7538.ocs',field='0',spw='',
   mode='velocity',start='-90kms',
   nchan=100,width='0.53km/s',
   niter=1000,gain=0.1,threshold=0.2,
   restfreq='231.060983GHz',interactive=T,
   npercycle=400,imsize=500,cell='0.3',
   pbcor=F,minpb=0.1)
```

Spectral Line Data

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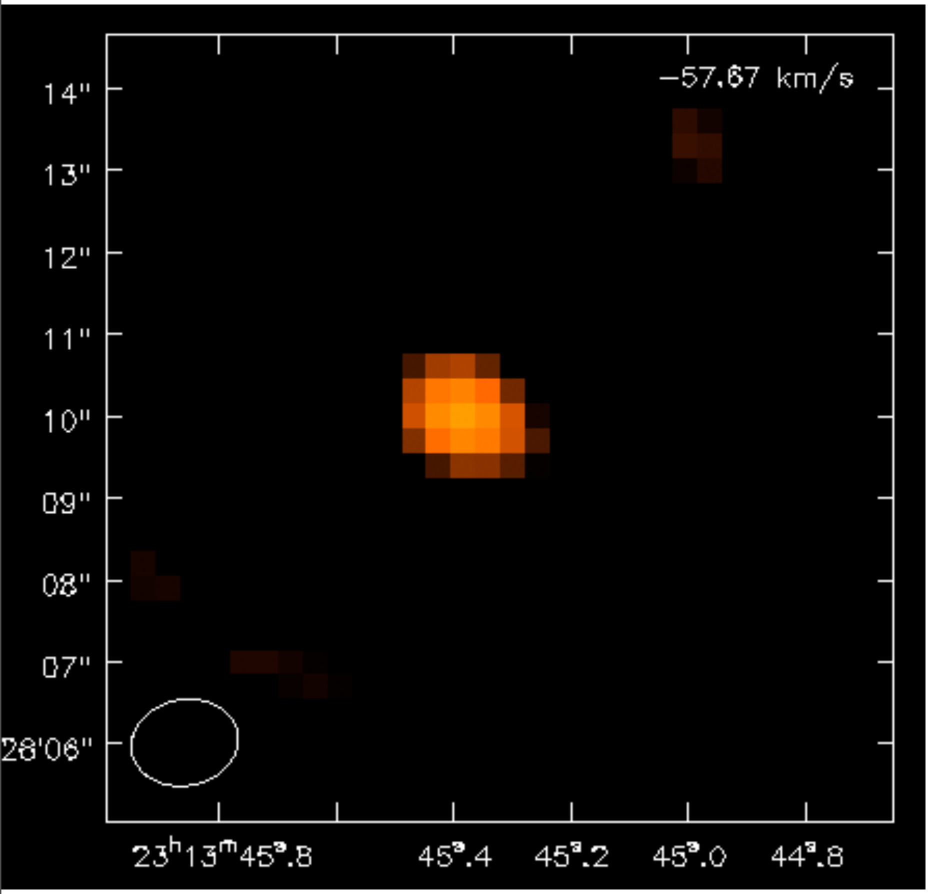
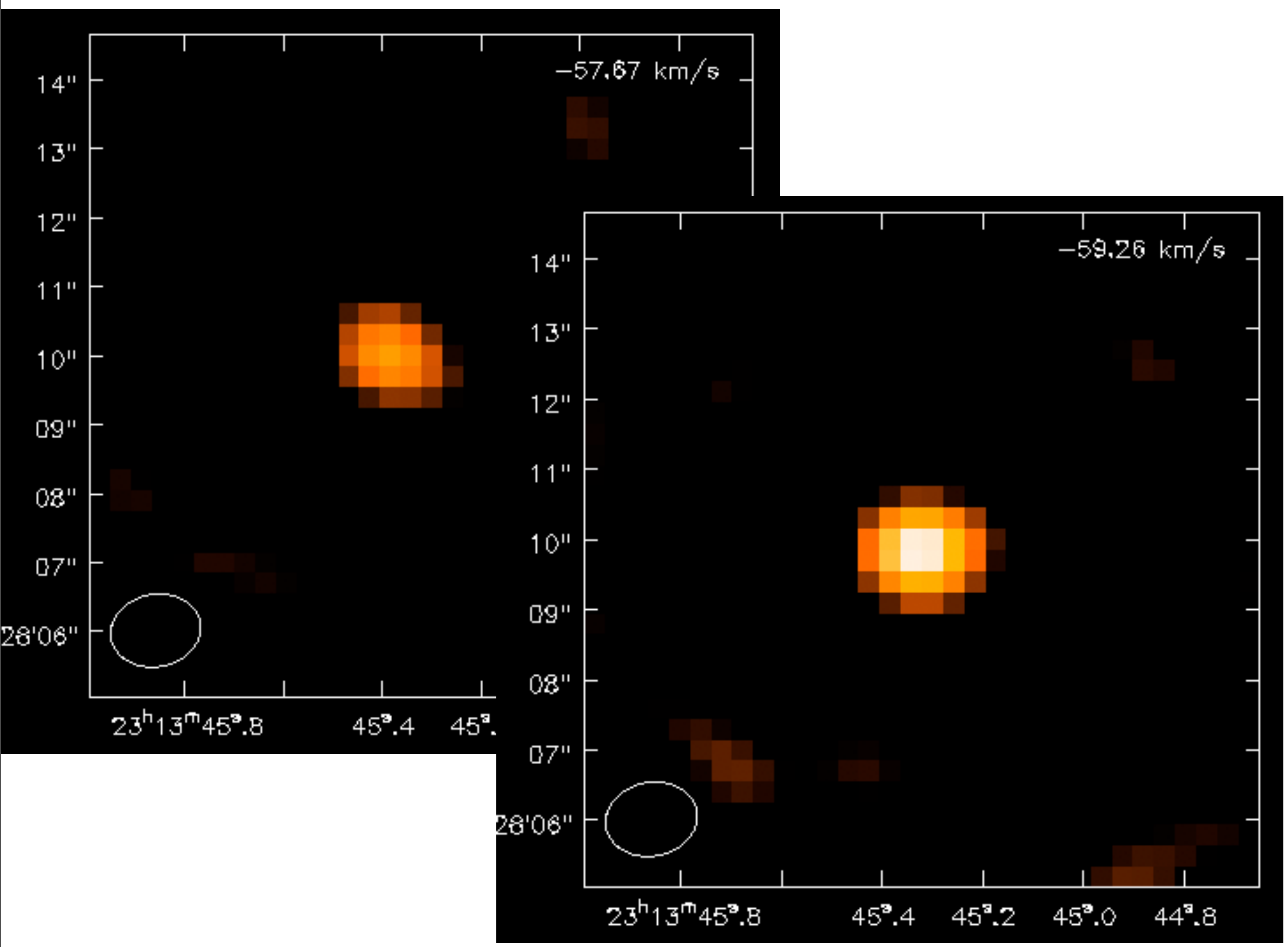
   npercycle=400,imsize=500,cell='0.3',
   pbcor=F,minpb=0.1)
```

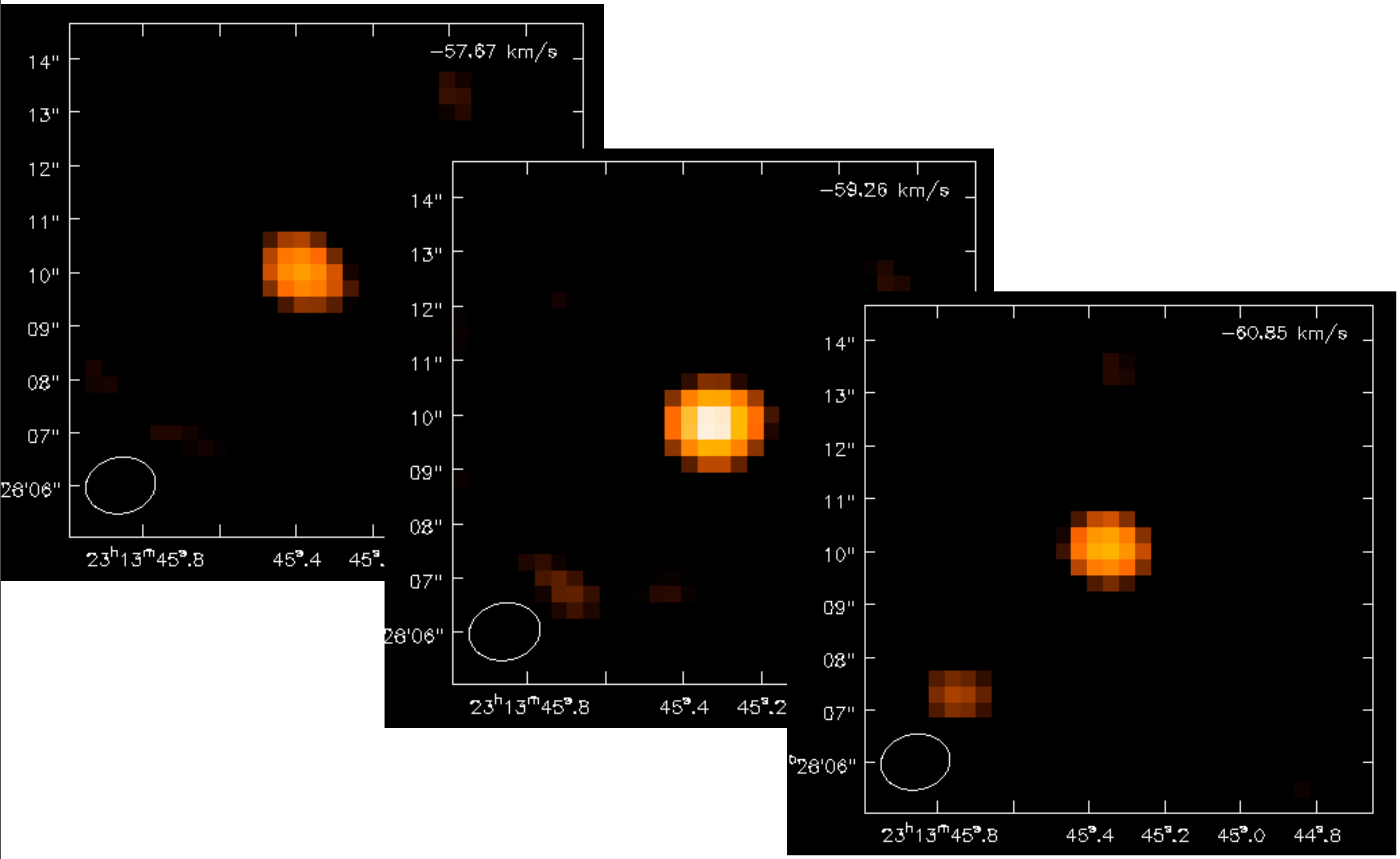
OCS Spectral Cube



OCS Spectral Cube



OCS Spectral Cube



OCS Spectral Cube

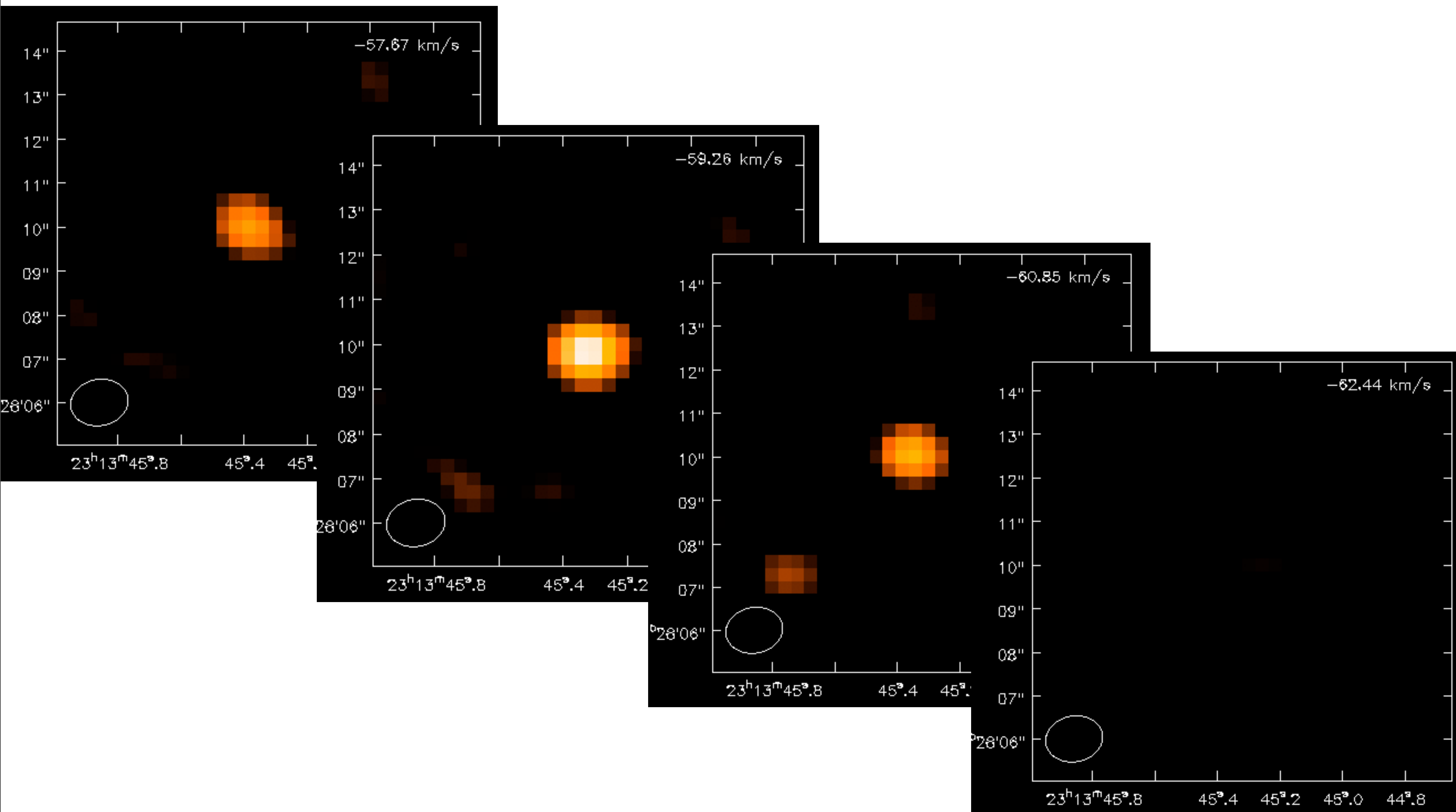


Image Analysis

Moment	Name
0	Integrated Intensity
1	Intensity Weighted Velocity
2	Velocity Dispersion
...	etc.

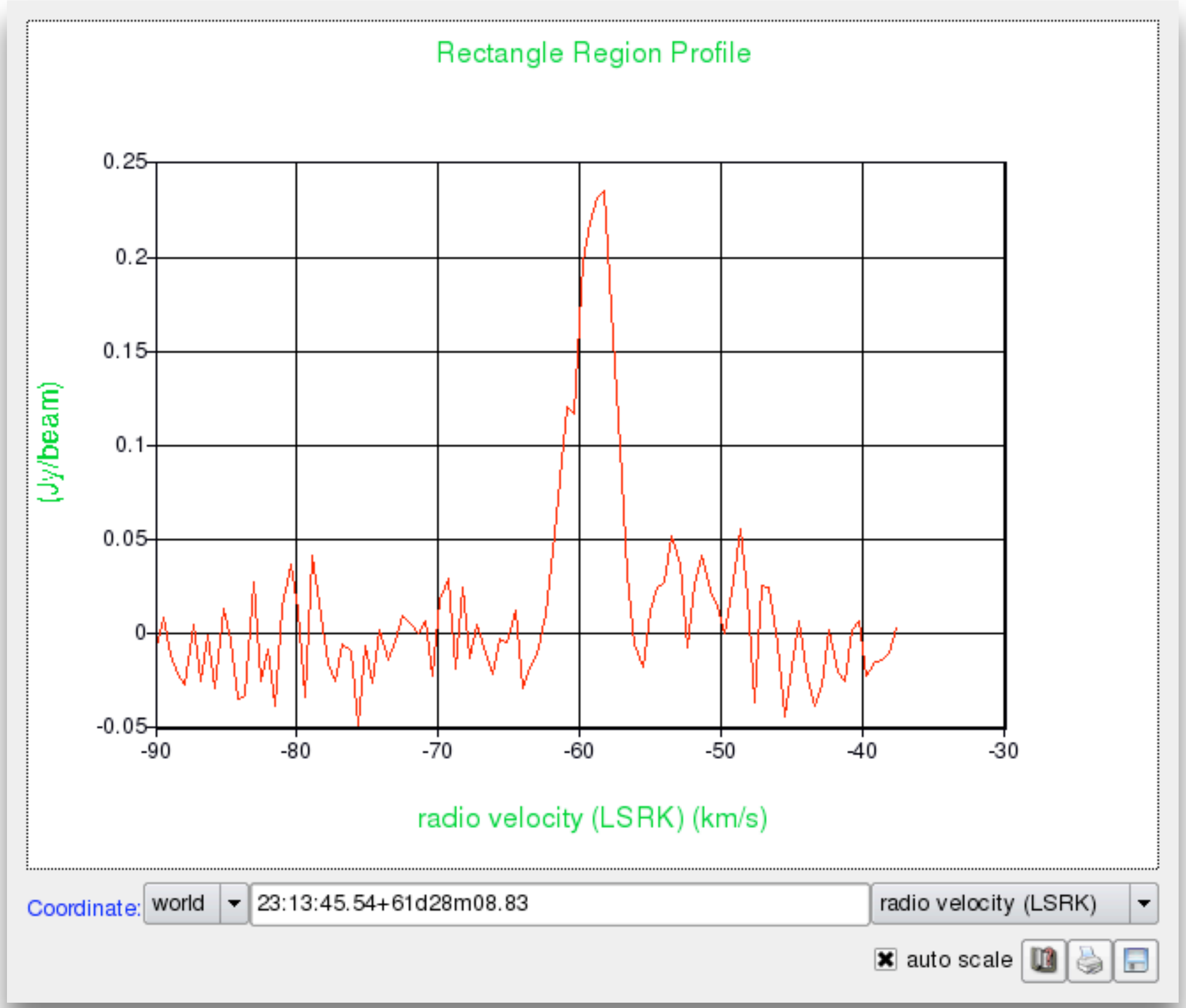
http://casa.nrao.edu/docs/casaref/image.moments.html

Moment Mapping

- Multiple moment maps can be made at the same time in CASA

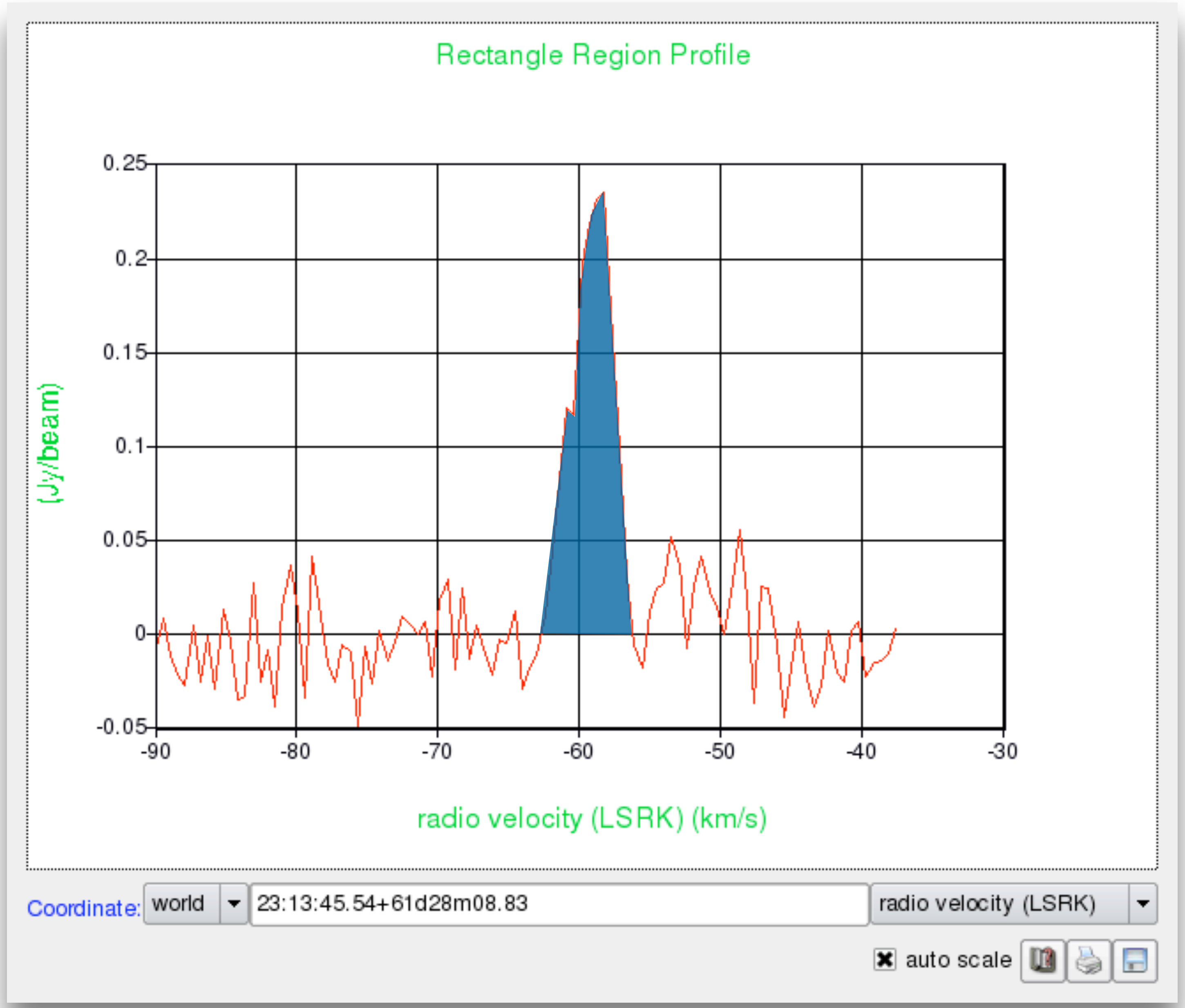
```
immoments(imagename='n7538.ocs.image',
    moments=[0,1],axis='spectral',
    chans='50~65',outfile='n7538.ocs',
    includepix=[0,1.78])
```

Intensity Map



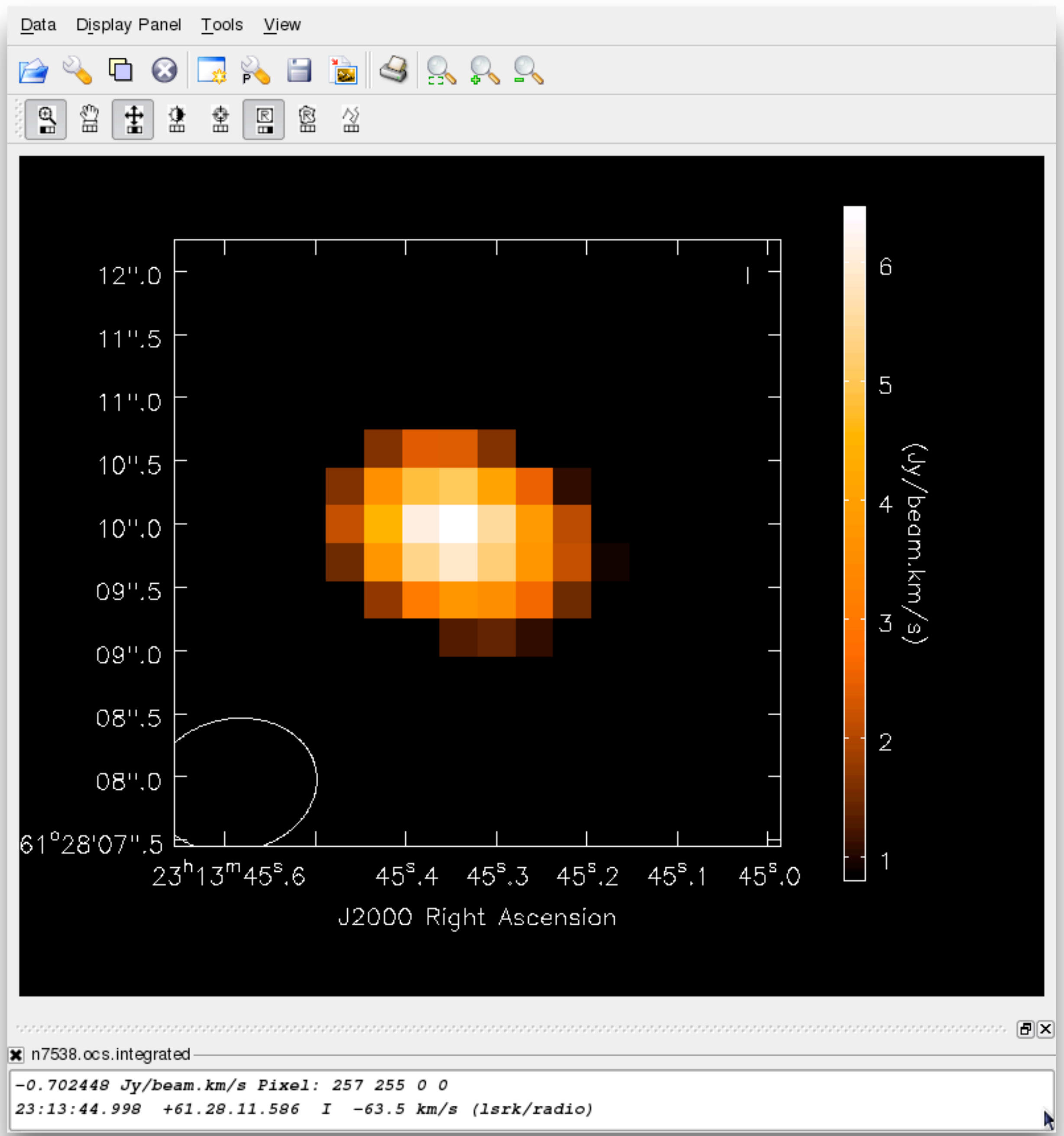
- We want the integrated intensity of the line in the map

Intensity Map



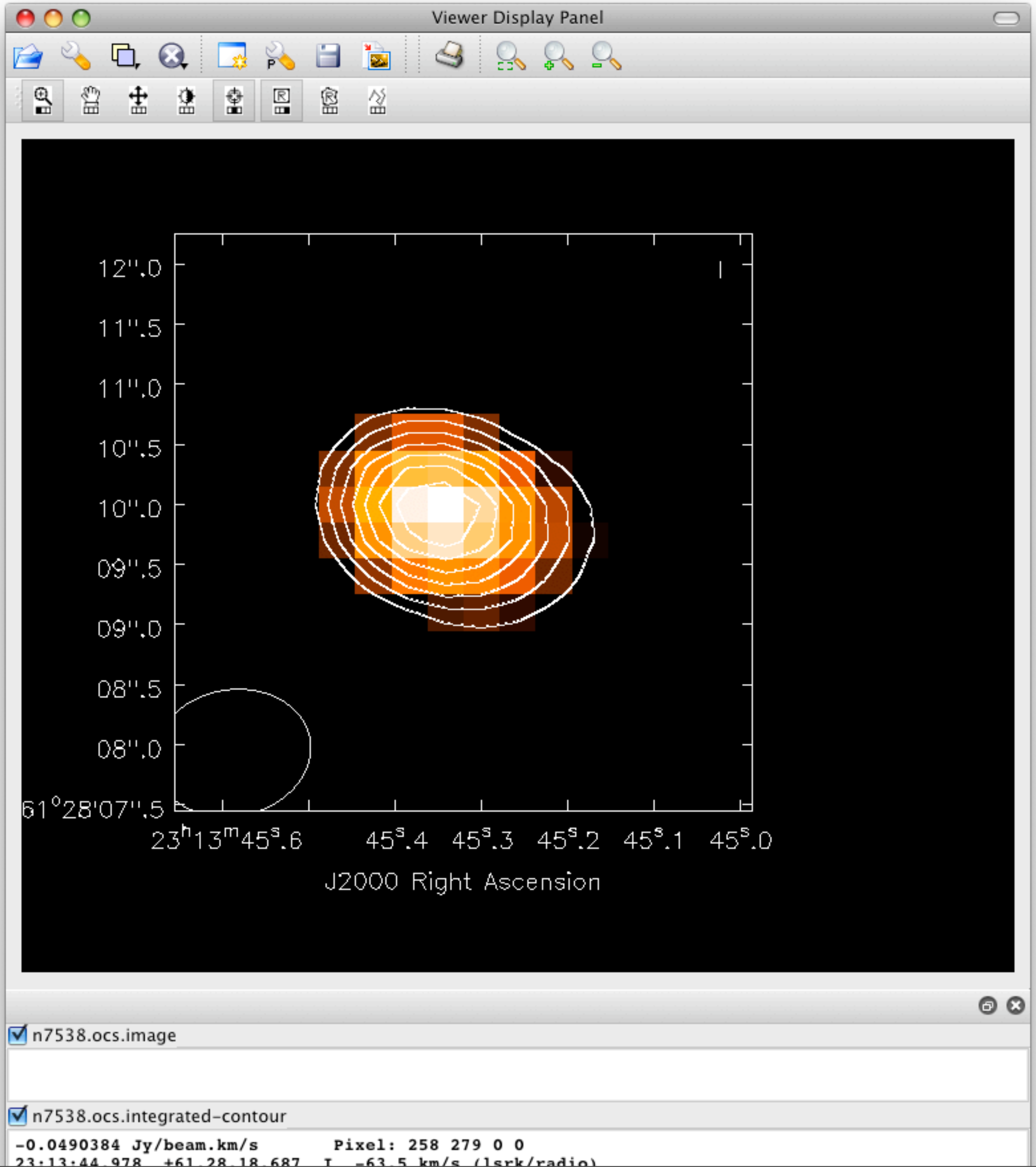
- We want the integrated intensity of the line in the map

Intensity Map



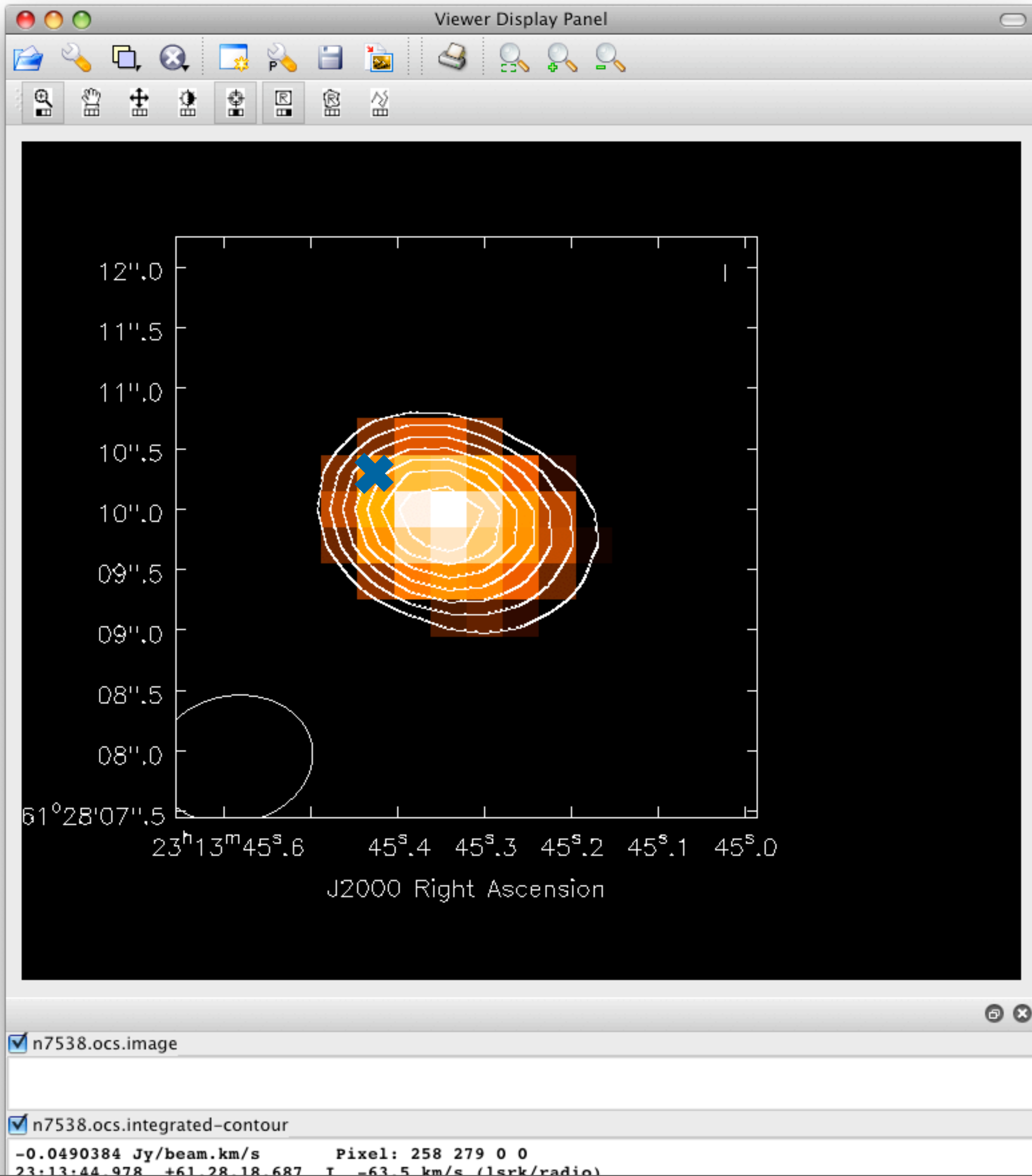
- Zoom in on small emission zone around HII region
- See where the emission peak is

Velocity Map

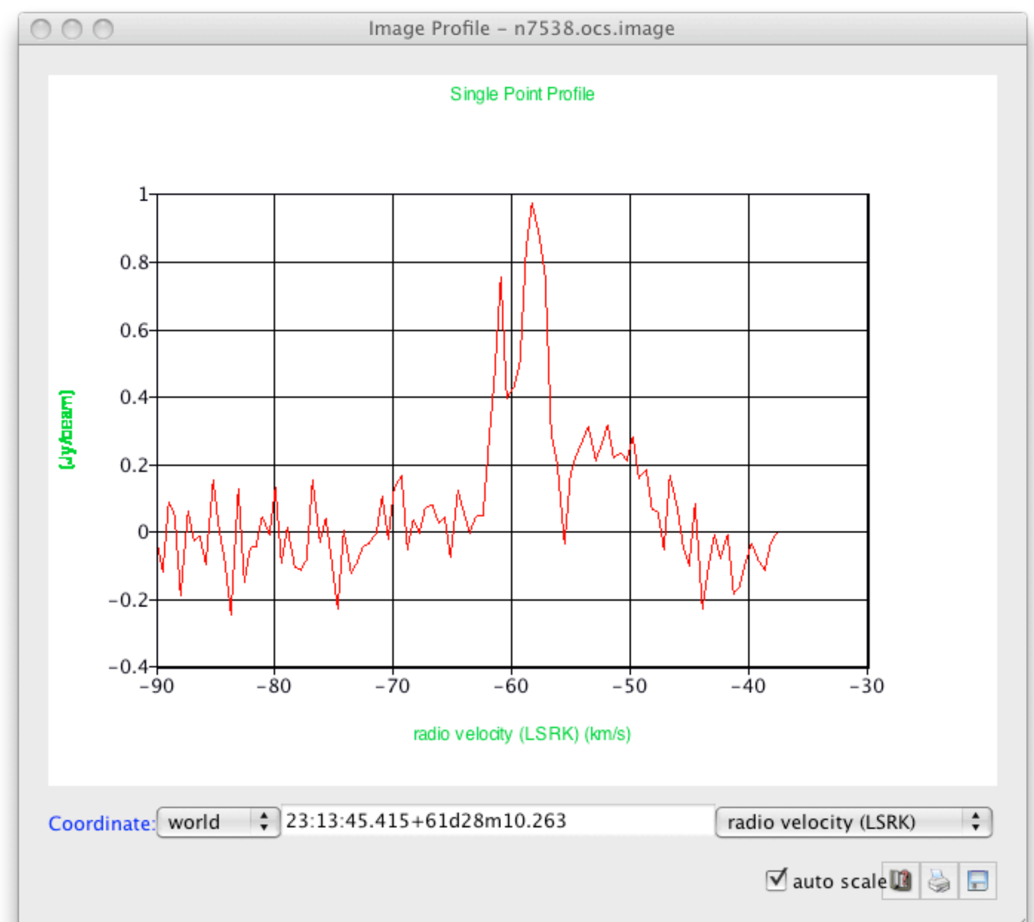


- How does the peak of the line change across the face of the source

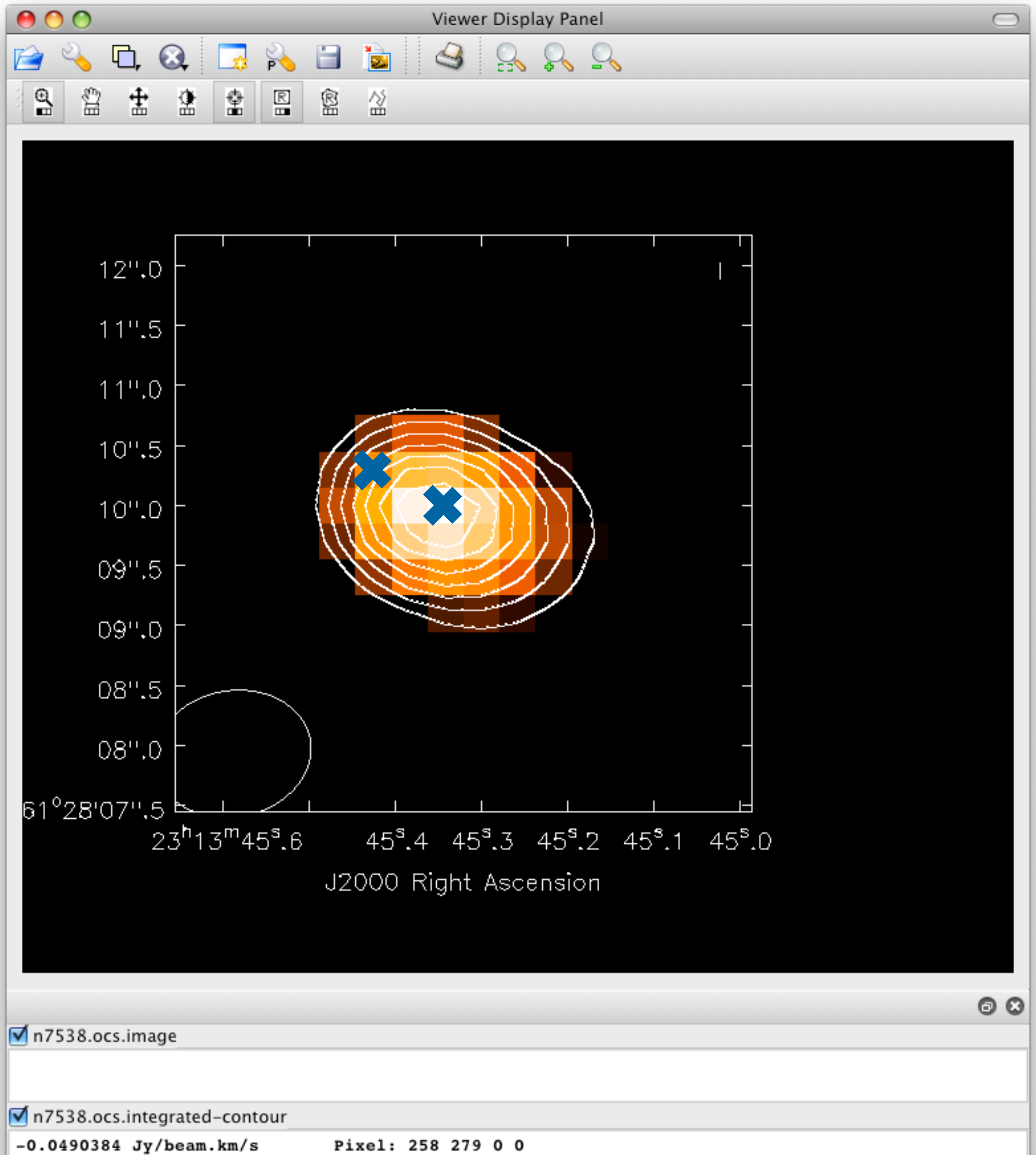
Velocity Map



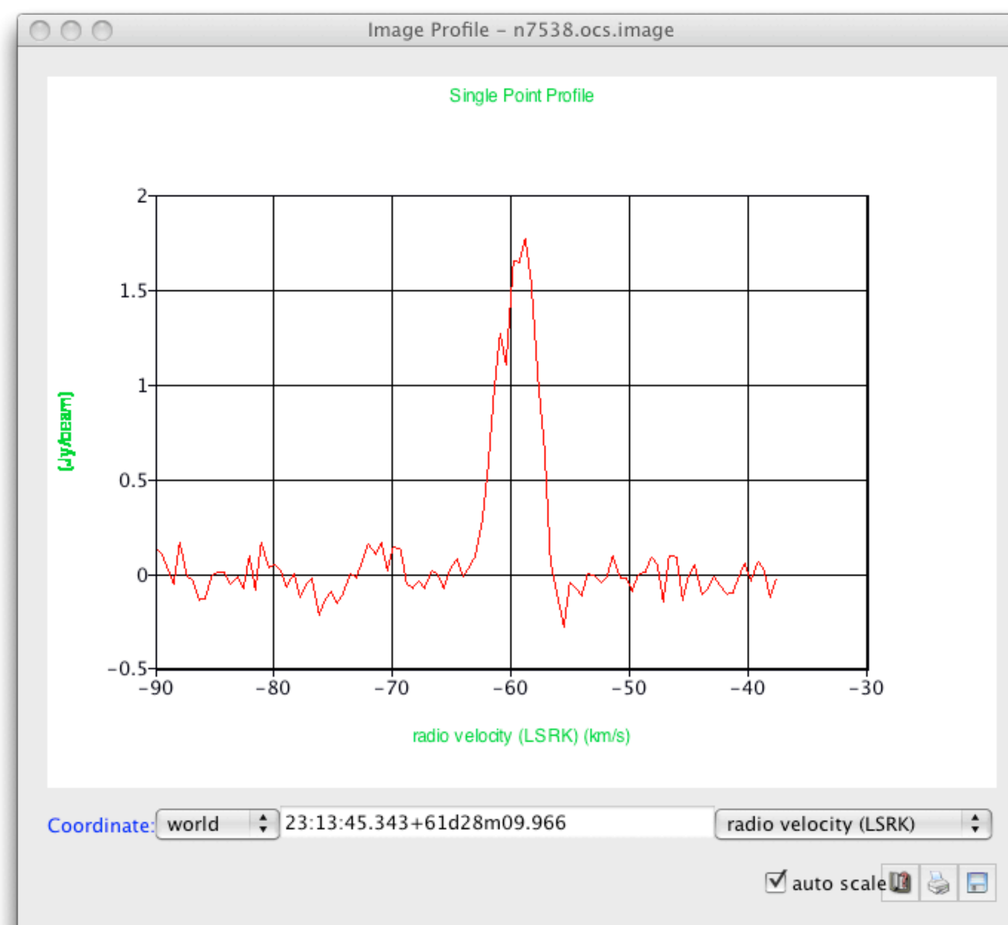
- How does the peak of the line change across the face of the source



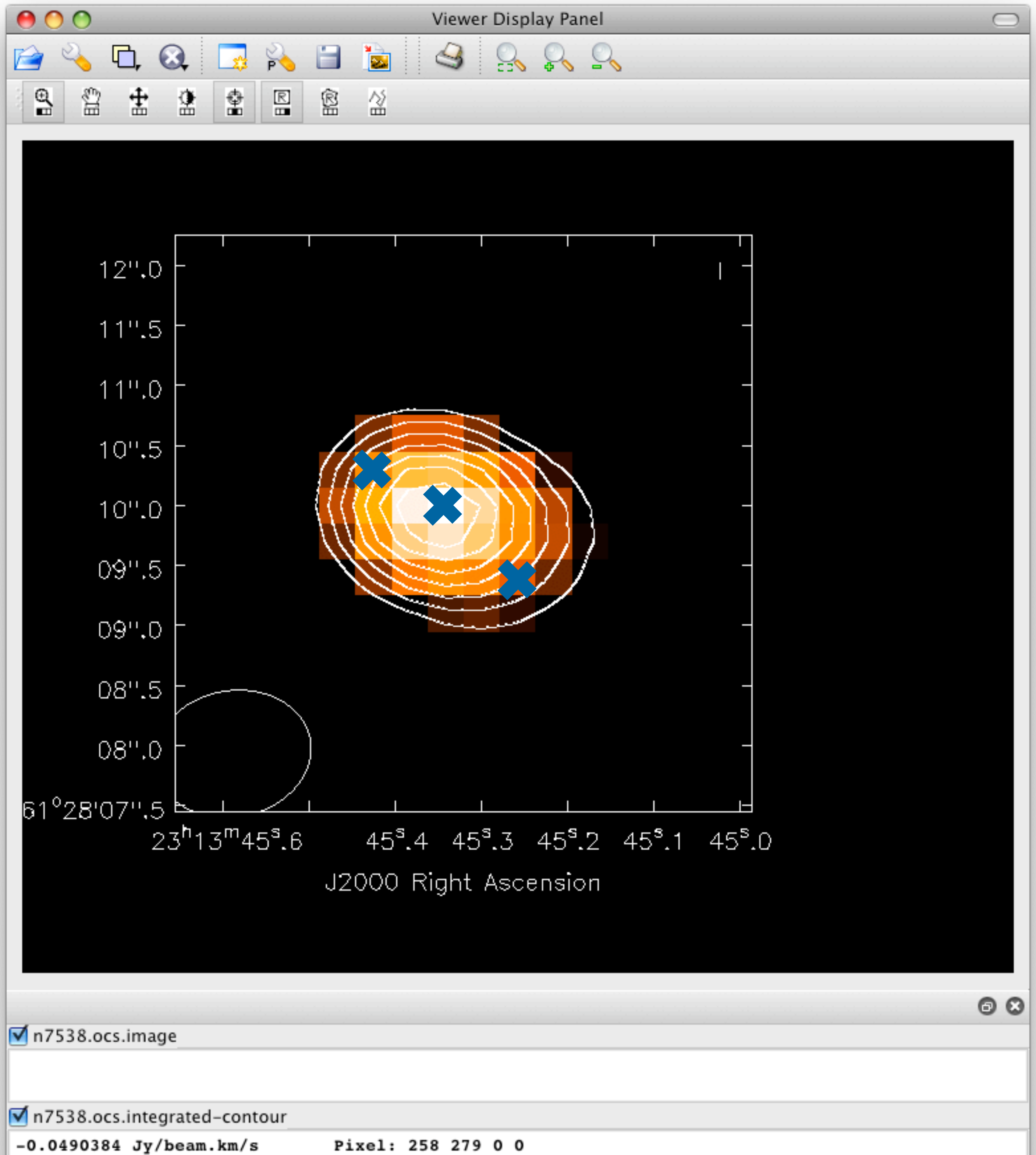
Velocity Map



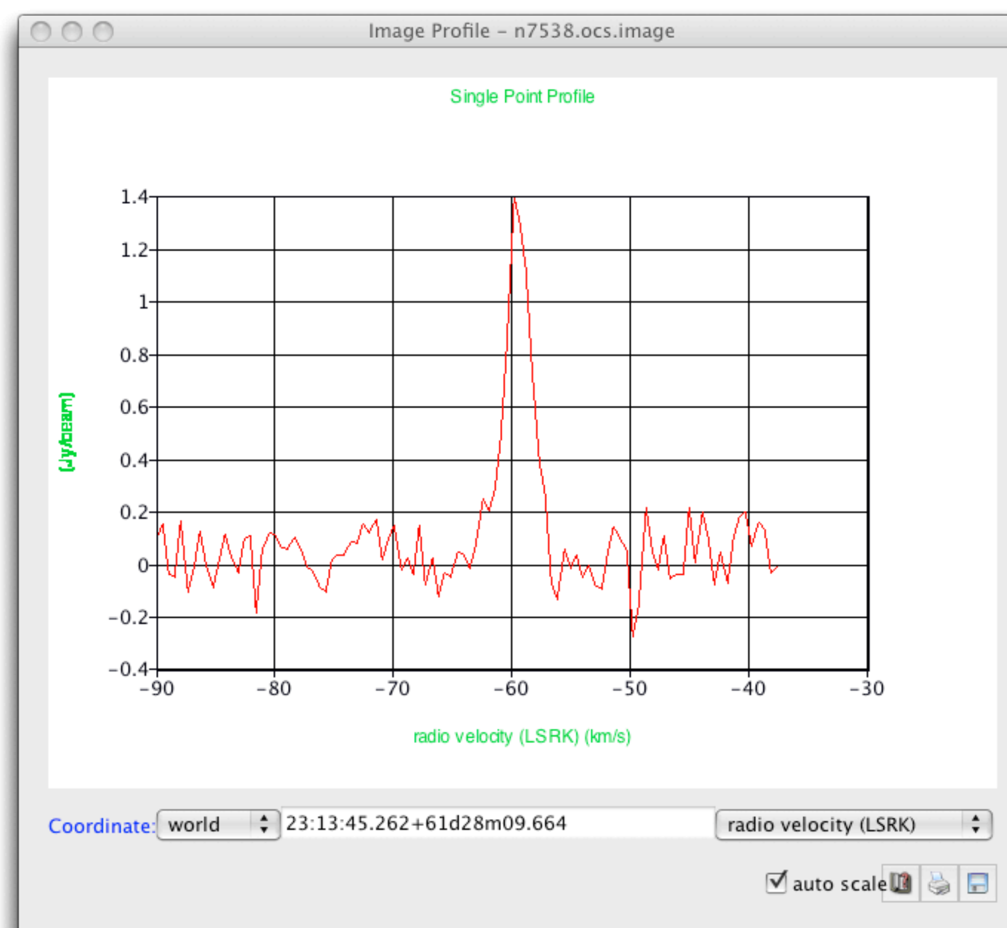
- How does the peak of the line change across the face of the source



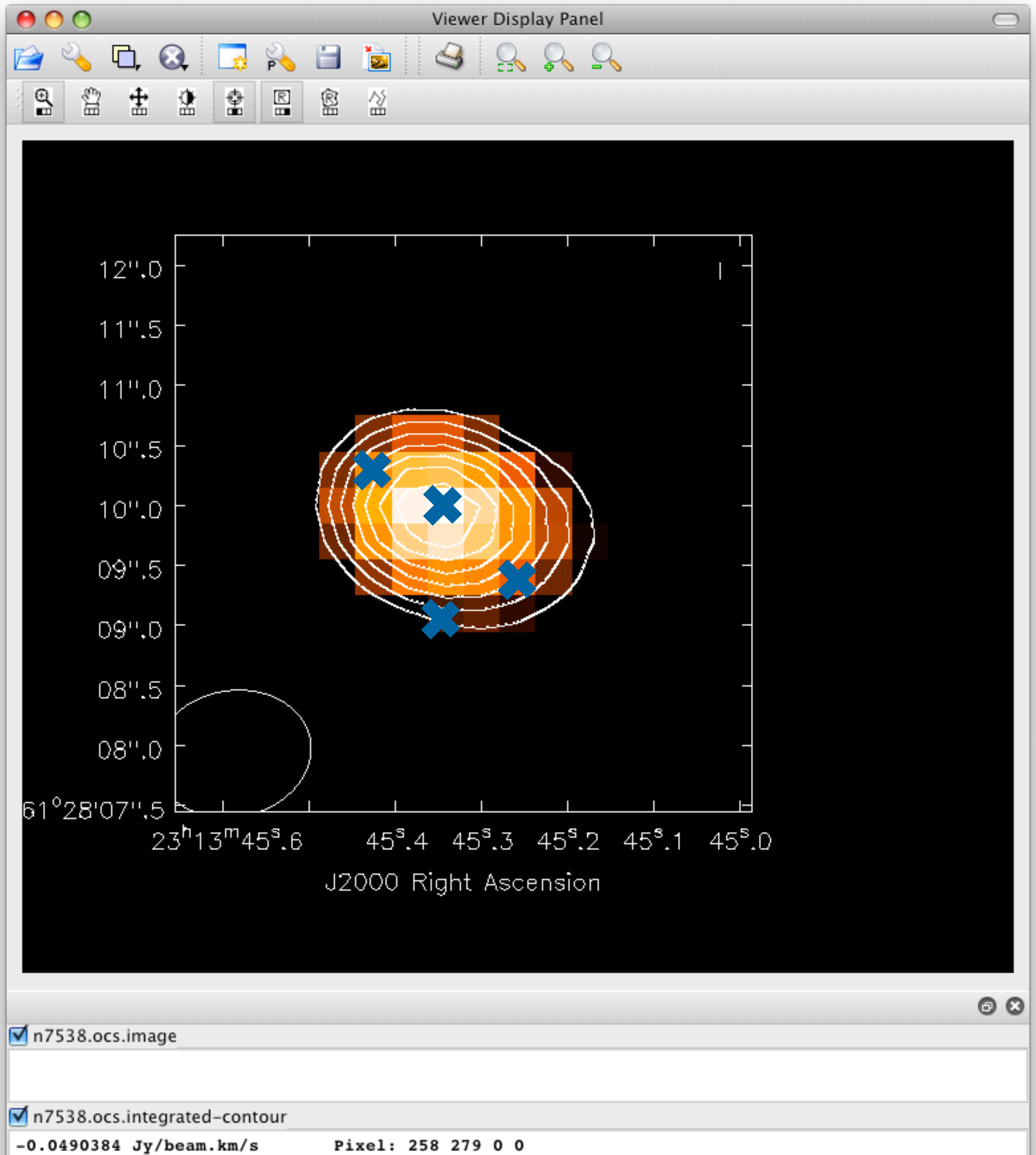
Velocity Map



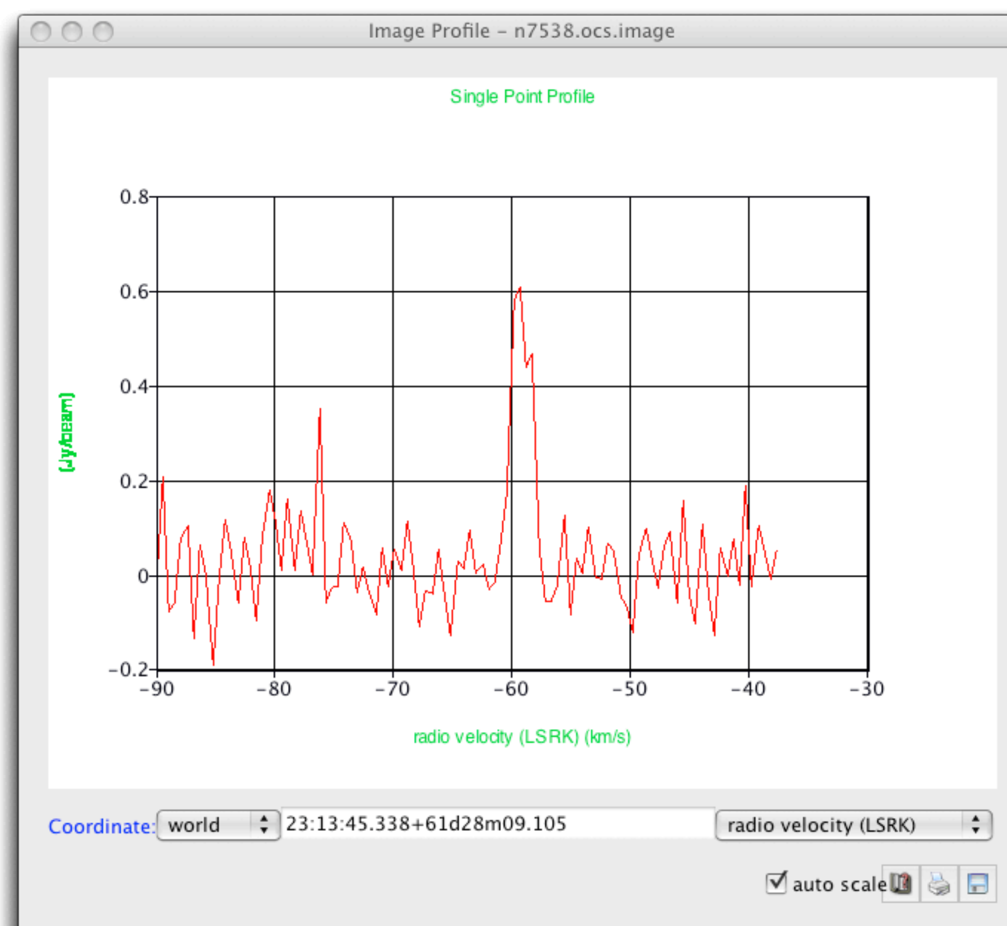
- How does the peak of the line change across the face of the source



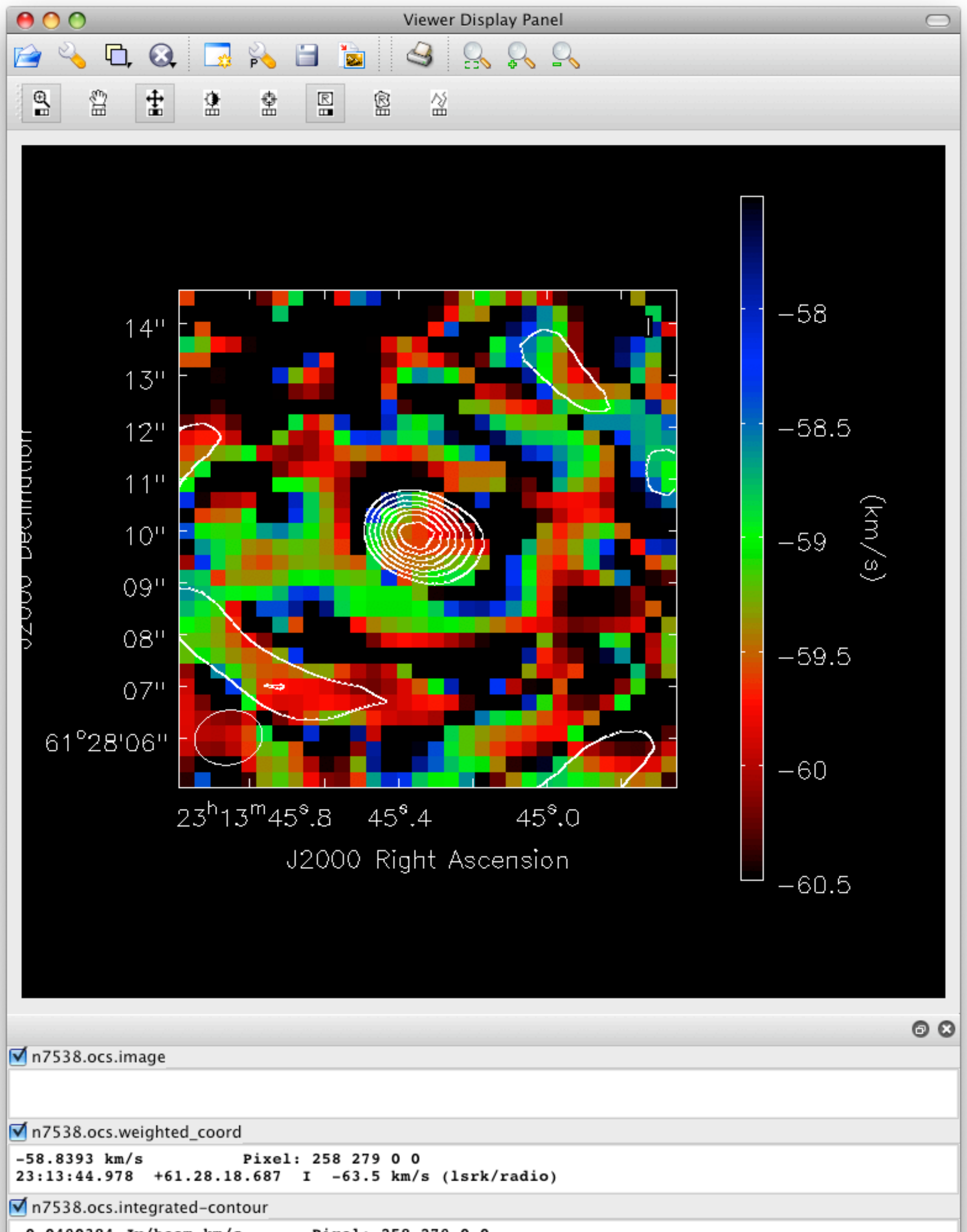
Velocity Map



- How does the peak of the line change across the face of the source

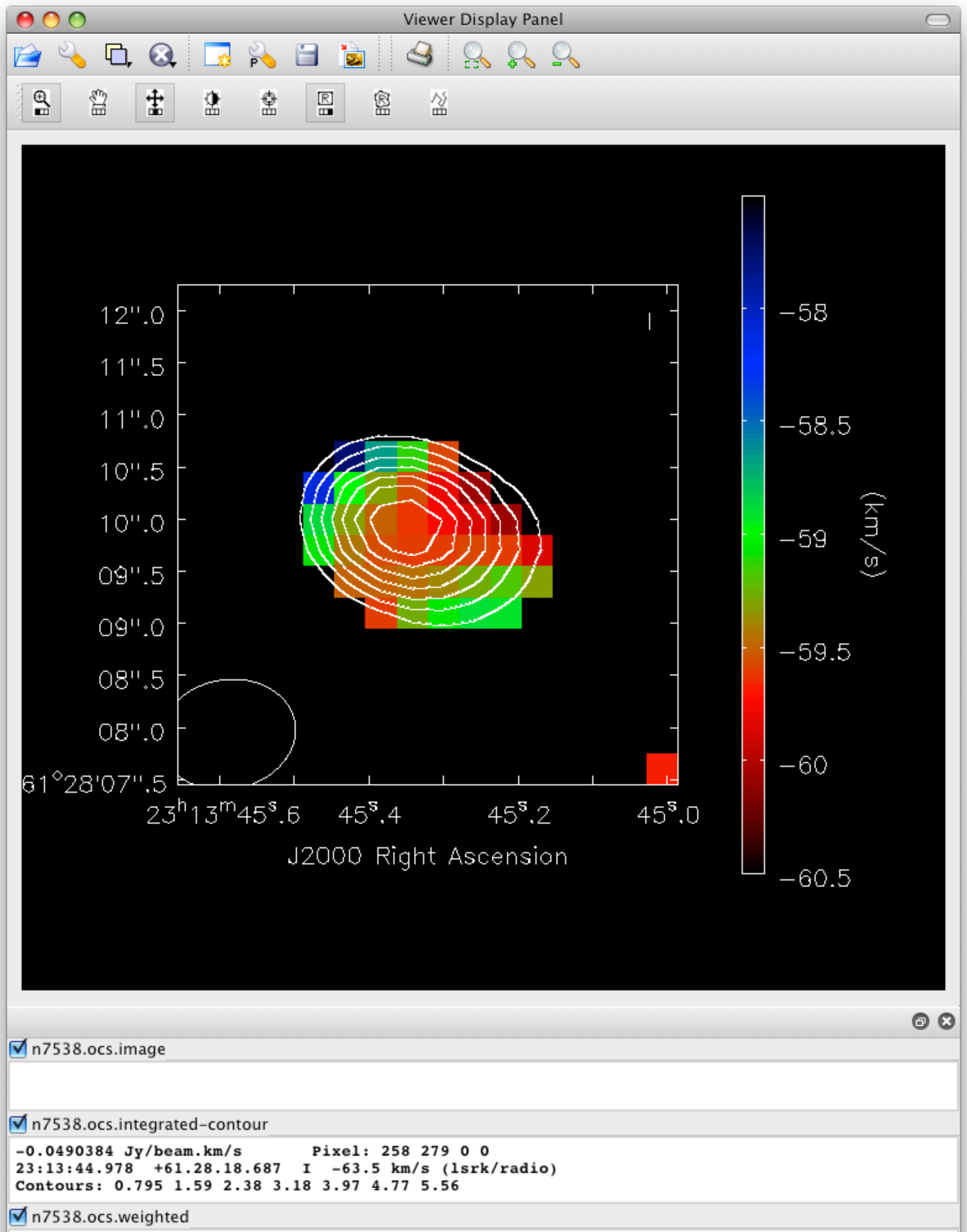


Velocity Map



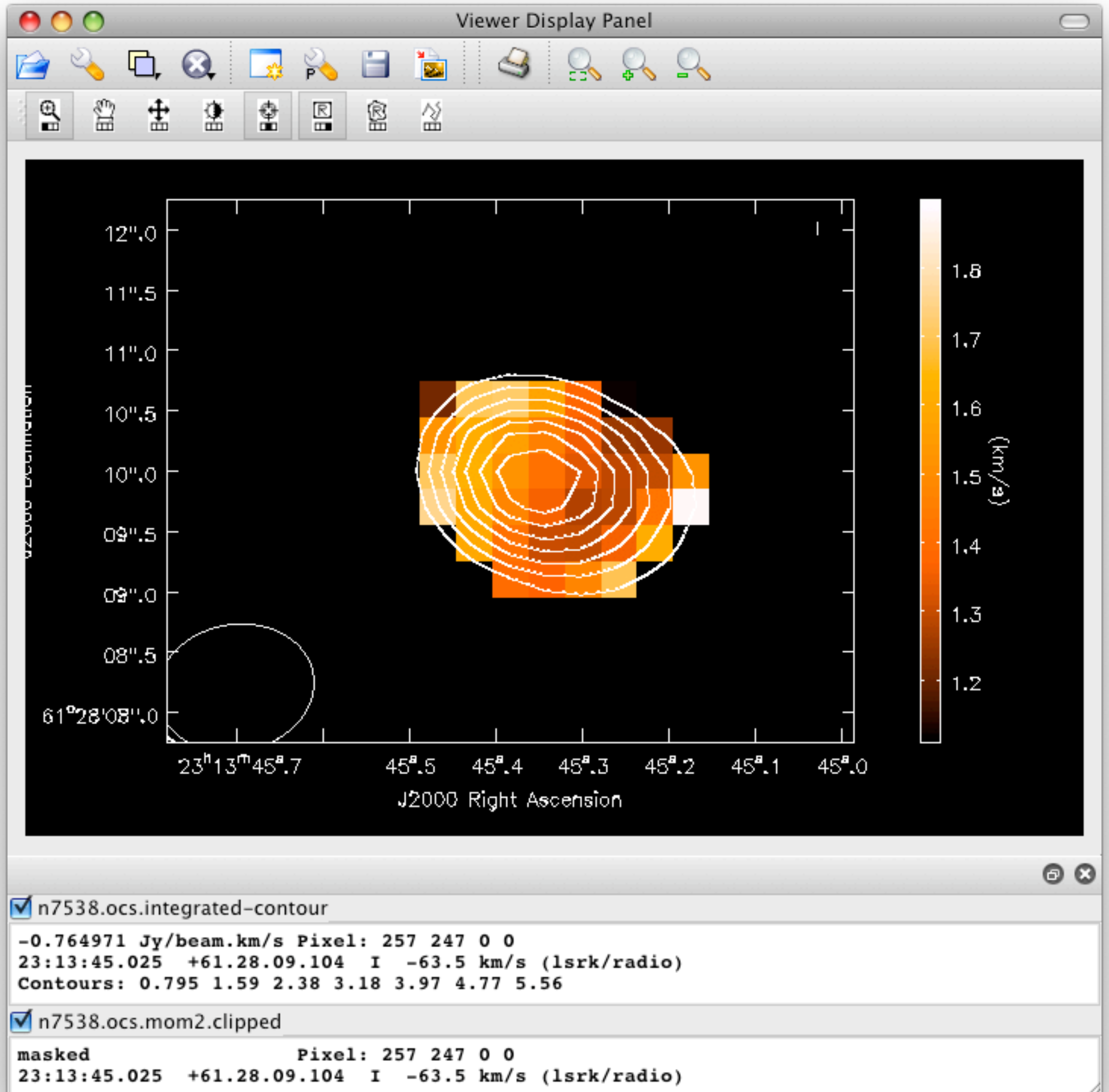
- No clipping applied
  - only range masking
- This needs to be done with `immath`

Velocity Map



- No clipping applied
  - only range masking
- This needs to be done with `immath`

Dispersion Map

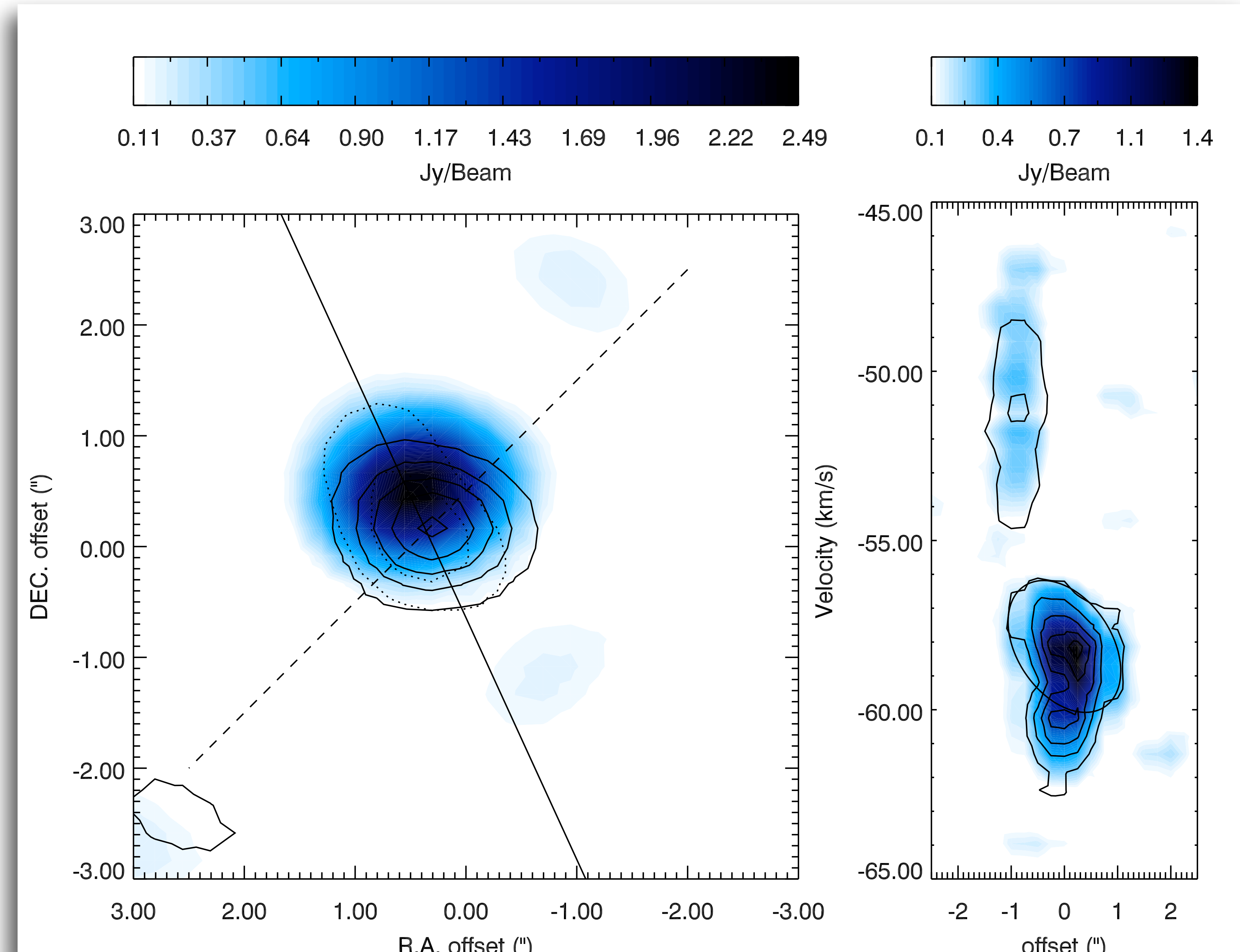


- Velocity Dispersion of the line across the source
- Also clipped like first moment map

Further Image Analysis

- PV Diagrams
  - To see gas kinematics
- Imaging Large Scale Structures
  - Multiple configs.
  - Mosaicing

Position Velocity Diagrams



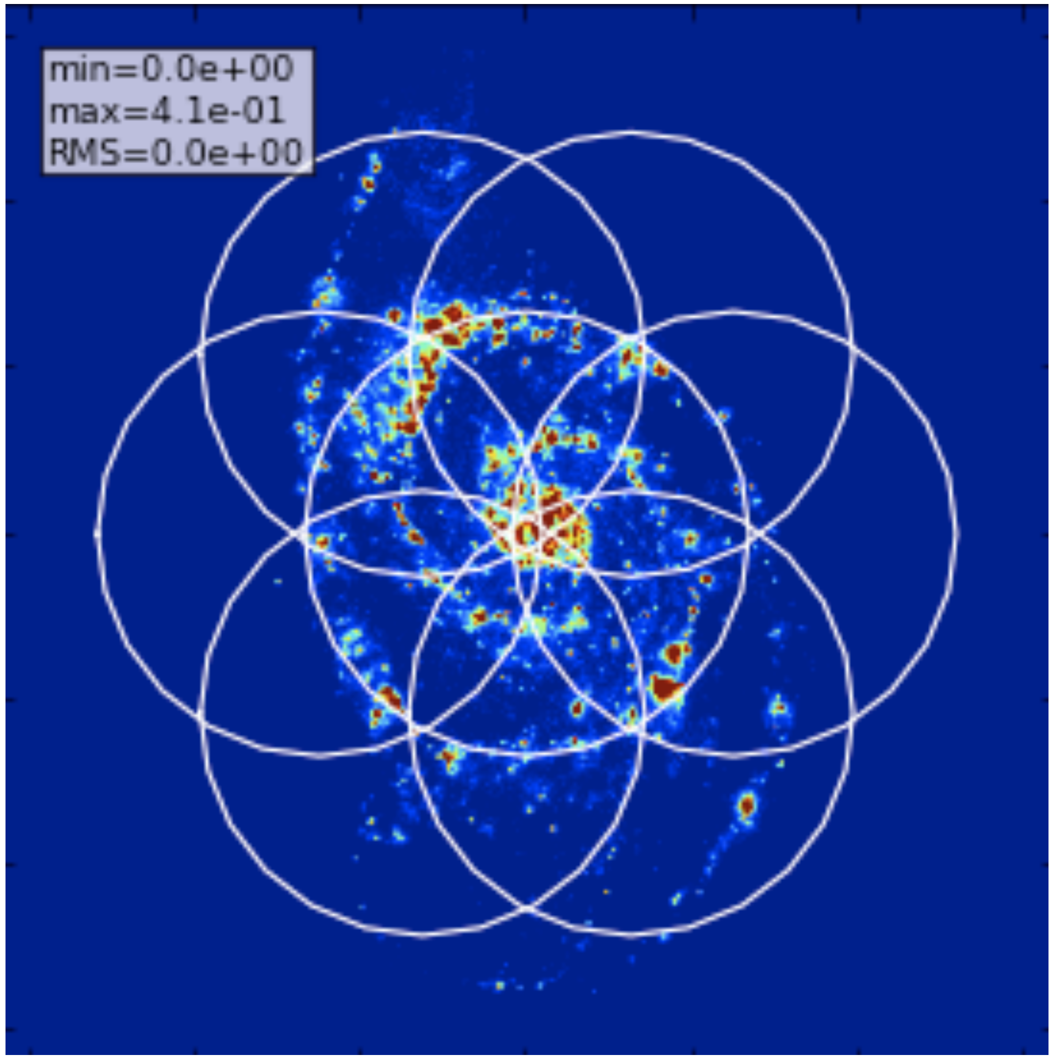
CASA can not make PV diagrams **YET**

But, data can be exported to fits

Klaassen et al. 2009

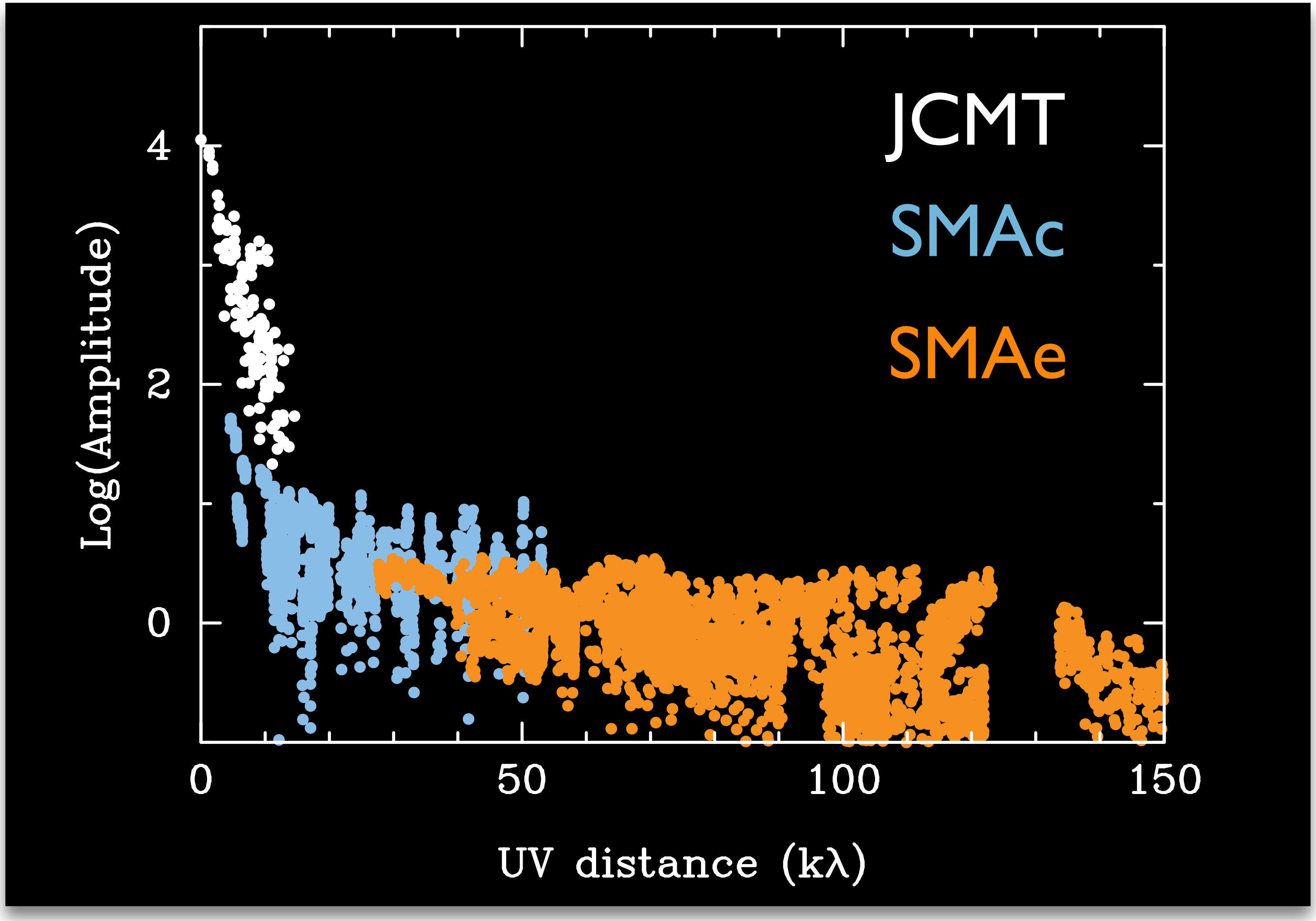
Combining Data

- Each ALMA field will be small
  - with large structures filtered out
- To counteract this, combine multiple:
  - pointings
  - configurations

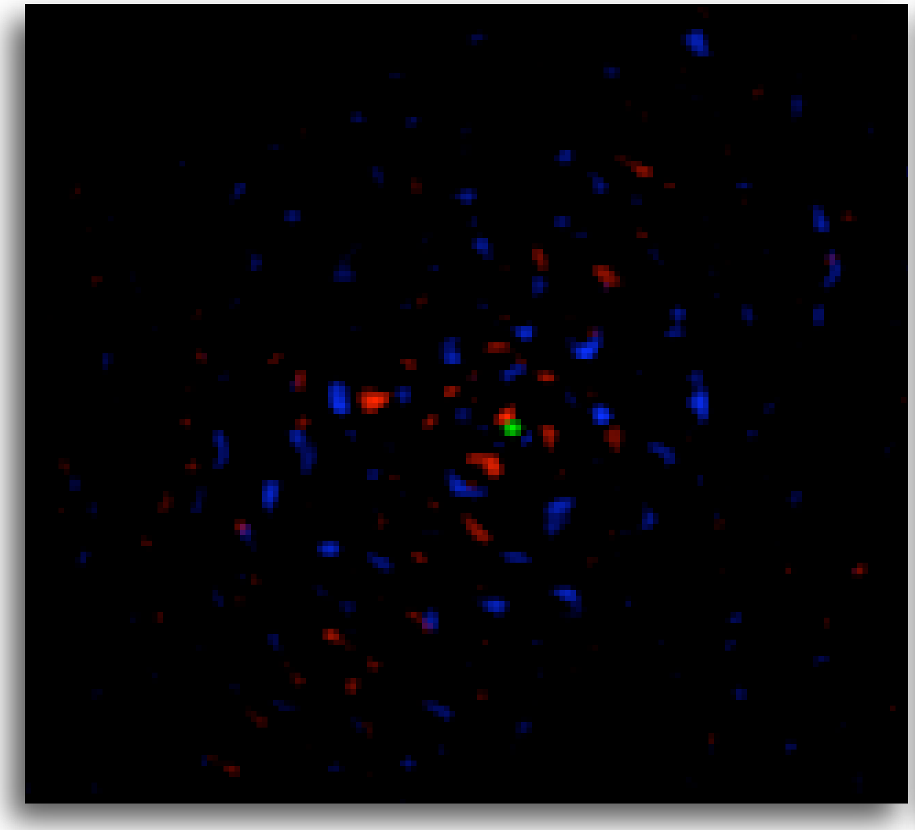


M51 from the ALMA simulator

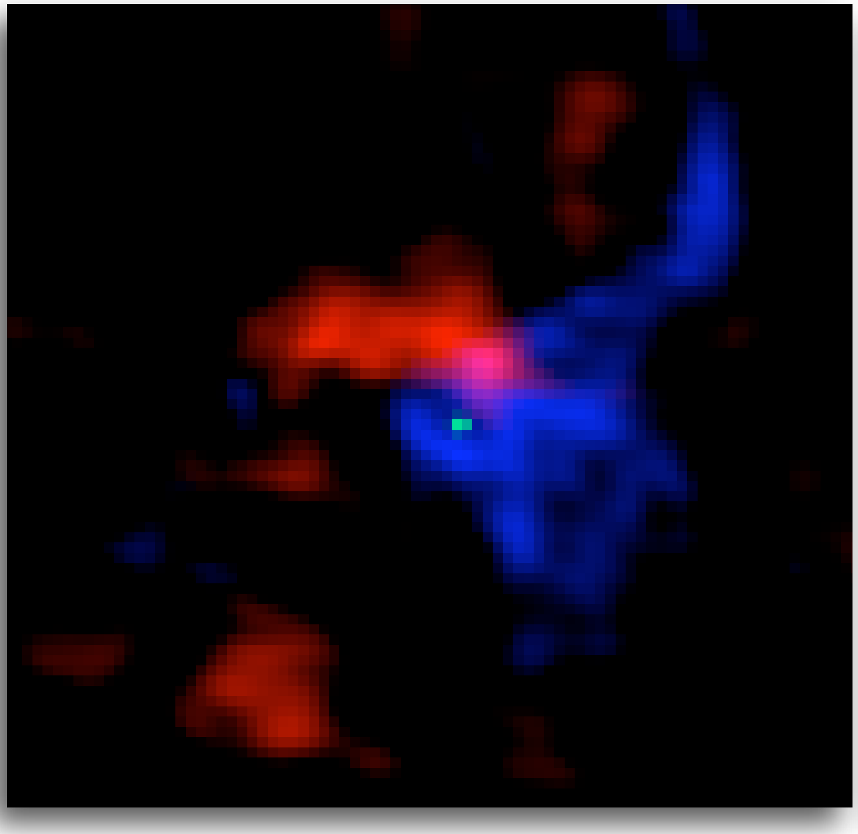
Imaging Large Scale Structures



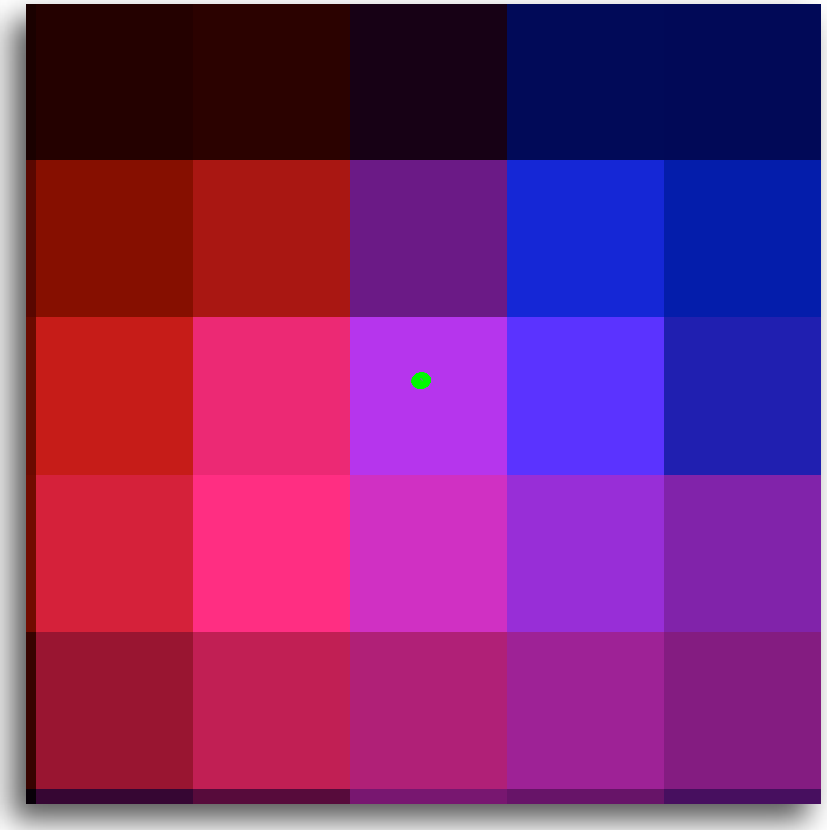
Imaging Large Scale Structures



SMA extended
(1”~10”)



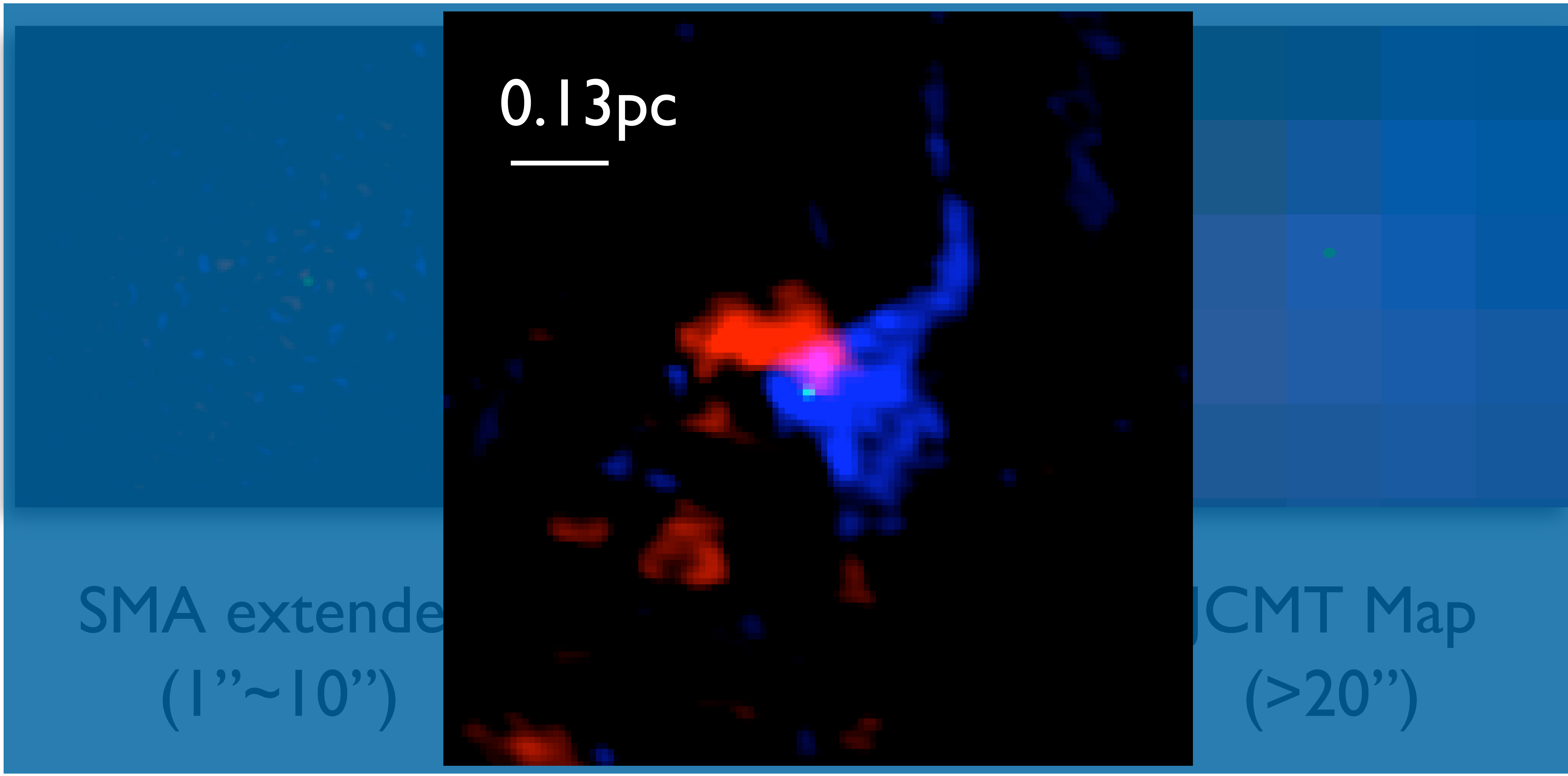
SMA compact
(3”~25”)



JCMT Map
(>20”)

In order to observe large scale structures at high resolution

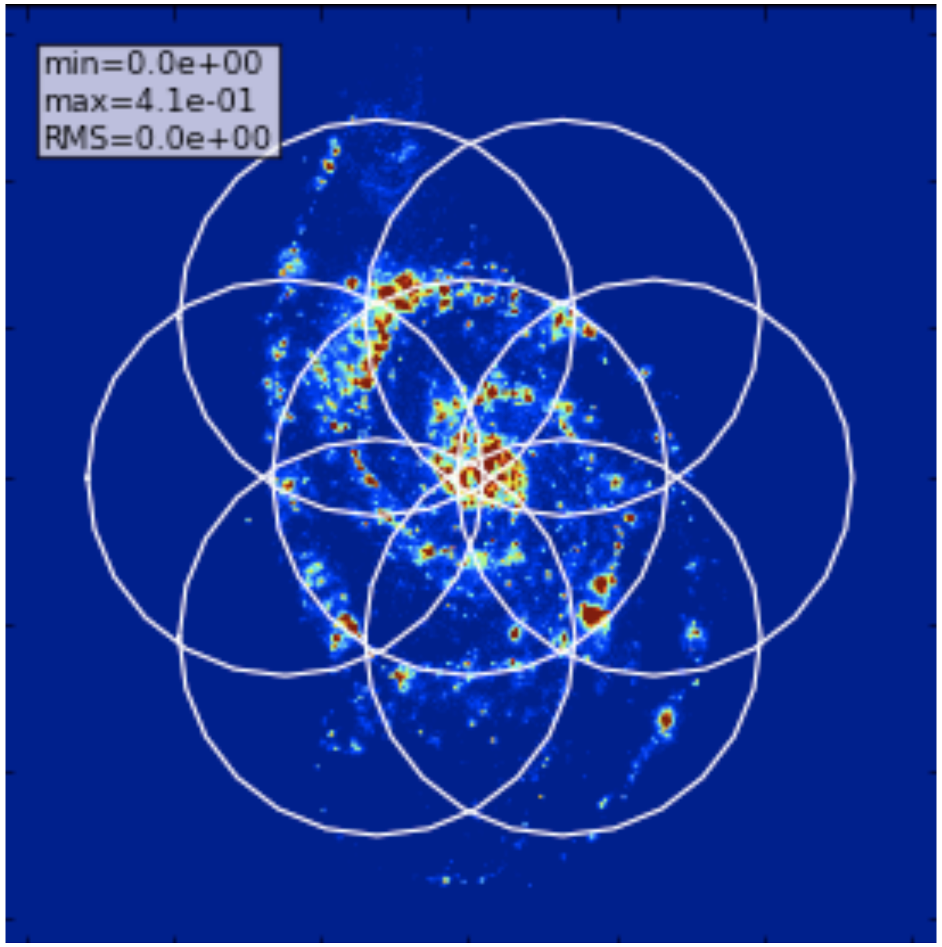
Imaging Large Scale Structures



In order to observe large scale structures at high resolution

Mosaicing

- Combine individual pointings to cover a larger area



12m antennae	54”	115 GHz
	27”	230 GHz
	18”	345 GHz
	9”	690 GHz

Mosaicing

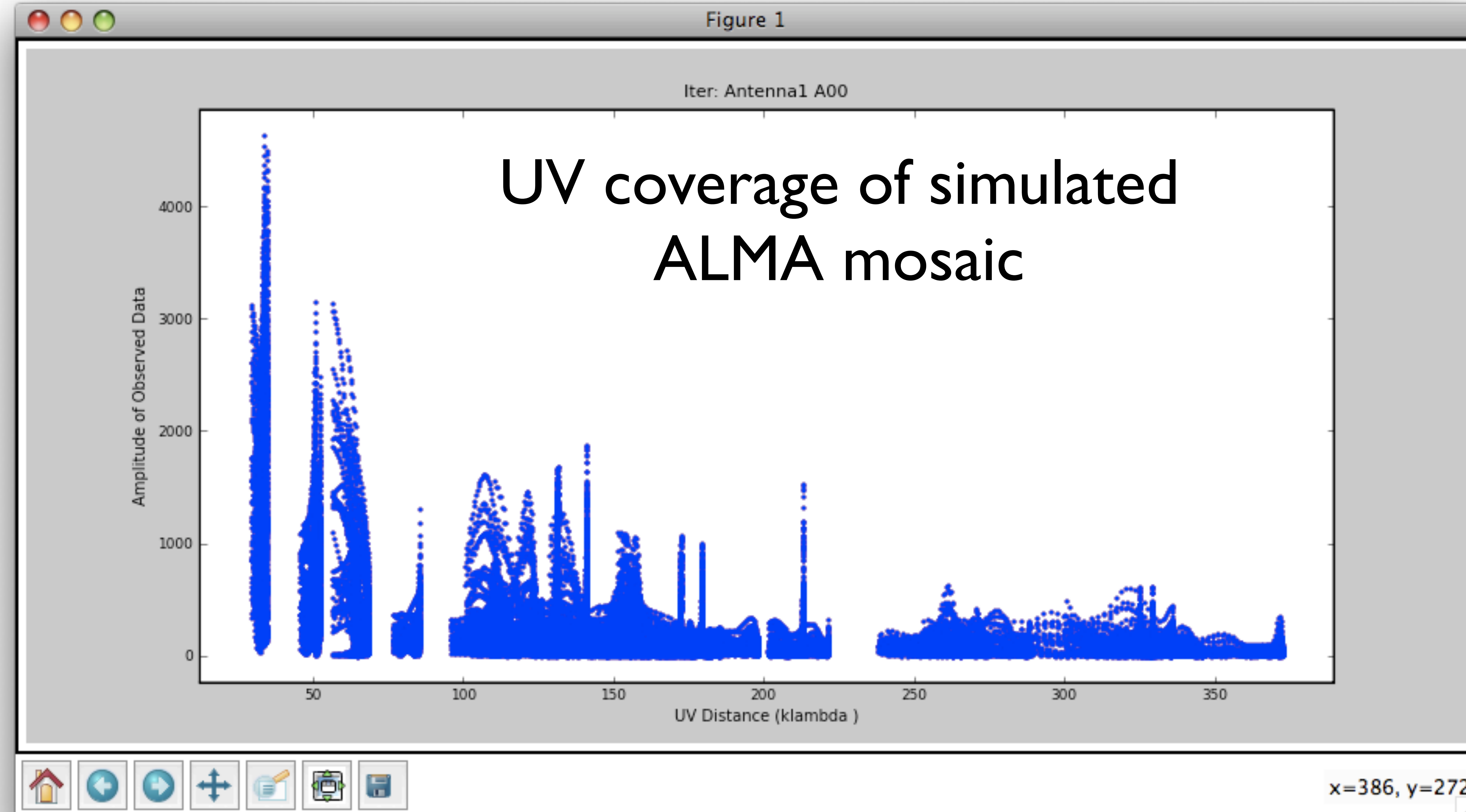
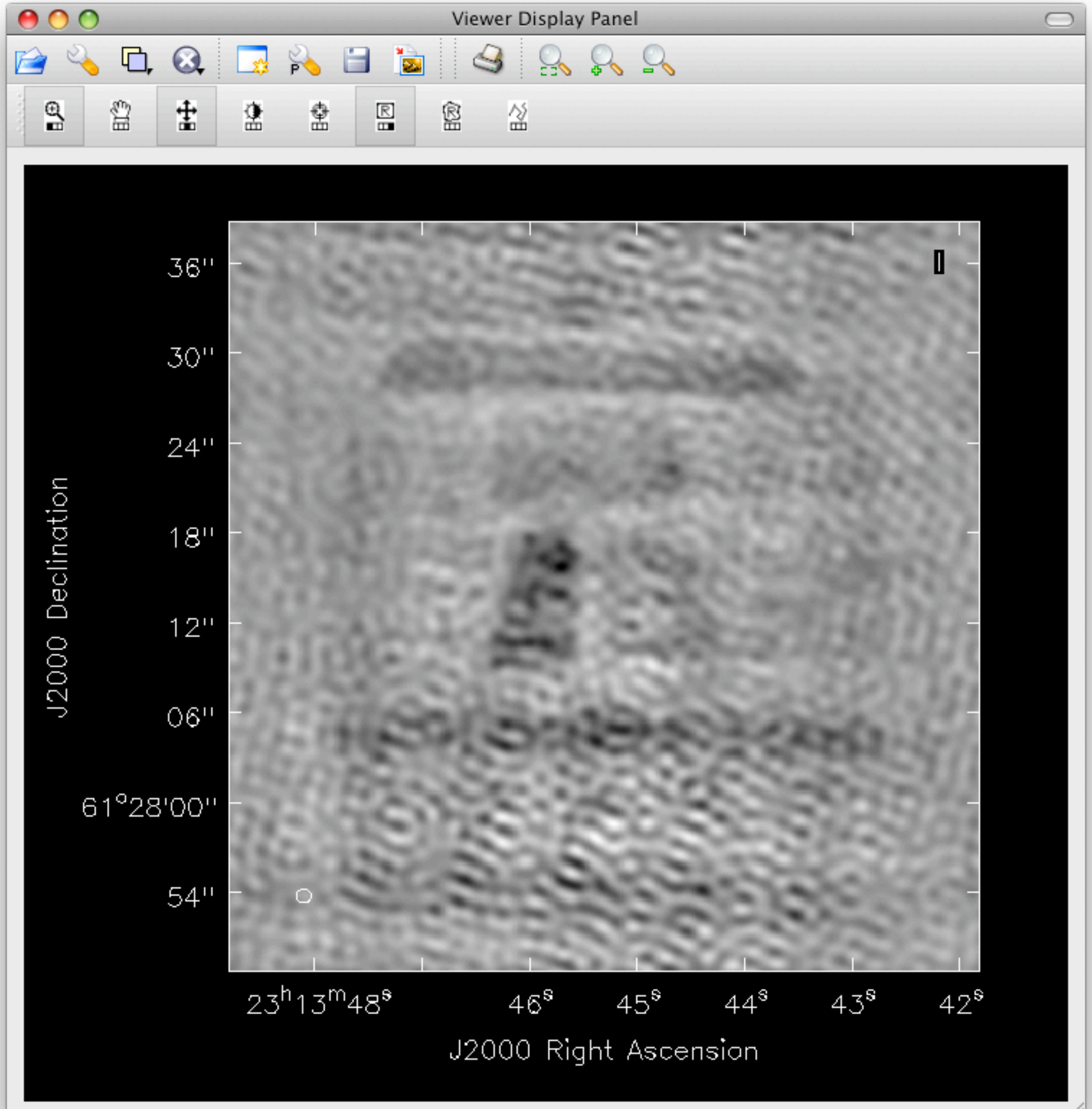


Figure 1
Iter: Antenna1 A00
UV coverage of simulated ALMA mosaic
Amplitude of Observed Data
0
1000
2000
3000
4000
50
100
150
200
250
300
350
UV Distance (klambda)
x=386, y=272

Mosaicing

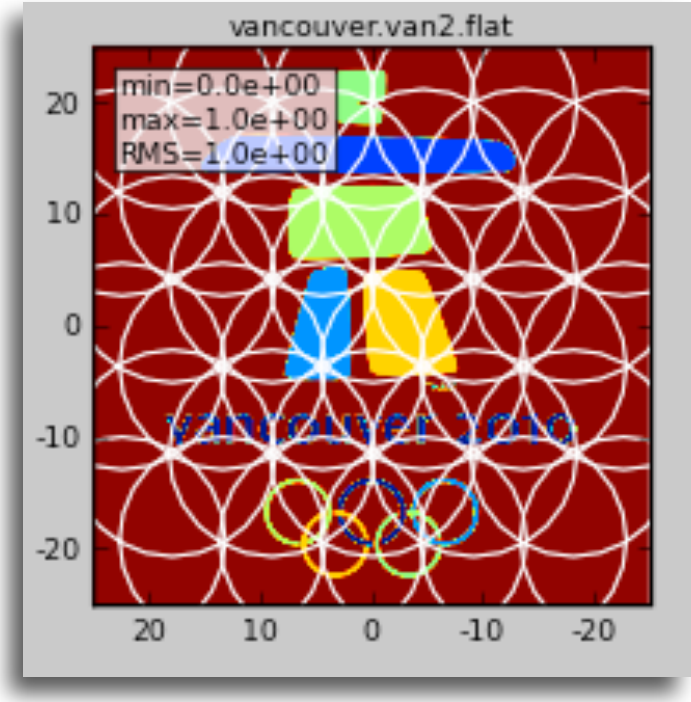
- 15 hours SMA integration (668 GHz)
- 9” spacings



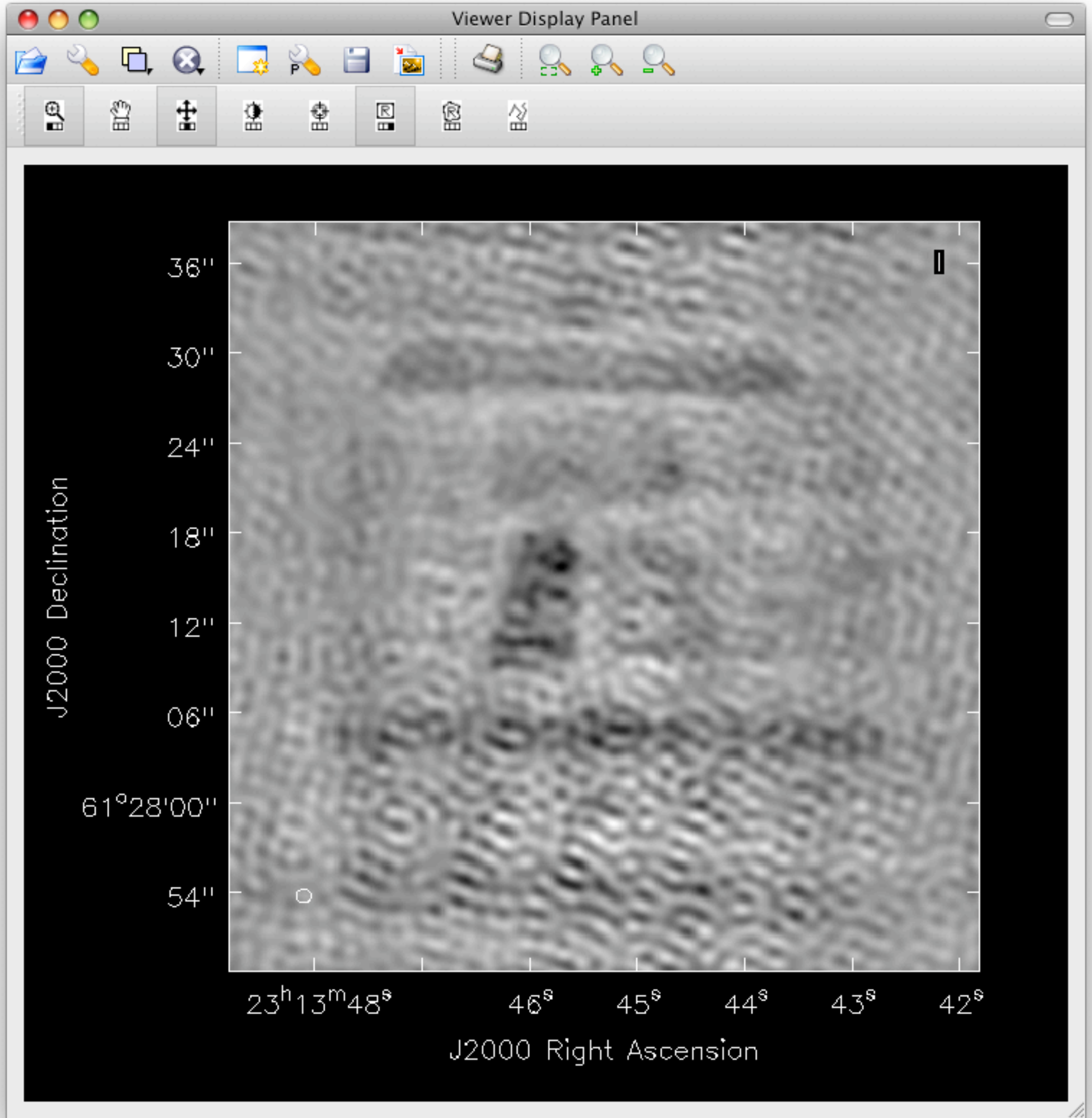
0.3” res

Mosaicing

- 15 hours SMA integration (668 GHz)
- 9” spacings



0.3” res



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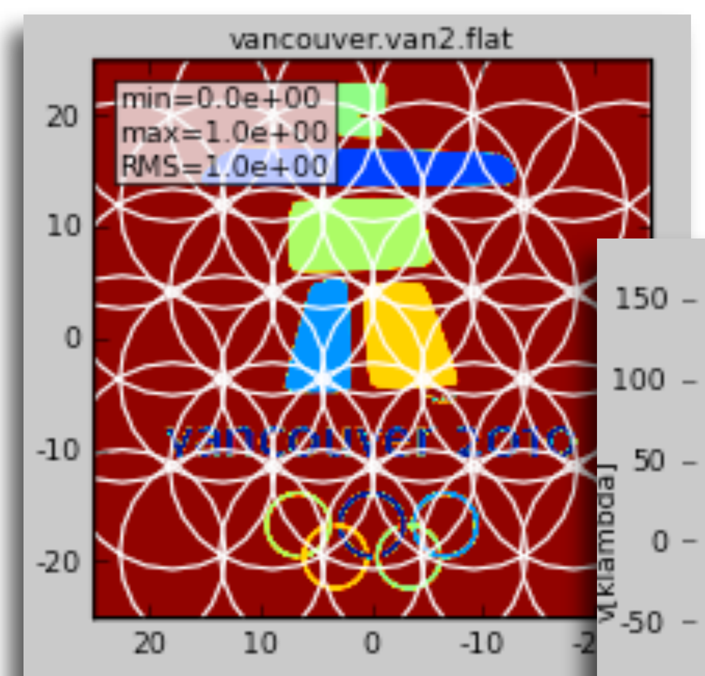
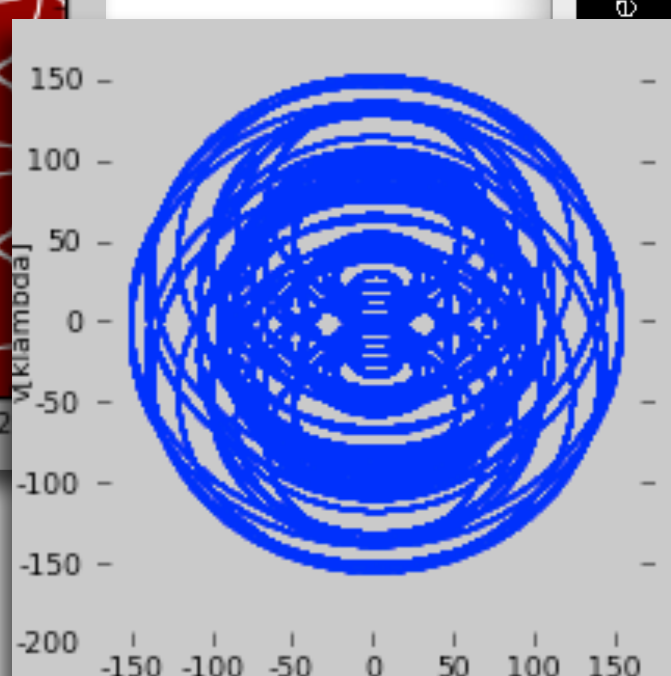
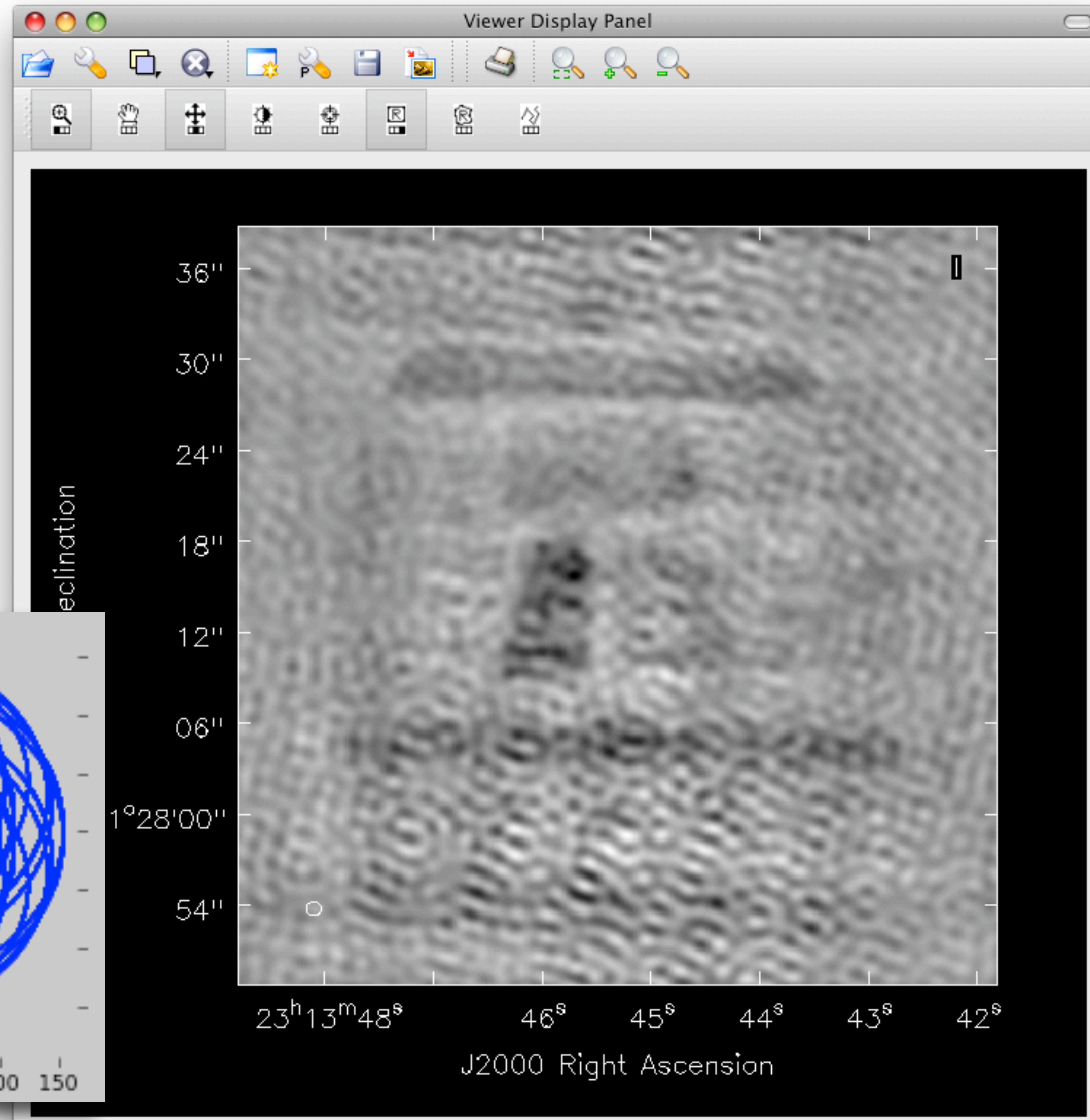


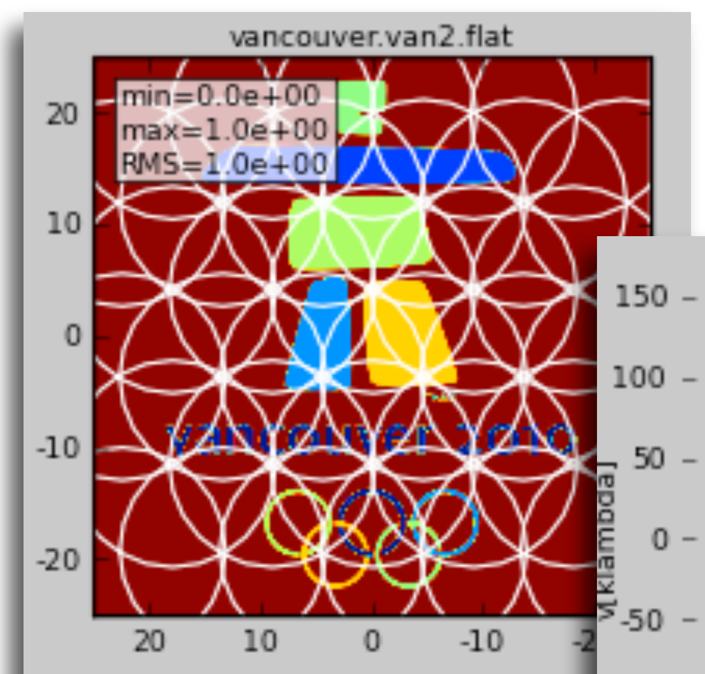


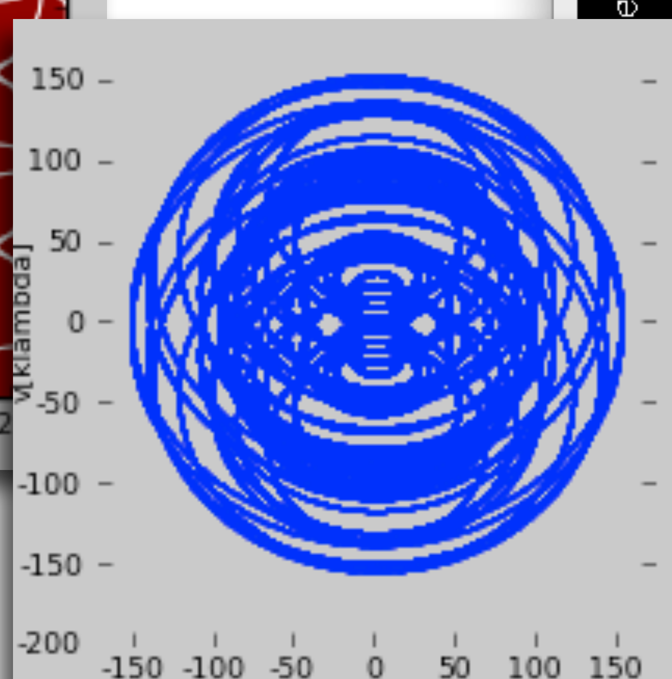


0.3" res

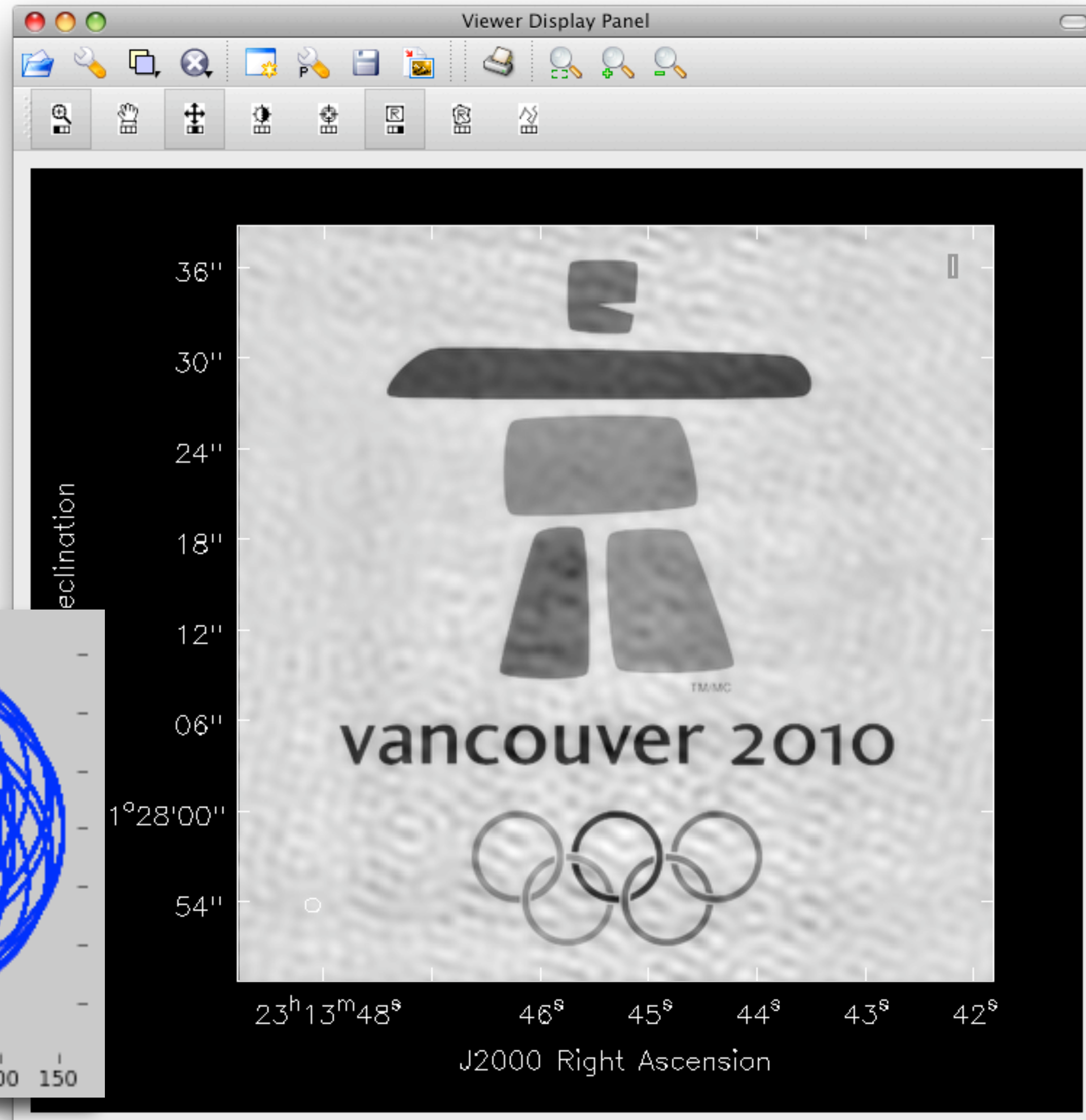
Mosaicing

- 15 hours SMA integration (668 GHz)
- 9” spacings



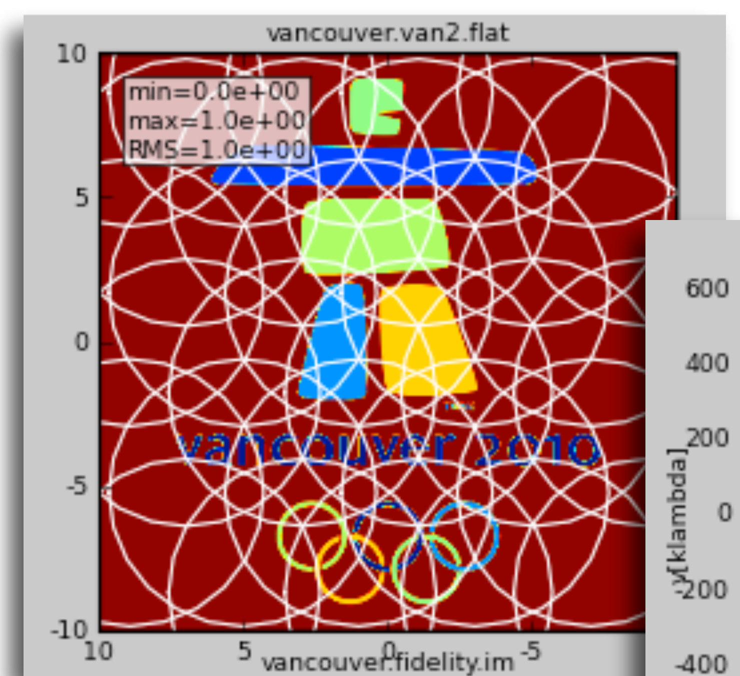


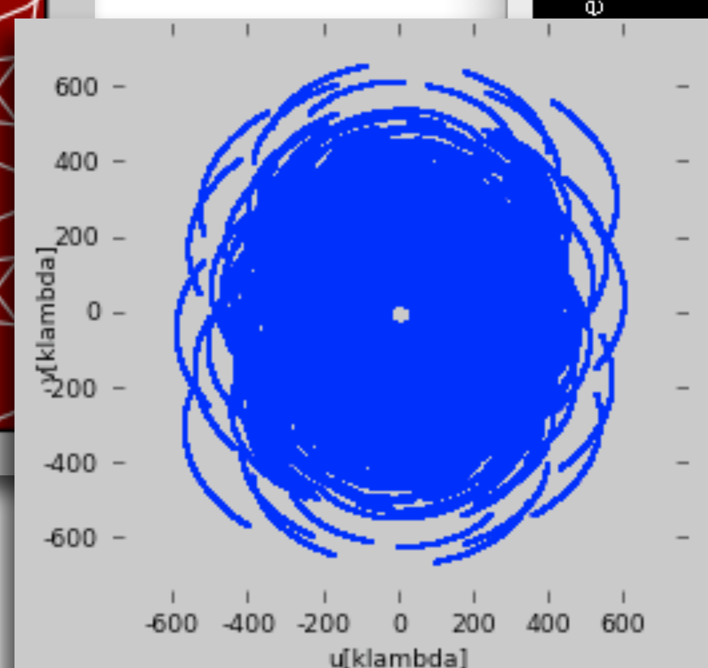
0.3” res

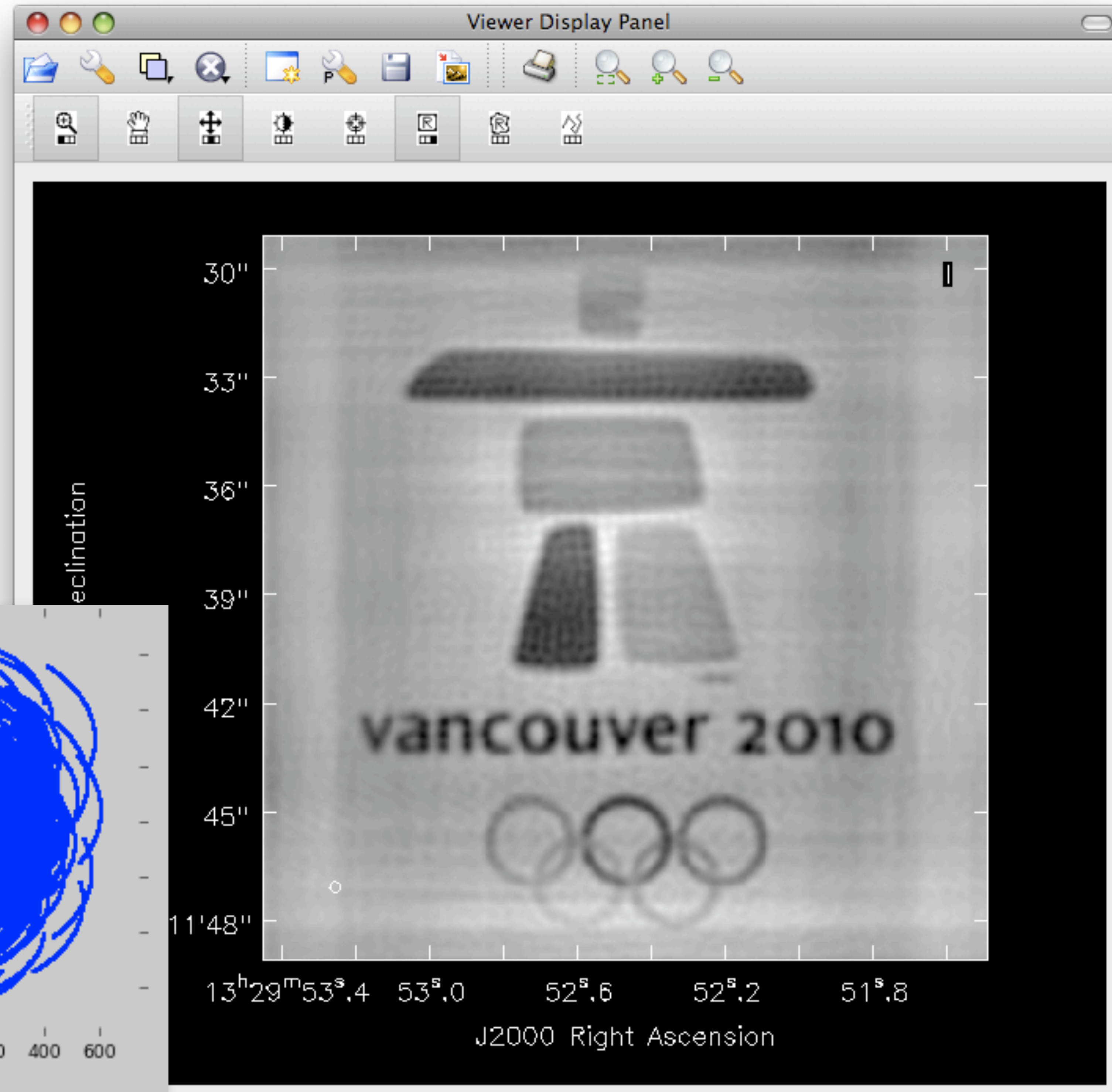


Mosaicing

- 1.5 hour ALMA integration (668 GHz)
- 4” spacings





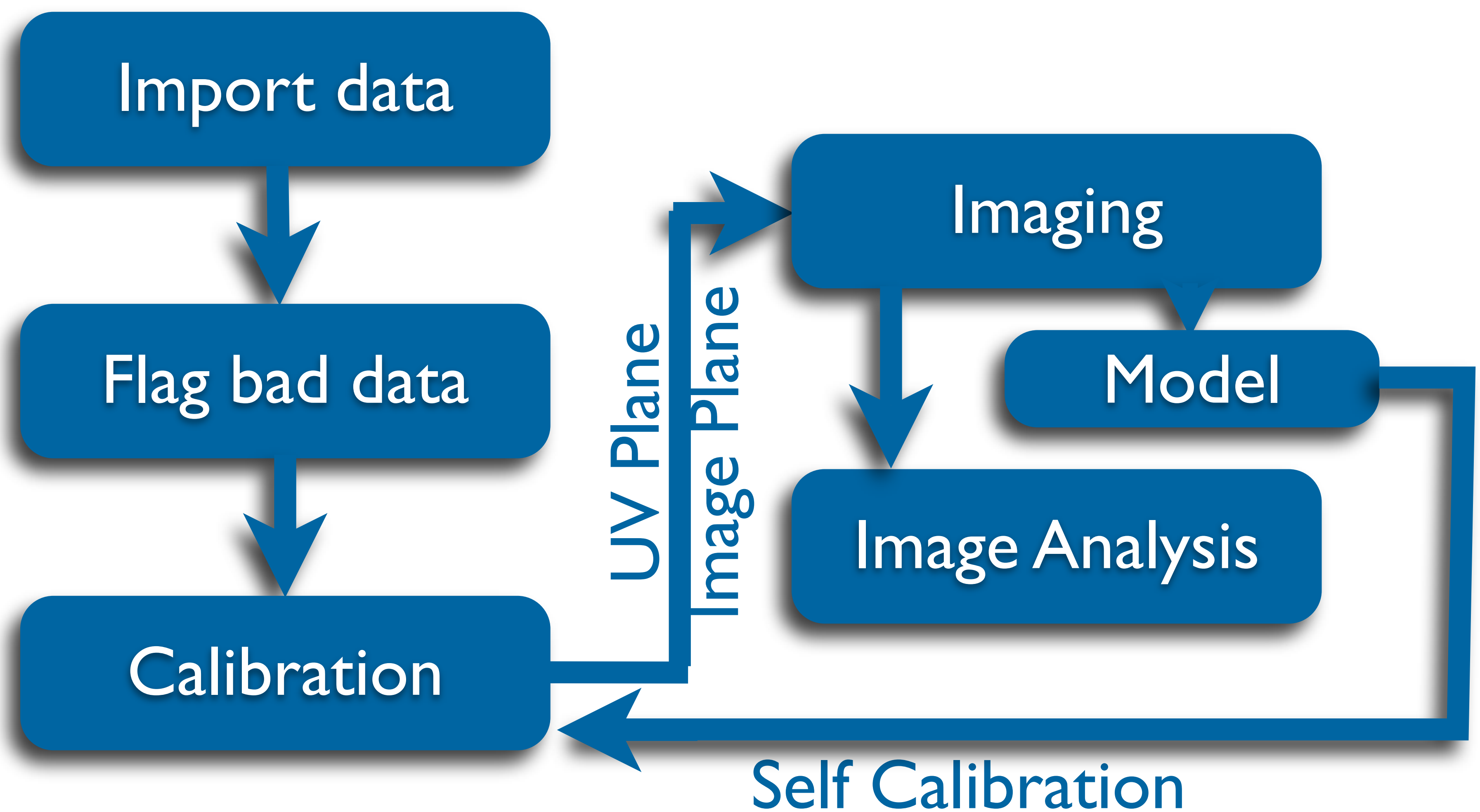


0.08” res

Summary

What information we can get from radio interferometers

Line, Continuum, Masers, Polarization



Calibration

- Done by Pipeline

Imaging

- Cont. Subtraction
- Inverting
- Cleaning

Image Analysis

- Moment Maps
- PV Diagrams
- Mosaics
- Multi-Scale